World Geomorphological Landscapes

Mauro Soldati
Mauro Marchetti *Editors*

Landscapes and Landforms of Italy

Springer

World Geomorphological Landscapes

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Editors

Landscapes and Landforms of Italy

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Series Editors' Preface

Landforms and landscapes vary enormously across the Earth, from high mountains to endless plains. At a smaller scale, Nature often surprises us creating shapes which look improbable. Many physical landscapes are so immensely beautiful that they received the highest possible recognition—they hold the status of World Heritage properties. Apart from often being immensely scenic, landscapes tell stories which not uncommonly can be traced back in time for tens of million years and include unique events. In addition, many landscapes owe their appearance and harmony not solely to the natural forces. Since centuries, or even millennia, they have been shaped by humans who modified hillslopes, river courses, and coastlines, and erected structures which often blend with the natural landforms to form inseparable entities.

These landscapes are studied by Geomorphology—'the Science of Scenery'—a part of Earth Sciences that focuses on landforms, their assemblages, surface and subsurface processes that moulded them in the past and that change them today. Shapes of landforms and regularities of their spatial distribution, their origin, evolution, and ages are the subject of research. Geomorphology is also a science of considerable practical importance since many geomorphic processes occur so suddenly and unexpectedly, and with such a force that they pose significant hazards to human populations and not uncommonly result in considerable damage or even casualties.

To show the importance of geomorphology in understanding the landscape, and to present the beauty and diversity of the geomorphological sceneries across the world, we have launched a new book series *World Geomorphological Landscapes*. It aims to be a scientific library of monographs that present and explain physical landscapes, focusing on both representative and uniquely spectacular examples. Each book will contain details on geomorphology of a particular country or a geographically coherent region. This volume presents geomorphology of Italy—a country with highly diverse landscapes, from lowlands crossed by big rivers to active volcanoes and very high mountains. It is also very dynamic geomorphology, continuously shaped by earthquakes, eruptions, landslides, floods and vigorous erosion in clayey materials producing spectacular badlands. Each of these aspects of Italian geomorphology has received its due coverage. More than thirty selected examples from mainland Italy and its islands are presented, along with fascinating stories behind the marvellous sceneries, including long-term interactions between physical landscapes and people. Thus, the book is not only suitable for scientists and students of Geography and Earth Science, but can also provide guidance to holidaymaking geoscientists as to where to go to enjoy the very best scenery.

The World Geomorphological Landscapes series is produced under the scientific patronage of the International Association of Geomorphologists—a society that brings together geomorphologists from all around the world. The IAG was established in 1989 and is an independent scientific association affiliated with the International Geographical Union and the International Union of Geological Sciences. Among its main aims are to promote geomorphology and to foster dissemination of geomorphological knowledge. I believe that this lavishly illustrated series, which sticks to the scientific rigour, is the most appropriate means to fulfil these aims and to serve the geoscientific community. To this end, my great thanks go to Profs. Mauro Soldati and Mauro Marchetti for coordinating the efforts of Italian geomorphological community and expertly editing the book, as well as to all individual contributors who worked together to show us the Italian landscape at its best.

Piotr Migoń

Foreword

The great variety of landscapes makes Italy a very significant country from the geomorphological point of view. The geological history has given fundamental imprint to the morphology of the country, building two large chains, the Alps and the Apennines, still evolving. To the north, the Po Valley, between these chains, completes the continental portion of the territory. The Italian peninsular area has its main framework in the Apennine ridge that, starting from the mainland, wedges powerfully into the Mediterranean and launches poetically its string of islands as a safe harbour to the Mediterranean populations. The peninsular Italy, together with the main islands reaches to the south latitudes comparable to those of the northern coast of the African continent. This large latitudinal extension, from north to south, makes Italy a country with extreme climate and, consequently, landscape variability. Climate variability and tectonic events are the foundation of current and past geomorphological evolution. During the Pleistocene the latter created most of the landforms currently observed at different scales and that mainly derive from glacial, fluvial, coastal, volcanic, karst, gravitational and aeolian morphogenetic processes. As in other parts of the world, in Italy the natural geomorphological processes have created beautiful and highly scenic landscapes; next to these, anthropic landscapes of great cultural value are overlapped. A wide range of these landscapes is described in this volume that contains more than thirty cases, representative of all morphogenetic environments, both natural and human. About the cultural value of the Italian landscape, I like to point out that, among the cultural and natural properties recognized by UNESCO as heritage of humanity, Italy is the country that has the largest number of sites included in the World Heritage List. Not by chance, the Italian territory has been a crossroads of peoples and cultures unique in the world where man, over the centuries, has changed river courses, swamps, coasts, slopes, forests, creating sites and morphologies that have been integrated into the natural landscape forming a unique and harmonious entity.

In the European Landscape Convention (ELC), landscape is considered as common heritage of individuals and active subject for the construction of a national and European identity, that people cannot ignore. In this context, the Italian landscape is, in my opinion, the cradle and the laboratory of multi-ethnic cultural and technological identities that go beyond the European context and that are made through the centuries with the participation of many peoples such as Greeks, Phoenicians, Gauls, Romans, Byzantines, Goths, Lombards, Carolingian, Arabs, Normans and, finally, Spanish and French. These peoples, together with the Italians, overlapped their cultures and their way of operating into the landscape, making Italy the largest historical artistic and environmental library. The European Convention defines the landscape as "a certain part of the territory, as perceived by people, whose character derives from natural and/or human factors and their interrelationships." Including all the territory in the concept of active landscape is crucial because each location or natural space is related to other places; all together they establish complex interconnections between them and the urban and rural areas. Therefore, three typologies of landscapes are considered: the exceptional landscapes, the daily-life landscapes and the degraded landscapes. In this context, Geomorphology plays a major role (at different scales): interprets the relations among the great morphodynamic systems (hills, valleys, coasts); identifies the supporting skeleton and that of greater visual impact among different types of landscape; identifies forces and pressures (natural and anthropic) that can transform them; presents protection and enhancement solutions, in a sustainable perspective. The study of the landscape is characterized by a clear diversity of disciplinary approaches and the consequent relational processes are the main theme of the Convention, which then takes a great effect of stimulation and dialogue between various disciplines. The approaches of each individual discipline to the landscape in many cases lead to consider only some components. However, in my opinion, the issues of "Geomorphology" are the "substrate" of the landscape and contribute significantly to a holistic vision of the same, having the intrinsic ability to relate all the system components (abiotic, biotic and cultural). Fundamental is the contribution of geomorphology to the identification of macro and micro landforms and exploitation of their origin (natural or human), as well as their evolution over time. The contribution of geomorphological methods to the implementation of the Convention guiding philosophy is, in my opinion, considerable and may even result as a good base for dialogue between the various disciplines involved.

Gilberto Pambianchi

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About the Editors

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Introduction to the Landscapes and Landforms of Italy

1

Mauro Soldati and Mauro Marchetti

> *Alle bellezze ed alle ricchezze scientifiche delle Alpi, noi aggiungiamo quelle così diverse dell'Appennino; e quando avremo descritto i nostri ghiacciai, le nostre rupi e le gole delle Alpi e delle Prealpi, troveremo altri nuovi mondi da descrivere; le emanazioni gazose, le fontane ardenti, le salse e i vulcani di fango, i veri vulcani o vivi o spenti, il Vesuvio, l'Etna, poi ancora il mare e le sue isole, i climi diversi, le diverse zone di vegetazione dalla subtropicale alla glaciale, e così discorrendo, chè l'Italia è quasi (non balbetto nel dirlo) la sintesi del mondo fisico.*
>
> *To the beauty and scientific richness of the Alps, we add those so diverse of the Apennines; and when we have described our glaciers, our cliffs and gorges of the Alps and Prealps, we will find other new worlds to describe; the gaseous emissions, the fiery fountains, the mud volcanoes, the true volcanoes either alive or extinguished, the Vesuvius, the Etna, and again the sea and its islands, the different climates, the different vegetation zones from subtropical to glacial, and so on, because Italy is almost (I do not mumble in saying it) the synthesis of the physical world.*
>
> Antonio Stoppani 1876
> II Bel Paese (The Beautiful Country)

Italian landscapes and landforms show an outstanding variety due to long-term geological processes and climate changes. Landscape diversity in many regions of the country is also deeply connected with human presence since ancient times, cultural and political diversity as well as highly varied customs and traditions. Also for these reasons, Italy has been a privileged destination for generations of travellers, intellectuals and artists attracted by fascinating landscapes which perfectly frame architecture and art masterpieces. Nowadays Italy is one of the most important tourist destinations in the world, with more than 50 million international visitors every year.

The first comprehensive essay on the landscape of Italy, *II Bel Paese* ('The Beautiful Country'), was written by Abbot Antonio Stoppani in 1876. The 'natural beauties, geology and physical geography of Italy' are marvellously described in the original form of conversations to be held on 29 different evenings. Noteworthy is also the first compendium of Italian topographic maps produced in the form of an 'Atlas of Geographic Types' by the Florentine professor Olinto Marinelli—admirer and friend of William Morris Davis—which was published by the Istituto Geografico Militare in 1922. Further and more traditional treatises on the landscape of Italy came a few years after the Second World War as a witness of the increasing interest for landscape appraisal. Roberto Almagià in 1959 provided an outstanding overview of the geography of Italy, included in two weighty volumes (entitled *Italia*) published by UTET publishing house. The first illustrates in detail the physical aspects of the country with the aid of remarkable photographs and a series of valuable historic and topographic maps, whilst the second takes into account economic and human-related aspects. Aldo Sestini in another milestone on the physical geography of Italy, the book entitled *Il Paesaggio* ('The Landscape') and published in 1963 by Touring Club Italiano, stated that the Italian '*landscape acquires higher interest and offers more spiritual pleasure when it is observed by those who are able to recognise the compositional elements, the peculiar variety and the natural and human factors that contributed to form it*'. This is a key issue for those who wish to approach and get to know the Italian territory.

A strong input to the study of physical landscape of Italy was made in 1980s by the National Group 'Geografia Fisica e Geomorfologia' (founded in 1982) of the National Research Council (CNR) which in the year 2000 turned into the Associazione Italiana di Geografia Fisica e Geomorfologia (AIGeo) currently representing Italy as National Scientific Member of the International Association of Geomorphologists (IAG). Within this frame, noteworthy is the

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Fig. 1.1 Location of landscapes and landforms described in Part II of the book (in brackets are the numbers of respective chapters). *1* Glaciers of Piedmont and Valle d'Aosta (Chap. 6); *2* Valtellina and Como Lake (Chap. 7); *3* Adamello-Presanella massifs (Chap. 8); *4* Trentino ancient landslides (Chap. 9); *5* Dolomites of Alta Badia (Chap. 10); *6* Vajont Valley (Chap. 11); *7* Karst in Friuli Venezia Giulia (Chap. 12); *8* Tagliamento River (Chap. 13); *9* Garda Lake (Chap. 14); *10* Venice Lagoon (Chap. 15); *11* Po Delta (Chap. 16); *12* Northwestern Apennines' structural landscape (Chap. 17); *13* Emilia large-scale landslides (Chap. 18); *14* Emilia-Romagna mud volcanoes (Chap. 19); *15* Cinque Terre terraced landscape (Chap. 20); *16* Tuscany hills and valleys (Chap. 21); *17* Urbino Apennine landscape (Chap. 22); *18* Northern Marche coasts (Chap. 23); *19* Central Italy badlands (Chap. 24); *20* Central Italy tuff cities (Chap. 25); *21* Latium ancient ▶ volcanoes (Chap. 26); *22* Umbria-Marche intermontane basins (Chap. 27); *23* Abruzzo mountains (Chap. 28); *24* Rome urban landscape (Chap. 29); *25* Sardinia granites (Chap. 30); *26* Sardinia coastal dunes (Chap. 31); *27* Tremiti Islands (Chap. 32); *28* Vesuvius and Campi Flegrei (Chap. 33); *29* Sorrento peninsula and Amalfi coast (Chap. 34); *30* Cilento coasts (Chap. 35); *31* Salento peninsula (Chap. 36); *32* Aspromonte Massif (Chap. 37); *33* Aeolian Islands (Chap. 38); *34* Capo San Vito Peninsula (Chap. 39); *35* Etna Volcano (Chap. 40); *36* Pantelleria Island (Chap. 41). The *blue* rectangle includes the Lampedusa and Linosa islands which are located southward, outside the frame (base map courtesy of Litografia Artistica Cartografica S.r.l., Firenze)

journal *Geografia Fisica e Dinamica Quaternaria* which has been an important recipient of studies on the Italian landscapes and landforms since 1978; the journal is managed by the Comitato Glaciologico Italiano and supported by the AIGeo.

The book *Landscapes and Landforms of Italy*, which comes under the auspices of both the IAG and AIGeo, aims at providing a synoptic overview of the most spectacular landscapes of Italy and at showing outstanding landforms from both a scientific and scenic viewpoint. The volume is divided into three parts. *Part I* introduces the great variety of landscapes and landforms of Italy, providing a background on geological, geomorphological and climatic aspects. *Part II* includes 36 chapters (Fig. 1.1) illustrating different landscapes in a sequence ranging from the high mountains of Northern Italy (the Alps) to the coastal areas of Southern Italy and the islands, passing through hilly and mountain areas of Central Italy (the Apennines). Outstanding landscapes of different origin are described, showing the high geodiversity of the country which includes glacial, fluvial, lacustrine, karst, volcanic, coastal, structural, gravity-induced and aeolian landscapes. Cultural implications on landscapes are also taken into account by two specific chapters devoted to the capital city of Rome and its urban geomorphology, and to landscapes of Central Italy as depicted in Italian Renaissance paintings by famous artists such as Leonardo da Vinci. *Part III* is concerned with peculiar aspects of the country and collects thematic chapters on geoheritage, geomorphodiversity and wine landscapes. Attention is also given to the famous travel of Johann Wolfgang von Goethe and its appraisal of Italian geological landscapes in the eighteenth century.

This book is the result of an exciting joint venture established among Italian geomorphologists, which has also included the participation of valuable experts from other disciplines. More than 80 authors from 29 universities as well as eight research centres and public agencies have contributed to the book.

Every chapter has undergone a thorough peer-review by a team Italian and foreign experts who acted as reviewers, providing precious contribution to the enhancement of the quality of the manuscripts. In this respect, we would like to thank Pierluigi Brandolini, John J. Clague, Doriano Castaldini, Sirio Ciccacci, Paola Coratza, Sunil Kumar De, Maurizio Del Monte, Marta Della Seta, Monique Fort, Paola Fredi, Christian Giusti, Giuseppe Mastronuzzi, Piotr Migon, Gilberto Pambianchi, Mario Panizza, Alessandro Pasuto, Manuela Pelfini, Luisa Pellegrini, Emmanuel Reynard, Daniele Savelli, John A. Schembri and Claudio Tellini.

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Part I

Physical Environment

2 The Great Diversity of Italian Landscapes and Landforms: Their Origin and Human Imprint

Mauro Marchetti, Mauro Soldati, and Vittoria Vandelli

Abstract

An outstanding variety of landscapes and landforms are present in Italy due to its complex geological history, repeated climate changes and increasing human impact through time. This chapter highlights the reasons for the geological and geomorphological diversity of the country by illustrating its geological evolution since the Mesozoic, outlining the paleogeographic changes that occurred as a consequence of Quaternary climate variations, and tracing the unique human civilization history that has so strongly influenced landscape evolution since the Neolithic. Special attention is devoted to the complex history of the country, where peoples coming from different geographical areas met each other contributing to make Italy a compendium of cultural diversity capable of attracting travellers from all over the world. Landscape conservation and protection are finally taken into account.

Keywords

Landscape • Climatic change • Paleogeography • History • Italy

2.1 Introduction

Italy is characterized by extraordinary diversity of landscapes due to its complex long-term geological and climatic evolution, and its unique human civilization history.

From a geological viewpoint, the shape and physical configuration of Italy originates from the collision between the African and Eurasian plates that occurred during the Cenozoic. This geological event caused the closure of the Tethys Sea, and was accompanied by the compression and piling up of its sediments which determined the formation of the two mountain chains that now characterize the Italian territory: the Alps and the Apennines. This tectonic evolution is still ongoing, causing remarkable seismic and volcanic activity, which threaten human settlements and activities. The diversity of Italian landscapes is also due to the wide variety of lithotypes, including the pre-orogenic basement and the successive sedimentary cover.

Dramatic climate changes affected Italy in the last 25,000 years leading to relevant geographical and morphoclimatic changes, including remarkable coastline variations. At present, diverse climatic conditions characterize the country influencing landform evolution. This is principally due to the wide latitudinal extent of Italy, and to the altitudinal range from over 4800 m to sea level, and locally below. In addition, the presence of the Alps and Apennines significantly influences the general air circulation; the fact that the country is enveloped by the sea along *ca.* 7500 km determines also a significant variety of regional and local morphoclimatic conditions.

The human presence since prehistoric times has itself profoundly contributed to the shaping of Italian landscapes. Numerous and different communities who alternatively ruled and lived in the Italian territory have left a clear imprint in

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the land use and management (such as terracing, land reclamation, management of water courses, land division, farming), providing the means to make Italy a compendium of environmental diversity where, through time, a melting-pot of different cultures developed thanks to Mediterranean, Slavic and German influxes. This has also provided the ground for the development of Italian “cultural landscape” which has attracted travellers and visitors for a long time.

2.2 Physiography of Italy

Italy consists of a peninsula elongated in a N–S direction into the central Mediterranean Sea and of two major islands, Sardinia and Sicily (Fig. 2.1). The peninsula and Sicily show a peculiar boot shape delimited in the north by the Alps. The Mediterranean Sea enveloping Italy locally takes different names, such as the Tyrrhenian Sea to the west, the Adriatic Sea to the east, and the Ionian Sea to the southeast of the mainland.

From an administrative viewpoint, Italy borders France to the west, Switzerland and Austria to the north and Slovenia to the east. It is worth noting that within the Italian peninsula two foreign states are included: San Marino (61.2 km^2) and Vatican City (0.44 km^2).

Coasts represent an important geographic feature of Italy, since they extend for 7375 km (ISTAT 2015) offering a great diversity of coastal landscapes and landforms (Fredi and Lupia Palmieri 2017). Mountainous and hilly areas prevail over lowlands (Table 2.1) due to the presence of the Alps and the Apennines which dominate the country from a physiographic viewpoint due to their continuity and significant average altitude (Federici 2000). The Alps, as well as the seas encircling the peninsula, protected Italy from invasions; in historic times, the Apennines constituted the backbone of the country and also a geographical and cultural divide.

The two mountain chains heavily influence the climate of the country since they control wind circulation and precipitation patterns. The Alps protect the Po Plain from the cold currents from Central Europe, while the Apennines restrain the influence of maritime humid air to the west-facing Tyrrhenian side (Fratianni and Acquaotta 2017). The Alps also host a number of glaciers, especially in its western side (Giardino et al. 2017).

The distribution and regime of rivers are strongly influenced by the presence of the Alps and Apennines, with the

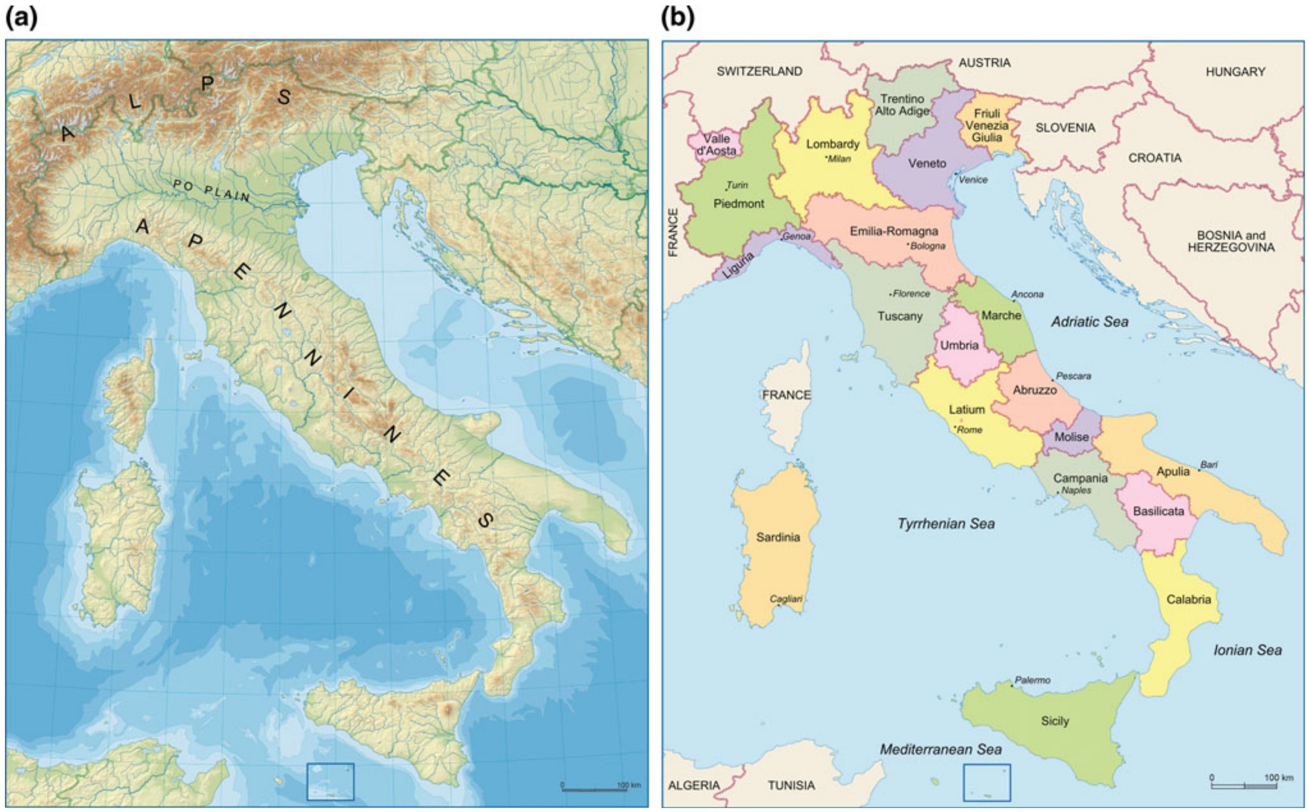
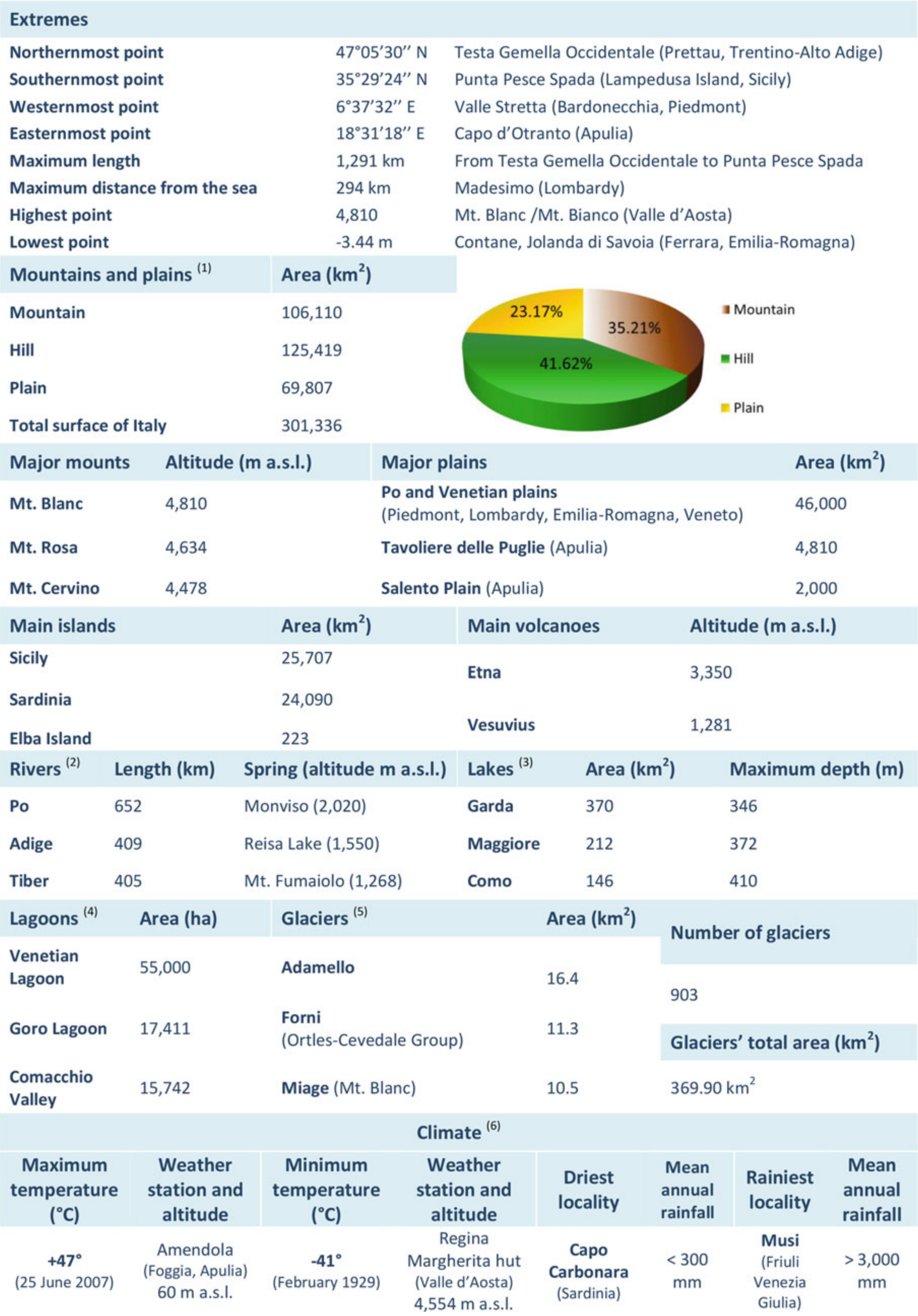


Fig. 2.1 Italy: physical and political setting. The latter displays the 20 administrative regions. The *blue* rectangles include the Lampedusa and Linosa islands which are located southward, outside the frame (base maps courtesy of Litografia Artistica Cartografica S.r.l., Firenze)

Table 2.1 Numbers of Italy



Extremes		
Northernmost point	47°05′30″ N	Testa Gemella Occidentale (Prettau, Trentino-Alto Adige)
Southernmost point	35°29′24″ N	Punta Pesce Spada (Lampedusa Island, Sicily)
Westernmost point	6°37′32″ E	Valle Stretta (Bardonecchia, Piedmont)
Easternmost point	18°31′18″ E	Capo d'Otranto (Apulia)
Maximum length	1,291 km	From Testa Gemella Occidentale to Punta Pesce Spada
Maximum distance from the sea	294 km	Madesimo (Lombardy)
Highest point	4,810	Mt. Blanc /Mt. Bianco (Valle d'Aosta)
Lowest point	-3.44 m	Contane, Jolanda di Savoia (Ferrara, Emilia-Romagna)

Mountains and plains (1)	Area (km^2)
Mountain	106,110
Hill	125,419
Plain	69,807
Total surface of Italy	301,336

Major mounts	Altitude (m a.s.l.)	Major plains	Area (km^2)
Mt. Blanc	4,810	**Po and Venetian plains** (Piedmont, Lombardy, Emilia-Romagna, Veneto)	46,000
Mt. Rosa	4,634	**Tavoliere delle Puglie** (Apulia)	4,810
Mt. Cervino	4,478	**Salento Plain** (Apulia)	2,000

Main islands	Area (km^2)	Main volcanoes	Altitude (m a.s.l.)
Sicily	25,707	**Etna**	3,350
Sardinia	24,090	**Vesuvius**	1,281
Elba Island	223		

Rivers (2)	Length (km)	Spring (altitude m a.s.l.)	Lakes (3)	Area (km^2)	Maximum depth (m)
Po	652	Monviso (2,020)	**Garda**	370	346
Adige	409	Reisa Lake (1,550)	**Maggiore**	212	372
Tiber	405	Mt. Fumaiolo (1,268)	**Como**	146	410

Lagoons (4)	Area (ha)	Glaciers (5)	Area (km^2)	Number of glaciers
Venetian Lagoon	55,000	**Adamello**	16.4	903
Goro Lagoon	17,411	**Forni** (Ortles-Cevedale Group)	11.3	**Glaciers' total area (km^2)**
Comacchio Valley	15,742	**Miage** (Mt. Blanc)	10.5	369.90 km^2

Climate (6)							
Maximum temperature (°C)	**Weather station and altitude**	**Minimum temperature (°C)**	**Weather station and altitude**	**Driest locality**	**Mean annual rainfall**	**Rainiest locality**	**Mean annual rainfall**
+47° (25 June 2007)	Amendola (Foggia, Apulia) 60 m a.s.l.	**-41°** (February 1929)	Regina Margherita hut (Valle d'Aosta) 4,554 m a.s.l.	**Capo Carbonara** (Sardinia)	< 300 mm	**Musi** (Friuli Venezia Giulia)	> 3,000 mm

Schematic description of main physiographic features of Italy according to: (1) ISTAT (2015); (2) Marchetti (2008); (3) Fredi and Pelfini (2008); (4) De Pippo and Valente (2008); (5) Smiraglia and Diolaiuti (2015); (6) Fratianni and Acquaotta (2017) rivers flowing from the Alps being longer and having higher discharge. Plain areas are not frequent in Italy though the northern part of the country is dominated by the Po Plain (constituting 70% of level areas of Italy) which results from the accumulation of fluvial sediments deposited by the main Italian river during the last one million years. Lakes of different origin are present throughout Italy. The main lakes located at the southern margin of the Alps are related to both structural causes and action of ancient glaciers (Table 2.1). Central Italy is instead characterized by a series of volcanic lakes (Fredi and Ciccacci 2017).

The main geographic features of the country are reported in Table 2.1.

2.3 Long-Term Geological History and Paleogeography of Italy

Italy is characterized by considerable geological diversity which is largely related to its long-term geological history (Bosellini 2005, 2017). The topical geological events which have made Italy such a complex land from a tectonic and lithologic viewpoint will be briefly described below, as well as the main climatic phases which profoundly changed the geography of Italy through time due to remarkable sea-level variations.

At the beginning of the Mesozoic (*ca.* 250 Ma BP), when all continents were joined into one (Pangea supercontinent) and surrounded by a single ocean (Panthalassa) most of the Italian peninsula was submerged by the relatively shallow and warm waters of the Tethys Gulf (Fig. 2.2). The Triassic Italian landscape was substantially different from the present-day one: most of the contemporary lands were covered by a shallow, epi-continental sea. Locally there were groups of white sandy atolls surrounded by deep sea branches and protected by huge coral reefs. The latter, due to mountain building processes, have been uplifted more than 3000 m and nowadays constitute some of the most spectacular landforms of the Dolomites (Soldati 2010). Coastal areas hosted tidal flats, lagoons and small evaporitic basins where fine calcareous sediments were rhythmically deposited constituting today's thick layered dolomitic rocks. At that time only part of Sardinia and Tuscany were emerged within the arid paleo-European continent. The Triassic landscape did not last more than *ca.* 50 Ma years; in fact, with the Jurassic opening of the Piedmont-Liguria Ocean all previous emerged lands were covered by an extensive oceanic basin.

In the Paleogene (from *ca.* 66 to 23 Ma BP), in effect of Piedmont-Liguria Ocean closure and the consequent continental collision, uplift of the Alpine and Apennine chains occurred. During the Tortonian (from 11.6 to 7.2 Ma BP) most of the Italian peninsula was still under the sea level: Apulia, most of the Alps and Apennines, Corsica and Sardinia were the only emerged areas. Between the Corsica-Sardinia block and the Apennine chain, the youngest of the Italian seas was born: the Tyrrhenian Sea. The latter at present reaches depths of 3800 m and is characterized by a series of volcanic islands and submerged volcanoes; among the latter noteworthy is Marsili which is considered the largest European volcano. Thanks to the opening of the Tyrrhenian Sea the Apennine chain migrated towards the east and progressively emerged above sea level.

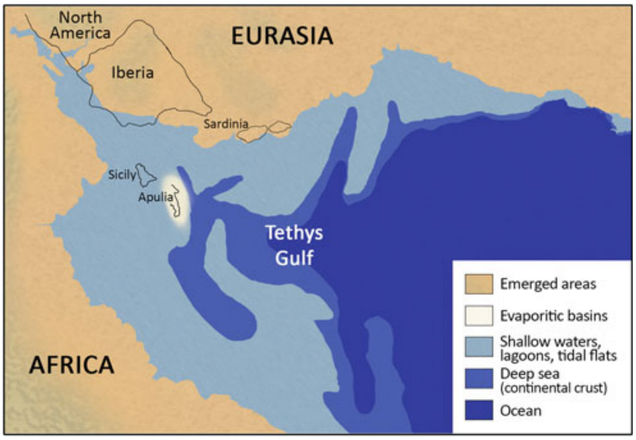


Fig. 2.2 Southern Europe at the beginning of Mesozoic (*ca.* 250 Ma BP)

During the Messinian (from 7.2 to 5.3 Ma BP), evaporation was dominant in the Mediterranean Sea and, like today, the inflows coming from the Atlantic Ocean played a fundamental role in sustaining the sea level. At that time the communication with the Atlantic Ocean was drastically interrupted—the reasons for which are still debated—leading to almost complete desiccation of the Mediterranean basin and to huge precipitation of evaporites (e.g. gypsum and halite). At the same time, during the drying up of the Mediterranean Sea, the Apennine uplift continued. As a consequence, today it is possible to find outcrops of evaporites along the entire Apennine chain, from Piedmont to Sicily, such as the spectacular Vein of Gypsum of Romagna Apennines. At the time of the Messinian salinity crisis, the Tyrrhenian Sea was reduced to a brackish basin delimited by a steep arid slope, the Messina Strait was an emerged plateau and all along the peninsula spectacular canyon systems developed in correspondence with former rivers.

Once the communication with the Atlantic Ocean was re-established (early Pliocene; about 5 Ma BP), the sea quite rapidly invaded the Mediterranean basin reaching a level higher than today. At the same time the Apennines almost reached their present position and the Tyrrhenian Sea increased in its depth. Next to the Apennine chain new volcanic centres were formed such as Colli Albani and Campi Flegrei (Aucelli et al. 2017; Fredi and Ciccacci 2017).

During the Pliocene (from 5.3 to 2.5 Ma BP), Italy still showed landscape configuration very different from that of today. The sea enveloped the Alps and the Apennines, the latter displaying a multitude of archipelagos (Fig. 2.3). The Po Plain did not exist yet and the coastline was shifted up to a few hundred kilometres inland. Many species characteristic of tropical seas such as sharks, marine mammals, shells of different shape and colours—of which outstanding remnants

Fig. 2.3 Italy during the Pliocene (from 5.3 to 2.5 Ma BP) (base map courtesy of Litografia Artistica Cartografica S.r.l., Firenze)

are preserved as fossil records—populated the Pliocene sea which was much warmer than today. In correspondence to the present Po Plain there was a wide and deep gulf where Pliocene rivers flowed into and built fan-deltas. At that time the shoreline was adjacent to the foothills of the Apennines (Pede-Apennines). This gulf would have been filled by debris if it had not been for the contemporary basin subsidence. The transition from marine to continental environments was due to the prevailing sediment supply outpacing subsidence, and also to incipient glacial phases during which a considerable increase in sediment production took place in mountain areas. In fact, during the glaciation a great quantity of water was stored within continental glaciers and thus the sea level was lower than today and large amounts of sediment reached the plain (Marchetti 2002; Fontana et al. 2014).

During the Quaternary, that is during the last 2.5 Ma, the Italian peninsula experienced well-documented cyclic alternations of sea-level highstands and lowstands. The three principal contributions to sea-level changes along the Italian coasts are eustatic variation, glacio-hydro isostasy and vertical tectonic movements, such as the uplift of Calabria and Sicily and subsidence of the northern Adriatic area (Lambeck et al. 2011).

The last glaciation, which commenced *ca.* 110,000 years BP, has profoundly influenced landscape evolution and its traces are still clearly visible, especially in northern Italy. The shift of morphoclimatic belts determined different distribution of flora and fauna, the latter being drastically reduced and forced to migrate southward. During the Last Glacial Maximum (LGM, 24,000–18,000 years BP) the Alps were almost completely covered by glaciers as a nearly continuous thick ice sheet (it is estimated that in some areas the ice sheet reached 1800 m in thickness) that extended over an area of about 30,000 km^2 (Fig. 2.4) while the present glaciers' area is only of 500 km^2 (Antonioli and Vai 2004). Glaciers occupied large tracts of the Alpine foothills in northern Italy, since they expanded along the valleys and merged with each other to form typical piedmont glaciers. Glaciers also developed in some Apennine valleys, especially in those with northern aspect. During the LGM sea level was 130 m lower than today and a widespread alluvial plain developed over the entire northern Adriatic basin. The Po River Delta was located between Ancona and Pescara, in correspondence of the northern scarp of the Meso-Adriatic depression, and the Po River flowed in a slightly southern position from its present path. The Maltese archipelago and Sicily were linked by a bridge 105 km long and 38 km wide (Furlani et al. 2013) and Corsica and Sardinia were joined together, too. The landscape during the LGM was typically glacial and arid, with arctic tundra and grassy steppe covering the foothills of the Alps and Apennines and irregular deciduous and coniferous forest along the Mediterranean coast. Present-day Alpine glacial lakes and valleys testify to the erosive power of LGM glaciers whose maximum extension is revealed by majestic moraine amphitheatres.

After the LGM the global climate shifted towards warmer and wetter conditions through alternation between cool and mild periods. It is during the transition from glacial to interglacial conditions that Italy, as well as many parts of the Earth, underwent the most outstanding climatic and environmental changes during the last 20,000 years (Orombelli and Ravazzi 1996). Finally, during the early Holocene post-glacial Climatic Optimum—the warmest climate of the post-glacial period—the average surface temperature was *ca.* 2 °C higher than today (Vai and Cantelli 2004). Alpine and Apennine glaciers progressively diminished in size or even disappeared, whilst flora and fauna gradually recolonized mountain areas. The Adriatic Sea inundated once more the Po Plain and the Italian shoreline approached in stages its present arrangement.

Minor climate changes occurred in historical times, among which noteworthy are the warmer climate phase in correspondence of the Roman period and the so-called Medieval Climatic Optimum (between 800 and 1150 AD). The coldest period of the Holocene was the Little Ice Age that occurred between *ca.* 1550 and 1850 and has left remarkable traces within many Alpine valleys. During this period the Italian glaciers advanced significantly; for example the Rutor Glacier (Valle d'Aosta) was 1 km longer than now.

2.4 History and Civilization

Until the early Holocene the shaping of Italian landscape was exclusively driven by natural processes. Starting from about 7000 years ago—in correspondence with the spreading of agriculture in Italy—Man has progressively become the principal actor of landscape modelling in many regions of the country.

The first hominin traces discovered in the Italian peninsula date back to 850,000 years ago thanks to the dating of layers including lithic tools at Mt. Poggiolo, in the Pede-Apennines of Emilia-Romagna (Muttoni et al. 2011). However, the most ancient human remains found so far is a child's tooth collected at the Palaeolithic archaeological site of La Pineta, near Isernia (Molise, Central Italy), which is *ca.* 600,000 years old (Peretto et al. 2015).

In the second millennium BC, an Indo-European population moved towards the Po Plain and the Terramara culture developed in correspondence to a climatic period characterized by a decrease in temperature and by an increase of rainfall (Pinna 1996). These climate conditions could have forced the Terramara civilization to live in stilt houses to protect themselves from recurring floods; in this context they tried to modify the landscape to manage water resources through canalizations, deforestation for building, agricultural and grazing purposes. The deforestation of the Po Plain, which already started during the Neolithic period, dramatically increased during the Terramara civilization. At the start of the Iron Age, between ninth and eighth century BC, the Villanovan civilization characterized a large area between Emilia-Romagna and Campania.

Fig. 2.4 Italy during the LGM, 24,000–18,000 years BP; Alpine and Apennine glaciers are outlined in *turquoise*; *red dots* indicate glaciers of limited extension (base map courtesy of Litografia Artistica Cartografica S.r.l., Firenze)

In the eighth century BC, the Etruscan civilization developed first on hilly, fertile and water rich areas of Central Italy, the so-called Etruria region (mainly corresponding to the present Tuscany Region) and later they reached the Po Plain in the north, and Campania in the south. The Etruscans were expert farmers: they performed water canalizations for irrigation and modified river courses profoundly shaping the landscape. In the same period, Greek colonies widely developed in southern Italy. The Greeks also left a clear imprint on the landscape through the building of world famous cities and temples, such as at Agrigento and Siracusa (Sicily)—which implied the extraction of limestone from local quarries—and through the practice of intensive cultivations, especially of cereals, olive trees and grapevines.

However the most influential civilization which developed on the Italian territory in ancient times was the Roman one. Traditionally, the foundation of Rome is dated to 753 BC when the Etruscans in the north and the Greeks in the south were dominating over most of Italy. In 509 BC Rome became a republic. Starting from a small settlement of farmers and shepherds along the Tiber River (Del Monte 2017), the Romans soon conquered the whole Italian peninsula. As a result of the victory in the Punic Wars, fought against the Phoenicians between 244 and 146 BC, the Romans started their expansion and domination on the Mediterranean regions which in the following centuries resulted in a large empire (established by Emperor Augustus in 27 BC) stretching from northern Europe to the Middle East.

The Romans were responsible for a profound landscape transformation, whose traces remain visible nowadays in many parts of Italy. They created a dense, but extremely well organized network of urban centres characterized by extraordinary buildings and infrastructures, such as roads, bridges and aqueducts. Extraordinary roads were built to facilitate commercial activities and military actions (e.g. Via Appia from Rome to Apulia; Via Aurelia from Rome to France; Via Cassia from Rome to Tuscany). They all preserve their original path and are still in use. The most striking imprint on plain rural areas left by the Romans was the Centuriation, a regular square grid subdivision of cultivated lands outlined by orthogonal crossing roads and canals (Fig. 2.5). This practice started with its classical features in the third century BC and developed for about four centuries. The Po Plain was largely affected by this type of land management which followed intense deforestation (up to 60% of the Po Plain was deforested during Roman times). Deforestation caused a general increase in soil erosion which resulted in gully development in the hilly areas of the Northern Apennines and fluvial aggradation in the Emilia-Romagna plain due to the high availability of sediment. At that time there was also a substantial progradation of the Po Delta into the Adriatic Sea (Stefani 2017).

Since the Bronze Age attempts of land reclamation and drainage of marshy areas were several but almost all of them failed. The most famous land reclamation attempts during Roman times were the works on Pontine marshes ordered by Emperor Augustus and the implementation of a gallery (longer than 5 km) that linked the Fucino Lake to Liri Valley (Latium) by Emperor Claudius in the first century AD, to avoid the frequent lake floods.

After a period of prosperity (first and second century AD), characterized by warm climate conditions, starting from third century AD the Roman Empire fell into economic and political crises; in the fifth century AD repeated barbaric invasions—possibly related also to the search for more favourable quality of life during a cold and humid climate phase—progressively reduced the influence of the Western Roman Empire to Italy only (Fig. 2.6). Among those invasions, the most striking was probably that of Attila the king of the Huns (people coming from North Central Asia) which occurred in 452 AD. It seems that the birth of the city of Venice is related to these attacks when the inhabitants of villages of northeastern Italy moved to the Venetian Lagoon to protect themselves. In 476 AD Odoacre, coming from Pannonia (present western Hungary), deposed the last Roman Emperor of the Western Empire, Romulus Augustulus. The year 476 AD is conventionally attributed to the beginning of the Middle Ages.

During the Early Middle Ages, neglect in water and land management, accompanied by climate deterioration, resulted in frequent floods which periodically submerged plain areas causing the spread of malaria in former salubrious and dry areas. A famous catastrophic event is represented by the breach of Adige near Verona on 17 October 589 AD. As reported by Paul the Deacon, this flooding event partially destroyed the walls of the city of Verona. This period is characterized by economic and demographic crisis: barbaric invasions and epidemics, among which the terrible bubonic plague, reduced the Italian population to less than a half. As a consequence of the demographic crisis, agriculture activity drastically decreased; only some vegetable gardens and orchards remained around villages for local supply, and the forest expanded. Locally, clearings occurred carried out by monks and nobles devoted to agricultural practices.

During the Middle Ages attempts to restore the former Roman Empire failed under the advance of the Longobards, a people of Germanic origin that was ruling Italy between 568 and 774 AD. Only in the ninth century, Charles the Great (Charlemagne) once defeated the Longobards and added northern Italy to the Holy Roman

Fig. 2.5 Evidence of Roman Centuriation in the Emilia plain between Modena and Bologna (Northern Italy). *Red lines* outline the traces of the original land subdivision on satellite image (© 2016 Google) and topographic map (*Source* C.T.R. Emilia-Romagna, scale 1:25,000— licence at http://geoportale.regione.emilia-romagna.it/Projects/geoportale/get_license_view?tipo_licenza=CC-BY%202.5)

Empire of which he became the first Emperor on 25 December 800 AD. At the same time, central Italy was part of the Papal States and southern Italy and Sicily were contended by the Byzantine Empire and Arabs, until the progressive conquest (eleventh and twelfth century) by the Normans who were descendants of the Vikings. After the death of Charles the Great, the Holy Roman Empire progressively lost its original integrity due to power struggles and repeated invasions.

A generalized climate warming and consequent partial ice-melting happened between 800 and 1150 AD—the so-called Medieval Climatic Optimum—causing sea-level rise, altering river dynamics and favouring wide development of marshes in plain areas. The spreading of forests and marshes together with Arab and Norman invasions forced populations to move from the coast to the hinterland and settle in fortified villages on hills. The Mesola Forest represents a remaining patch of the ancient planitial and thermophile forest that once ran along the Adriatic shoreline toward the north. It grows on sandbars probably formed between twelfth and fifteenth century AD.

The expansion of Medieval Communes which turned into powerful City States during the eleventh century, together with commercial activities, determined the modification of rural landscape, especially in northern and central Italy, by means of deforestation, quarrying and road building. The most influent City States evolved in several kingdoms and dukedoms.

The Italian Renaissance (fifteenth–sixteenth century) saw the flowering of arts and culture; the rural transformation left the most widespread imprint on the territory: plain areas underwent canalization, wide fields were used for farming and for sheep's grazing purposes, hillslopes were extensively terraced for olive tree and grapevine cultivation, deforestation and tillage were extended up to mountain areas. Towers and fortifications rose in strategic sites and around cities. During this period the belief that nature had to be under man's control developed, for both productive and aesthetic needs. However, between 1494 and 1559, Italy repeatedly became the battleground in a dispute mainly between France and Spain for the hegemony on Europe. The Peace of Cateau-Cambrésis (1559) ratified the supremacy of Spain on half of the Italian peninsula including the Dukedom of Milan, the Kingdom of Naples and the Kingdom of Sicily, which lasted until the beginning of the eighteenth century.

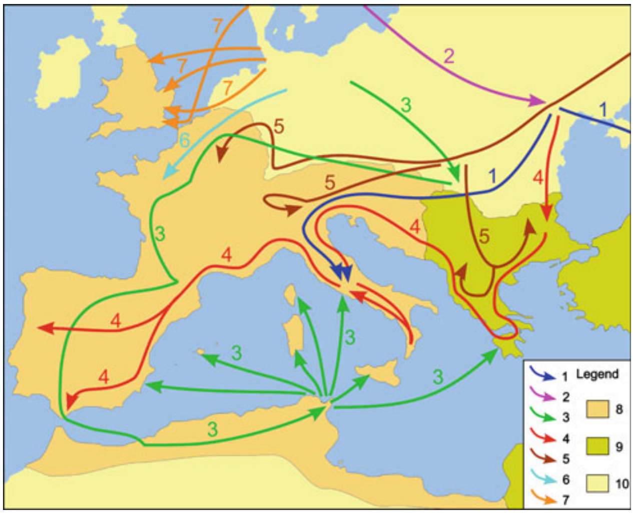


Fig. 2.6 Invasions of the Roman Empire between 100 and 500 AD. Legend: *1* Ostrogoths, *2* Goths, *3* Vandals, *4* Visigoths, *5* Huns, *6* Franks, *7* Jutes, Angles and Saxons, *8* Domain of Western Roman Empire, *9* Domain of Eastern Roman Empire, *10* Land outside the Roman empires

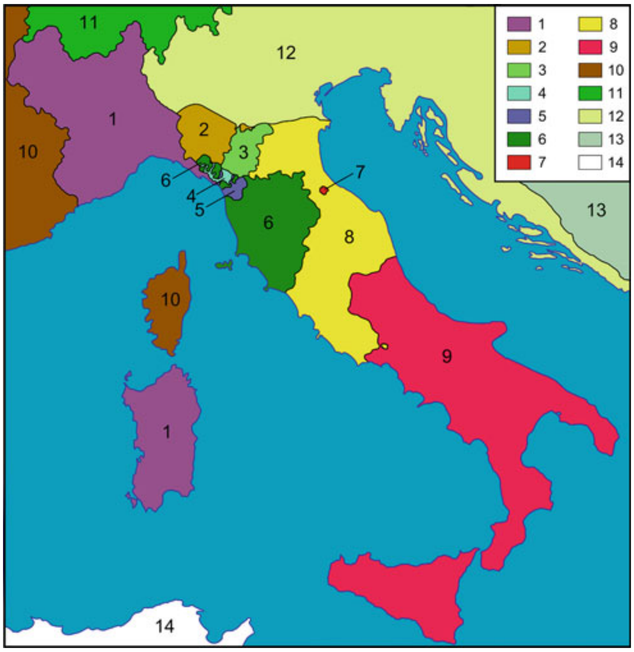


Fig. 2.7 Italy after the Vienna Congress (1815). Legend: *1* Reign of Sardinia; *2* Duchy of Parma, Piacenza and Guastalla; *3* Duchy of Modena and Reggio; *4* Duchy of Massa and Carrara; *5* Duchy of Lucca; *6* Grand Duchy of Tuscany; *7* Most Serene Republic of San Marino; *8* Papal States; *9* Reign of the Two Sicilies; *10* Reign of France; *11* Swiss Confederation; *12* Austrian Empire; *13* Ottoman Empire; *14* Other African States

As a consequence of the War of the Spanish Succession (1701–1714), the Spanish domain on the peninsula was replaced by Austrian Habsburgs domain with the Treaty of Utrecht (1713) according to which the Kingdom of Naples, the Kingdom of Sardinia and the Dukedom of Milan passed under Austria. Sicily instead became part of the Savoy domain.

Between 1802 and 1815, Napoleon Bonaparte conquered the peninsula: the northern part was named as the Reign of Italy and the southern as the Reign of Naples. After the Congress of Vienna (1814–1815), which was aimed at resetting the geography of Europe after the turbulent period of the French Revolution and the Napoleonic Wars, northern Italy came under the Habsburg control, southern Italy under the Bourbons and the Reign of Sardinia (including Piedmont) under Savoy. A large part of Italy was under the Papal States, while minor dukedoms survived (Fig. 2.7).

The nineteenth century was a period of further landscape changes due to urban development and the beginning of industrialization. In northern Italy, innovative cultivation techniques and irrigation works developed, and a new railway system was emplaced that increased deforestation rate. It is estimated that between the end of the nineteenth century and the beginning of the twentieth, forested areas diminished by 30% (Corona 2015).

The generalized discontent, provoked by the provisions established by the Congress of Vienna, animated new nationalistic inspirations that led to popular rebellion against foreign powers. In this context, the movement of Italian “Risorgimento” (literally Resurgence)—a period which eventually resulted in the unification of the Italian peninsula under a unique national state—developed. Initially, revolutionary popular uprising developed, successively after the First (1848–49) and the Second (1859) War of Independence and the crucial expedition of Giuseppe Garibaldi in the southern part of the peninsula, Italy was almost completely unified under a unique reign governed by King Vittorio Emanuele II (1861). After the Third Independence War (1866) Veneto was annexed to Italy while Rome—after the defeat of Papal States and the so-called Capture of Rome (20 September 1870)—became the capital city. Trentino and Alto Adige (South Tyrol) became however part of the Italian Reign only after the First World War (1915–1918, in Italy). During the latter, several areas of the present northeastern Italy were sites of hard battles which left evident traces. Noteworthy are mountain areas at the former boundary between the present regions of Trentino-Alto Adige to the north and Lombardy, Veneto and Friuli Venezia Giulia to the south.

A few years after the First World War, which determined severe social-economic conditions in Italy, Fascism (1922–1943) developed and lasted until the Second World War (1940–1945, in Italy). Beyond any political judgment, it must be emphasized that during this period the Italian urban landscape in particular underwent important transformations, including the emergence of considerable architectural works and redesign of many Italian cities. However, some rural landscapes still show the effects of relevant works carried out especially in suburban areas and in marshy and insalubrious lands (e.g. Agro Pontino) which were reclaimed. Noteworthy are the extensive works carried out in the Agro Pontino (Latium), Campidano (Sardinia), and coastal areas of Emilia-Romagna and Veneto (Federici 2008). It should be noted that 40% of the present agricultural areas consist of reclaimed lands which need constant maintenance.

During the Second World War the whole Italian territory was a battleground and as a result it was severely impacted and suffered from deep economic crisis for some years. However, on 2 June 1946 a referendum sanctioned the end of the monarchy and the birth of the Italian Republic, and two years later the Italian Constitution was proclaimed. Since then the present partition of Italy in 20 regions (and further subdivisions) was effective (Fig. 2.1). Since the Second World War the population increased by more than 30% from 45,910,000 (1946) up to 60,795,600 (2015) inhabitants following a constant growth trend which determined an increase of almost 300% since 1861 (Fig. 2.8). At present the population is mainly concentrated in urban and plain areas, also as a result of quite recent progressive migrations of people, especially from mountain areas to productive and urbanized areas. The most densely inhabited regions are Campania, Lombardy and Latium (Table 2.2). The abandonment of rural areas in the last decades locally resulted in enhanced slope instability and land degradation, as happened in some formerly cultivated terraced areas in Liguria (Brandolini 2017). Nevertheless, reforestation took place both naturally, on abandoned lands, and artificially. At present, forested areas more than double those present at the beginning of the twentieth century (Corona 2015).

2.5 Landscape Conservation and Protection

The reconstruction following the Second World War progressively led to an inexorable, widespread and sometimes disordered overbuilding of the territory. Starting from the end of the 1950s, the years of the second industrial revolution, in correspondence of the so-called Italian economic miracle, there was an over-exploitation of rural and coastal areas which implied disruption of pristine landscapes through deforestation, development of industrial settlements, enlargement of urban areas, colonization of coastal areas for tourism purposes, quarrying activities also within riverbeds (gravel and sand extraction) and so on.

The twentieth century is definitely the period during which human impact had the greatest influence on the Italian landscape. During the first half of the twentieth century, only cultural and political aristocracies and upper classes were well aware of the value of landscape, but the latter was appreciated and started to be protected mainly due to its aesthetic quality. However, during this period landscape protection issues were recognized also at the central governmental level. In this context, one of the first actions was the promulgation of law n. 1497 in 1939 which introduced land planning and restrictions as landscape protection tools. Subsequently, article 9 of the Italian Constitution (1948) included landscape as a matter under State protection.

A turning point in landscape protection is related to law n. 431 of 1985 (the so-called Galasso Law) according to which landscape assets had to be protected not only for their aesthetic and cultural significance but also for their physical features, both natural or human-related ones. This has led to the perception of landscape as part of cultural heritage. Currently, landscape protection is regulated by the Legislative Decree n. 42 promulgated in 2004 known as the "Code of Cultural Heritage and Landscape" which has collected and expanded the previously mentioned rules.

Fig. 2.8 Italian population growth from 1861 to 2015 (*source*: ISTAT database)

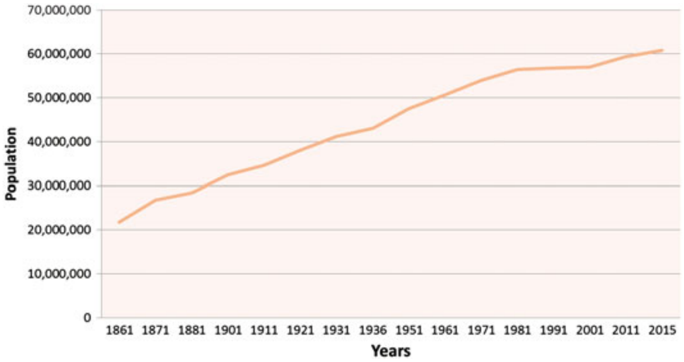


Table 2.2 Regional population density and percentage of inhabitants

Region	Population density (inhabitants/km²)	Inhabitants (%)
Lombardy	419	16.45
Latium	341	9.69
Campania	429	9.65
Sicily	197	8.37
Veneto	267	8.11
Emilia-Romagna	198	7.32
Piedmont	174	7.28
Apulia	209	6.72
Tuscany	163	6.17
Calabria	130	3.25
Sardinia	69	2.73
Liguria	292	2.61
Marche	165	2.55
Abruzzo	123	2.19
Friuli Venezia Giulia	156	2.02
Trentino-Alto Adige	77	1.74
Umbria	105	1.47
Basilicata	57	0.95
Molise	70	0.52
Valle d’Aosta	39	0.21
ITALY	201	100

The first protected areas established in Italy—Abruzzo National Park and Gran Paradiso National Park—date back to the early 1920s. Many more have been added even recently; this underlines the growing awareness of landscape importance and the need of land conservation and protection. Toward a wider protection of the environment stands the framework law n. 394 of 1991 which ratifies the main principles for the institution and management of protected areas at different spatial scales. As a result, the Italian territory is now including nearly 3 million hectares of terrestrial and marine protected areas constituting almost 10% of the country. At present 24 national parks, 140 regional parks, 27 marine protected areas, two submarine parks, one sanctuary of marine mammals plus a large number of natural reserves are listed by the Italian Ministry of Environment.

With special reference to geological and geomorphological landscapes, although the concept of geological heritage has only recently found a proper legislative definition in Italy, the development of conservation awareness regarding the physical elements and non-renewable landforms had already been growing among scientists since the nineteenth century. The first Italian scientist who recognized the indispensable aid given by physical elements in understanding the history of the Earth and mankind was Antonio Stoppani (1824–1891). In 1875 he wrote the famous and conceptually modern book “Il Bel Paese” (The Beautiful Country) which makes him—thanks to the valuable overview of the Italian landscapes—a forerunner and appraiser of those features that would have been later on defined as Geosites. Apart from the work carried out by a few authors, only in the 1990s a scientific approach to geoconservation started to develop (e.g. Panizza and Piacente 1993). The recognition and assessment of geosites was functional to protection and conservation actions as well as to educational activities and tourist promotion (Miccadei et al. 2011; Bollati et al. 2012; Reynard and Coratza 2013; Pica et al. 2016).

The first systematic census of geosites at regional level in Italy was carried out in Lombardy between the end of the 1970s and the early 1980s, and at present most of the Italian regions have geosite inventories. At the national level, the “National Inventory Geosite” project was launched in 2002. The Inventory contains information on sites of geological, pedological and geoarchaeological interest, which have been collected by the Italian National Institute for Environmental Protection and Research (ISPRA).

Research activity in this field has produced a vast amount of literature and is being carried on by the co-ordinated collaboration between research boards, universities and public administrations, witnessing the increasing awareness for preservation of geological and geomorphological features, as fundamental landscape components. The outstanding value of the Italian physical landscape favoured the inscription of a number of Italian areas within UNESCO natural World Heritage Sites (4) and the recognition of others as Geoparks (9). At present, the Italian natural World Heritage Sites are the Aeolian Islands, Monte San Giorgio, Dolomites and Mount Etna (Giovagnoli 2017).

2.6 Conclusions

The Italian territory is varied and fragmented into a multitude of regions having their own physical and cultural identity. This is also due to the rise of majestic mountain chains, locally covered by sparkling ice sheets, to massifs and sharp peaks located not far away from wide and populous plains crossed by a dense network of rivers, to limestone plateaus characterized by sinkholes, to gentle hills covered by vineyards and olive groves, to fertile volcanic areas, and to spectacular but desolate clayey slopes. To this variety of landscape features have contributed a long-term geological history, climate changes—which repeatedly modified the paleogeography of Italy—human activities since the Neolithic, and a complex history related to the strategic position of Italy in the Mediterranean region. Since ancient times, the elongated outline of Italy has favoured connections and exchanges with surrounding regions, but mountain chains have tended to separate and isolate people within specific geographic areas. This has led to an even higher variety of landscapes and landforms which are in many areas deeply connected with the human presence and different types of land use due to cultural and political diversity as well as to highly varied customs and traditions. This is still reflected in the extraordinary and valuable cultural heritage that characterizes and differentiates most of the Italian regions: architecture, literature, cultivation type and pattern, dialects, food, etc. Evidence of the complex evolution of Italian landscapes and landforms, which can be themselves considered as part of the national cultural heritage, is well preserved in many parts of the country despite the high density of population and industrial development that occurred in the last decades.

For the reasons mentioned above Italy has been a privileged destination for generations of well-educated travellers, intellectuals, poets and painters, for a long time attracted by the fascinating “Garden of Europe” where outstanding landscapes perfectly framed architecture and art masterpieces. Antonio Paolucci, art historian and the former Minister for Cultural and Environmental Heritage in the 1990s, stated that in the past “The Italian landscape was considered the emotional multiplier of the historic-artistic suggestion, meaning that the latter received from the landscape frame a sort of heroic and romantic amplification” (Paolucci 2000).

Nowadays Italy is a popular tourist destination. More than 50 million foreigners visited the country in 2015, making it the fifth in the world in terms of international visitations. The Italian tourist economy amounts to more than 10% of the national GDP and still with a large unexploited potential. Among the reasons to visit Italy is definitely the willingness to see extraordinary, often spectacular mountainous, volcanic and coastal landforms which make Italian landscape unique.

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Outline of the Geology of Italy

3

Alfonso Bosellini

Abstract
The Italian peninsula is an extremely active region from the geodynamic point of view as witnessed by the presence of active volcanoes (Vesuvius, Campi Flegrei, Stromboli, Vulcano, Etna) and by frequent earthquakes. Italian geology, however, is dominated by two different mountain chains, the Alps to the north and the Apennines to the south, along the peninsula. Geologically speaking, the Italian territory can be subdivided into seven specific sectors, i.e. The Alpine chain proper, the Po Plain, the Apennines, the Apulia foreland, the Calabrian-Peloritan arc, Sicily and Sardinia.

Keywords
Italian geology • Alps • Apennines • Mediterranean geodynamics

3.1 General Overview

Geologically speaking, Italy is in a quite active geodynamic evolution: volcanoes, earthquakes, land and coasts instability are a clear evidence. As a matter of fact, Italy, being situated in the middle of the Mediterranean, is subject to the same geological evolution which characterizes this entire region, controlled by the progressive approaching of two mega-plates, Eurasia to the north and Africa to the south (Bosellini 2005). The present geology of Italy, including the two major islands, Sicily and Sardinia, is remarkably varied and contains rock series from all eras and periods (Fig. 3.1). The Italian territory can be subdivided into seven specific sectors, which will be schematically described in the following pages.

3.2 The Alps

The Alpine chain, which extends from Provence and Ligurian coasts to Vienna and to the Hungarian Pannonian basin (Fig. 3.2), is the result of the convergence and collision of the European and African (Adria) continental margins, which took place between the Middle Cretaceous and the Late Eocene.

The Alps are a thrust belt with a double vergence. In other words, they are constituted by two different mountain chains which developed in opposite directions. In the north is the Alpine chain proper with European vergence, a pile of crustal nappes, overlapped northward since the mid-Cretaceous, whilst to the south a much younger tectonic system occurs, the so-called Southern Alps, similar to the Apennines, which since the Miocene has developed a southern vergence, i.e. toward the Po Plain. The boundary between these two large tectonic systems, with opposite vergence and different ages, is a series of faults, commonly and collectively identified as Insubric Line (Fig. 3.2), which from Turin and Canavese, through Valtellina and Tonale Pass, reaches Meran and more eastward Pusteria Valley, Gail Valley (Austria) and the Hungarian Pannonian basin.

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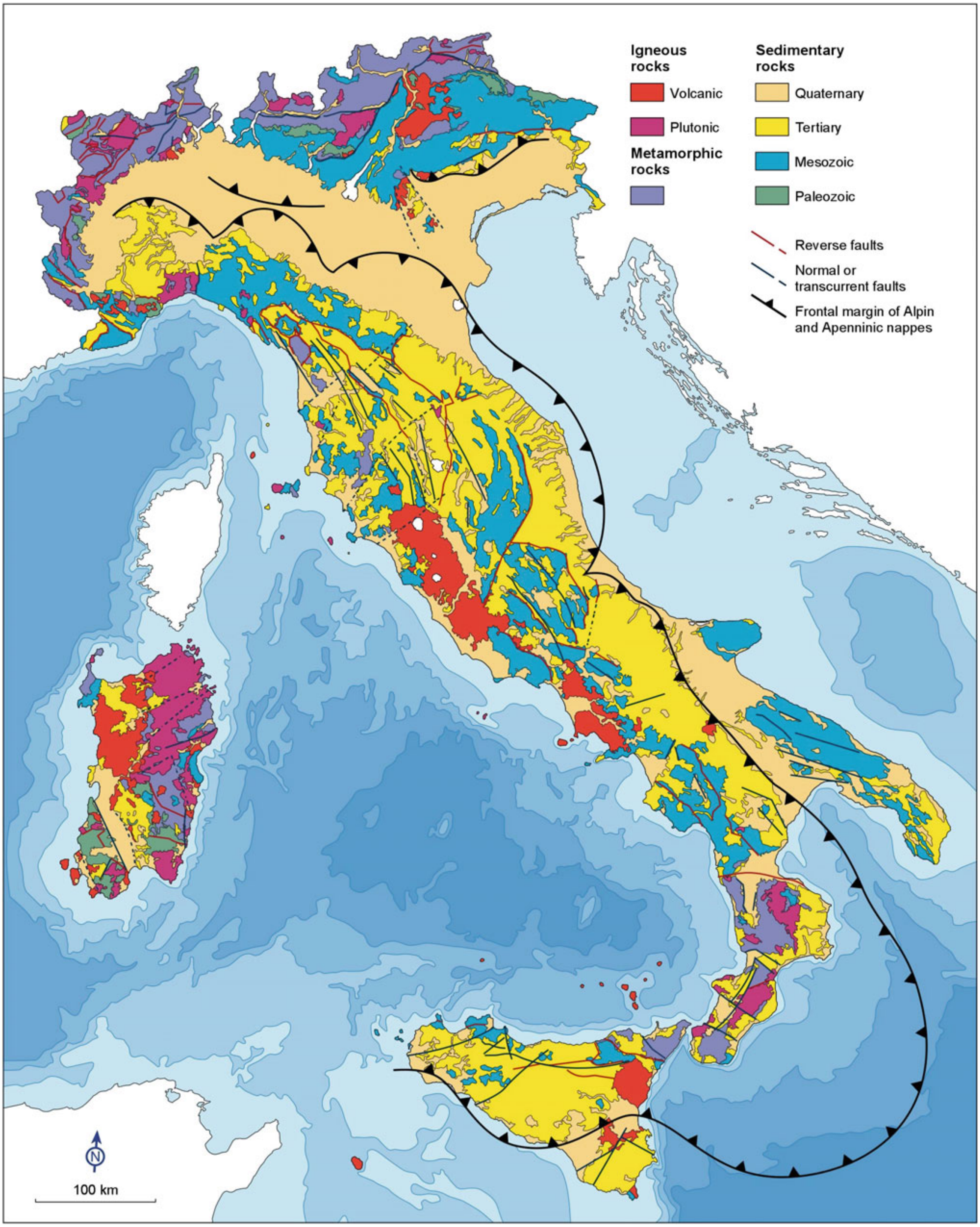

Fig. 3.1 Simplified geological map of Italy (modified after APAT 2005)

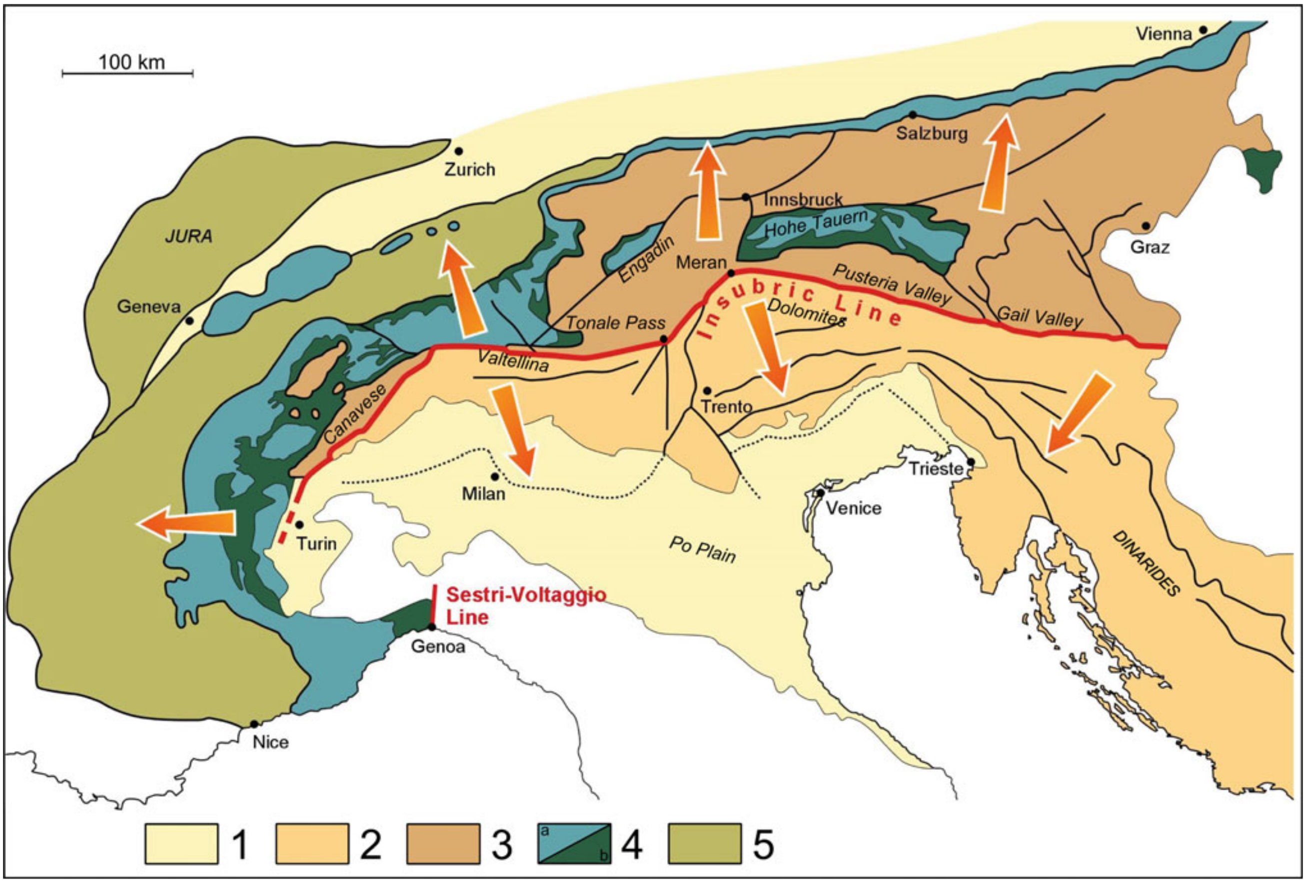

Fig. 3.2 Geological–structural map of the Alpine chain. *Arrows* indicate the opposite vergence of two sectors of the edifice: the Alps proper to the north, the Southern Alps to the south, separated by the Insubric Line (*red line*). Legend: (*1*) Plains bordering the alpine chain; (*2*) Rocks of the African south-vergent continental margin (Southern Alps and Dinarides); (*3*) Rocks of the African north-vergent continental margin (Austroalpines); (*4*) Rocks of the Penninic Ocean (Pennides): (*a*) sediments; (*b*) oceanic crust (ophiolites); (*5*) Rocks of the European continental margin (Helvetides)

The Alps proper, i.e. the north-verging sector, are constituted by three groups of nappes, the Helvetides, the Pennides and the Austroalpines (Argand 1924). These three groups of nappes consist of rocks belonging to the European continental margin, the former Penninic Ocean, and the African (Adria) continental margin, respectively. The Austroalpine nappes are the highest (structurally) in the Alps edifice, whereas the Helvetides lie along the frontal sector. The Pennides, which bear metamorphic ophiolites, crop out mainly in the Western Alps and within two large tectonic windows, the Hohe (High) Tauern to the east and the Engadin in the Swiss sector.

To the south, the Southern Alps consist mainly of Mesozoic sedimentary rocks deposited on the ancient Adria continental margin (Winterer and Bosellini 1981). Here spectacular carbonate sceneries include the Garda Lake area and the well-known Dolomite region.

3.3 The Po Plain

The Po Plain is an alluvial, relatively flat region, the result of an earlier marine and more recent fluvial sedimentation, mainly by the Po River and its tributaries. From the geological point of view, the Po Plain can be considered the foreland trough both of the Northern Apennines and the Southern Alps (Fig. 3.3). Large part of the Po Plain has a substratum of "buried mountains" (Fig. 3.4) which are the front of both the Apennine system and of the Southern Alps (Ghielmi et al. 2010; Fantoni and Franciosi 2010). This Apennine front is still active, and thus responsible for the earthquakes occurring so frequently in the Emilia region.

During the Pleistocene glacial periods, the future Po Plain was involved in repeated transgressions and regressions. In particular, during the Last Glacial Maximum (LGM), the shoreline was between Ancona and Pescara.

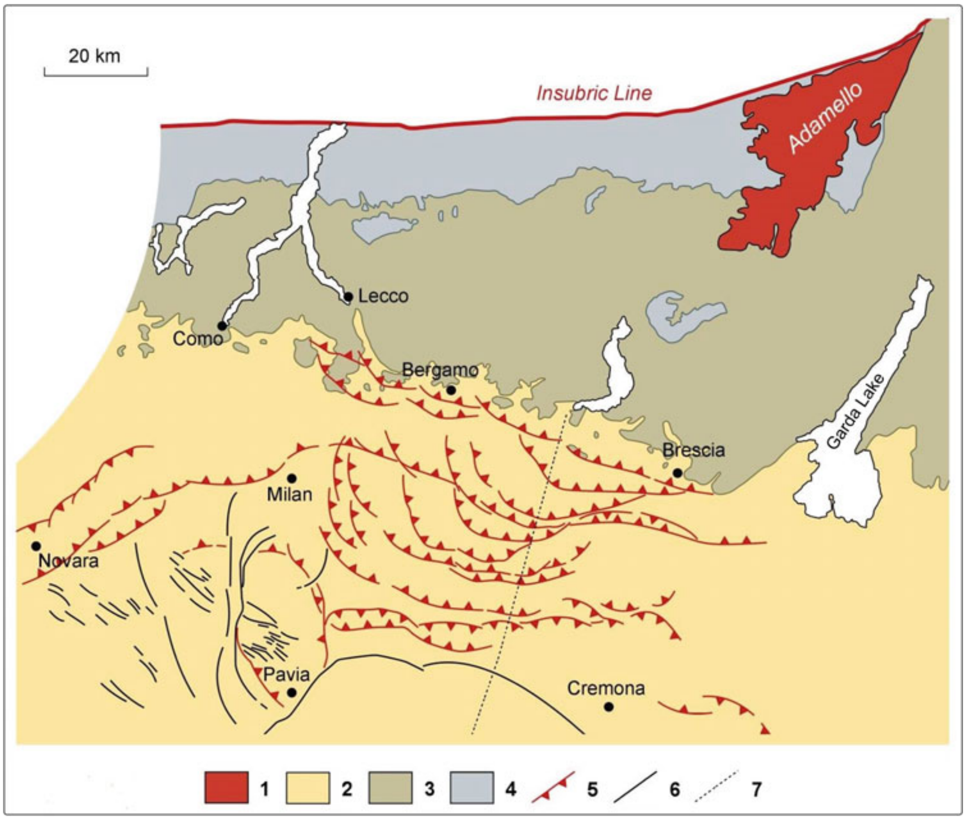

Fig. 3.3 Structural elements characterizing the central Po Plain in the Lombardy area. Legend: (*1*) Plutonic rocks; (*2*) Alluvial deposits of the Po Plain; (*3*) Sedimentary cover of the Southern Alps; (*4*) Crystalline basement; (*5*) Overthrusts; (*6*) Faults; (*7*) Section depicted in Fig. 3.4

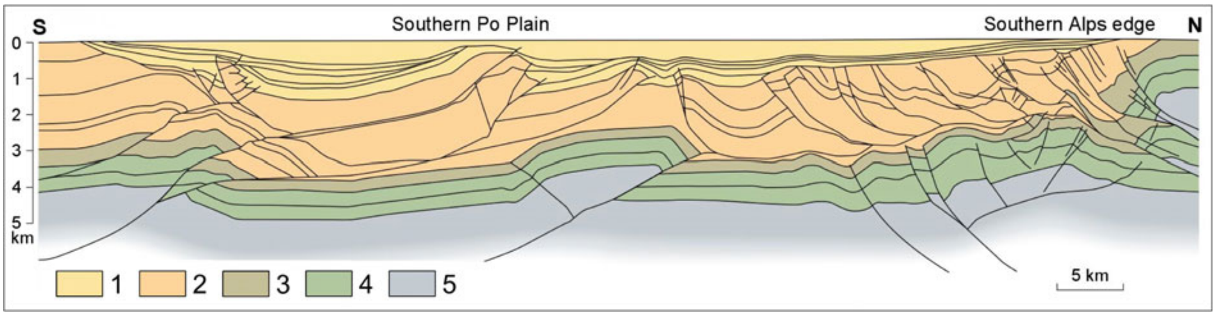

Fig. 3.4 Cross section of the Po Plain showing its deep complex structure (Lombardy area). Legend: (*1*) Plio-Quaternary; (*2*) Miocene; (*3*) Paleogene; (*4*) Jurassic–Cretaceous; (*5*) Triassic (modified from Bosellini 2005)

3.4 The Apennines

Geologically speaking, the Apennine chain extends from Genoa to the Sibari plain in Calabria. It can be subdivided into two principal sectors, the Northern Apennines and the Central-Southern Apennines (Fig. 3.5). These two sectors are bounded by regional transcurrent faults. To the north the Apennines are separated from the Alps by the so-called Sestri–Voltaggio Line, whereas the boundary between the Northern and Southern Apennines is marked by a series of faults collectively called Ancona–Anzio Line.

The Apennines are the result of the collision of the western continental margin of Adria (the African Promontory) with the Sardinia–Corsica block, which happened mainly during Miocene–Pliocene time (Castellarin and Cantelli 2010). The structural edifice of the Apennines consists of a series of east-verging nappes. The Ligurides, structurally the highest, include ophiolites and oceanic

Fig. 3.5 General outline of the Apennine chain. The *red line* is the active front of the chain. Legend: (*SV*) Sestri–Voltaggio Line; (*AA*) Ancona–Anzio Line; (*LS*) Sangineto Line

sedimentary rocks like radiolarites. The Ligurides originated from an ocean that has disappeared since, the so-called Ligure-Piemontese Ocean.

The Northern Apennines are characterized by the abundance of flysch formations ranging in age from Cretaceous to Miocene. There is also a large tectonic window (the Apuanian Alps), where the famous Carrara marbles are exposed. Many grabens (tectonic valleys) occur in the western (internal) part of the chain (mainly in Tuscany); they are the result of the collapse of the western part of the chain caused by the opening of the Tyrrhenian Sea.

The Southern Apennines are instead characterized by the presence of large carbonate platforms of Jurassic–Cretaceous age, which constitute the highest mountain of the Abruzzi region (Gran Sasso, Maiella). This southern sector of the chain has a tectonic boundary, the so-called Sangineto Line, with the adjacent Calabrian-Peloritan arc (Fig. 3.5).

3.5 The Apulia Foreland

The Apulia region consists of two geologically distinct zones, the foreland trough and the foreland bulge (Fig. 3.6). Mainly constituted of Cretaceous carbonate rocks, the region is totally outside of the Apennine mountain system and only mildly deformed by recent tectonics. Except the Gargano promontory, where the transition from the Jurassic–Cretaceous shallow-water platform to the Adriatic deep-water basin is exposed, the entire region is a sub-horizontal carbonate plateau.

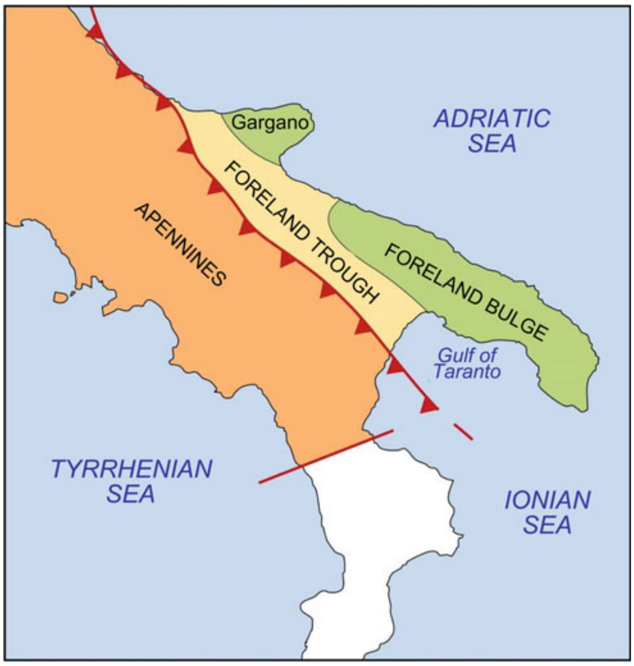

Fig. 3.6 Geological sketch of the Apulia region, showing the foreland trough (*yellow*) and the foreland bulge (*green*)

Fig. 3.7 The Calabrian-Peloritan arc (*brown colour*) and its regional geological framework

During the last fifteen years, several dinosaur footprints have been discovered in the Cretaceous shallow-water carbonates of Apulia (Bosellini 2002). These findings document the Mesozoic connection of Apulia with the African Continent.

The Apulia carbonates are deeply affected by karst as documented by the numerous dolines and caves (for example the famous Castellana caves).

3.6 The Calabrian-Peloritan Arc

This peculiar geological province extends from the Sibari Plain to the Messina Strait and beyond to the northeast corner of Sicily, where the Peloritan mountains are present (Fig. 3.7). The Calabrian-Peloritan block is an “exotic terrain” and a segment of the Alpine chain. Before the opening of the Tyrrhenian basin it was posted close to Sardinia. The arc includes metamorphic basement and granites of Paleozoic age and, moreover, it consists of a pile of east-verging nappes. In conclusion, the Calabrian-Peloritan arc must be considered a fragment of European crust, a terrain totally different from the remainder of Italy, which pertains to the African plate. Naturally, underneath the “exotic Alpine chain” the Apennine chain is present. It crops out in several tectonic windows.

At the margin of the mountains, near the sea, relatively undeformed Miocene–Pliocene terrains suture the front of the various nappes.

3.7 Sicily

The island of Sicily (except the Peloritani mountains) is the easternmost tract of the Maghrebian chain of north Africa (Fig. 3.8) and belongs to the northern continental margin of this continent. It consists of several south-verging nappes and a foreland area in the southeast corner (Iblei Mts.) (Abate et al. 1978). The Panormide carbonate platform of northwestern Sicily is considered to act, during the Jurassic–Cretaceous interval, as a temporary continental bridge between Africa and Adria (Zarcone et al. 2010). Moreover, the highest volcano of Europe, Mount Etna, is present along the eastern coast.

3.8 Sardinia

Geologically speaking, the island of Sardinia is not part of Italy. It is a fragment of the European continent, together with the island Corsica (France). It separated from Catalunia (Spain) about 30 Ma ago and reached the present position about 18 Ma ago. Large part of the eastern side of the island consists of granites and Paleozoic rocks formed during the Hercynian orogenesis. The most complete Paleozoic sedimentary succession of Italy is present in the island, where several Hercynian tectonic nappes have been discovered (Carmignani et al. 1992). The eastern side of the island is characterized by the presence of widespread volcanics, mainly of Tertiary age.

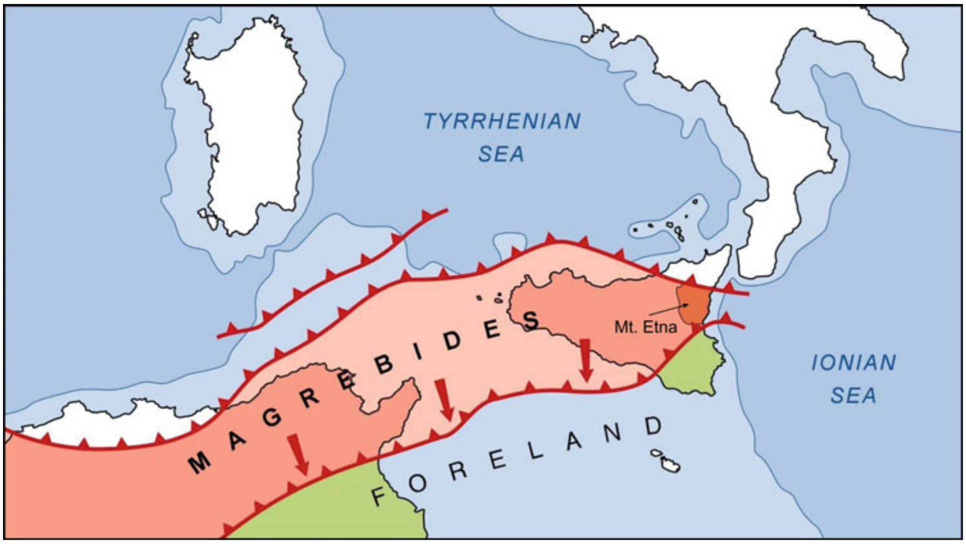

Fig. 3.8 The Maghrebian chain and its eastern Sicilian tract

3.9 Conclusions

Concluding this brief geological description of Italy, it should be emphasized that the Italian peninsula is an extremely active region from the geodynamic point of view, as witnessed by the presence of active volcanoes (Vesuvius, Campi Flegrei, Stromboli, Vulcano, Etna) and by frequent earthquakes.

Due to its geological complexity, the Italian territory shows extremely varied and spectacular landscapes which are of great interest from the geomorphological viewpoint. On the other hand, its intense geodynamic activity locally favours highly hazardous contemporary geological and geomorphological processes.

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The Climate of Italy

4

Simona Fratianni and Fiorella Acquaotta

Abstract

The chapter highlights the main features of the climate of Italy. In particular, it identifies and defines the main climatic regions and the local factors that control the type of climate according to the Köppen classification. Furthermore, it shows the distribution of the main meteorological variables, temperature and precipitation, and the climatic variations that affected Italy in the last decades. The Italian climate displays remarkably varied features due to the complexity of its territory. Climatic variations recently observed show some common elements throughout the country, i.e. a gradual increase in temperature and a change in the annual distribution of precipitation. These changes are more remarkable in the Alpine region.

Keywords

Italian climate • Climate regions • Temperature • Precipitation • Climate variations

4.1 Introduction

Italy stretches across the centre of the Mediterranean, from a latitude of 36°N to a latitude of 47°N. This remarkable extension makes the climatic conditions very variable. Moreover, the orography is very complex due to the presence of mountain chains of the Apennines and the Alps. They influence the pathway of weather fronts and interact with the dominant winds, thus exposing different areas of Italy to specific types of circulation. The Alps and the Apennines in fact have a barrier effect: the former protect the Po Plain and the Venetian Plain from the cold northerly currents, while the latter, developing along the entire peninsula, limit the influence of the moist westerly air to the Tyrrhenian side, which is in turn protected from the cold easterly winds that hit the Adriatic side during the winter season. Winter is in fact colder on the Adriatic coast than on the Tyrrhenian coast at the same latitude (Mennella 1967; Pinna 1977).

It is also necessary to point out the mitigating effect of the Mediterranean Sea, which generally has a destabilizing effect on the air masses that flow there, favouring the development of depressurizing systems (cyclogenesis) close to the Italian peninsula. The distribution of atmospheric pressure over the Peninsula and over the surrounding seas (Adriatic, Ligurian, Tyrrhenian, Ionian seas) during different seasons is one of the fundamental factors that condition the trend and regime of meteorological elements.

4.2 Local Factors and Climatic Regions

The concurrent influence of various geographic factors (including different altitudes, different distances from the sea, different morphological characteristics of marine basins, presence of particular coastal currents, exposition to dominant winds etc.) determines the existence of different climatic regions, whose borders can be represented as shown in

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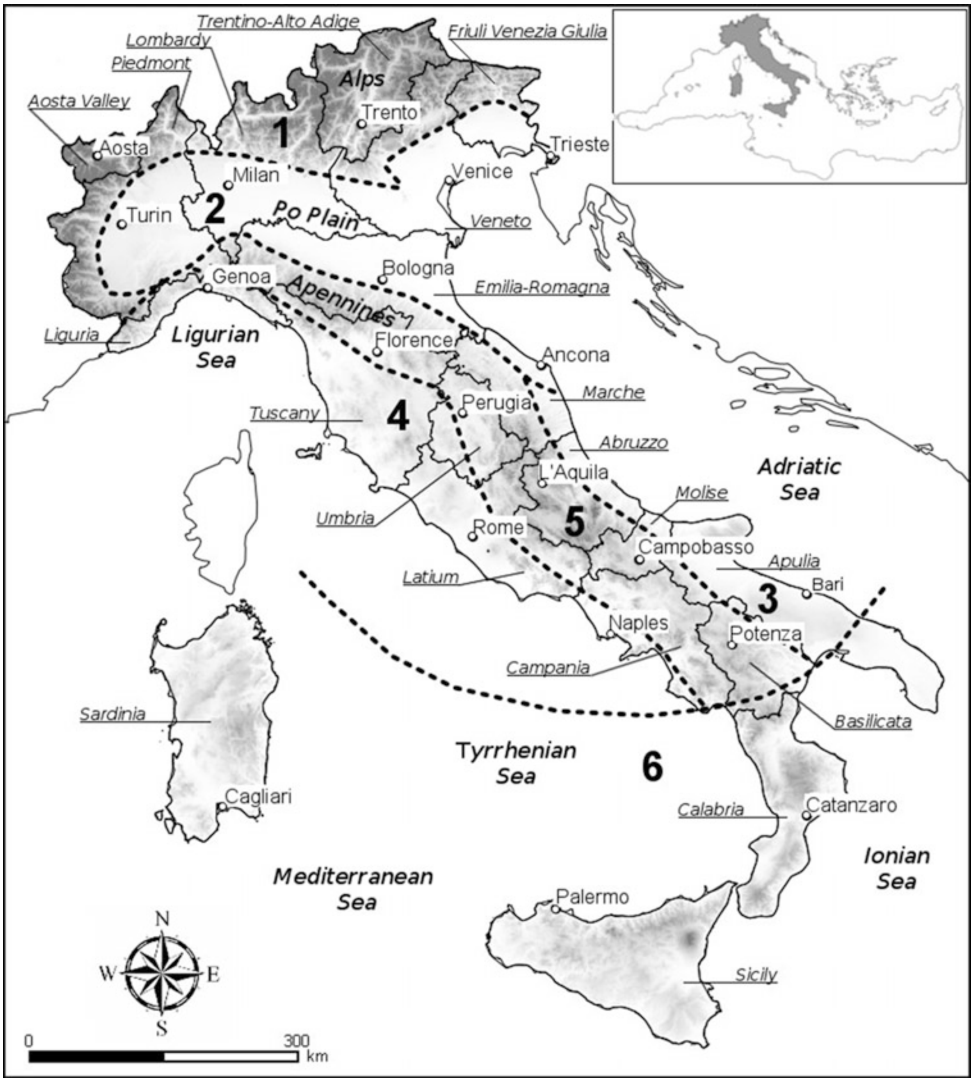

Fig. 4.1 The climatic regions of Italy: (*1*) Alpine Region, (*2*) Po Plain and Upper Adriatic Region, (*3*) Central-Southern Adriatic Region, (*4*) Ligurian and Tyrrhenian Region, (*5*) Apennine Region, (*6*) Mediterranean Region (scheme proposed by Cantù 1977, redrawn by D. Garzena)

Fig. 4.1, on the basis of the scheme proposed by Cantù (1977), which gives particular prominence to weather types that occur over the regions. These regions have to be considered as macro-sections; it is obvious that sub-units exist within these portions, each with its own particular climatic conditions. The main climatic regions are: (i) the Alpine Region, (ii) the Po Plain and Upper Adriatic Region, (iii) the Central-Southern Adriatic Region, (iv) the Ligurian-Tyrrhenian Region, (v) the Apennine Region and (vi) the Mediterranean Region.

The *Alpine Region* includes the Aosta Valley, Trentino-Alto Adige and the mountain sectors of Piedmont, Veneto, Lombardy and Friuli Venezia Giulia. This climatic region is all above 1000 m a.s.l. and—in autumn, winter and spring—is affected by a series of low pressure zones arriving from the Atlantic, the Gulf of Genoa and the Mediterranean Sea. The Alpine climate is conditioned by the altitude, and it can be considered as a cold temperate type, which becomes of a nival type at altitudes above 2700–2800 m. The Alps and the pre-Alps receive high amount of rainfall, with peaks of 3000 mm per year in the sectors which are more exposed to the cold air masses coming from the Pole and the hot air coming from Africa.

The *Po Plain and Upper Adriatic Regions* are made up of an extensive basin that is surrounded by mountain chains to the north, west and south, with no relief on the east side. Considering the orography, this climatic region is limited by the 1000 m contour line on the Alpine side and by the watershed line on the Apennine side. During winter, the entire region is covered by a layer of cold and stagnant air that is several thousands metres thick. The outstanding feature of this climatic zone is its accentuated seasonal excursion with maximum temperatures in summer that often exceed 30 °C and winter minimums that often fall below zero. Rainfall is not very abundant, between 600 and 800 mm per year, with a higher frequency in autumn and spring. During summer, stormy events are also quite frequent.

The *Central-Southern Adriatic Region* includes the eastern peninsular part of the Apennine watershed, between the 43° and 39° parallels. This region has thermal and rainfall behaviour of a Mediterranean type, but also shows continental characteristics that are dictated by the mitigating influence of the Adriatic Sea and the favourable exposition to currents flowing from the north and from the east. Rainfall is not abundant, between 600 and 700 mm per year. Rains are more frequent in spring and autumn, and the latter is the rainiest period of the year. When the synoptic situation is such that it favours currents from west to southwest, anomalous torrid hot or warm waves can also occur in the middle of winter. In the cold season, the minimum temperatures drop to values of around 0 °C, and in high summer they exceed 30 °C.

The *Ligurian and Tyrrhenian Region* includes Liguria, the coastal sectors and the bordering hinterland of Latium, Tuscany and Campania. Even the western part of Umbria, although it shows some continental aspects, is affected by the mitigating action of the Tyrrhenian Sea. The climate in these regions, which can be defined as Mediterranean, is milder and wetter than the Adriatic sector at the same latitude, because of the presence of the Apennines. On average, rainfall is between 800 and 1000 mm per year, but there are important differences in relation to the closeness of the Apennines to the coast. Summers are hot and dry, with maximum temperatures that often exceed 30 °C. Windward low pressure areas can be observed during autumn, causing flash floods and devastating effects in the provinces of Genoa and La Spezia, especially in recent years.

The *Apennine Region* includes the mountainous sectors of Emilia-Romagna, Tuscany, Latium, Marche, Campania, Abruzzo, Molise, eastern Umbria and most of Basilicata. The characteristics of this climatic area are determined by altitude, and are comparable with those of the cool continental temperate zones, with lower thermal values as the altitude increases. Rainfall reaches values of more than 1500 mm per year on the slopes that are more exposed to the dominant western winds.

The *Mediterranean Region* includes Calabria, Sardinia, Sicily, the coastal areas of Basilicata and south Apulia. These zones have a similar climate to that of the Tyrrhenian Region, but with a marked intensification of the Mediterranean characteristics, and the appearance of some subtropical sections in the internal parts of Sicily and Sardinia. The sea markedly influences climatic parameters. Summers are dry and hot, with temperatures that can even exceed 40 °C, when the African cyclone is developing, while winters are very wet with rainfall that is prevalently of a downpour or stormy type.

The occurrence of different baric situations and specific local conditions determines the frequency, intensity and direction of winds in Italy. Anemometric observations show that only generally moderate variable winds (with the exception of local breezes), which precede, accompany or follow atmospheric low pressure areas, are present throughout Italy.

In general, the areas which overlook the Ligurian Sea and Tyrrhenian Sea suffer above all from winter westerly winds. These winds have northwest direction over Sardinia (Mistral), southwest direction over the eastern Ligurian coasts and over the upper part of the Tyrrhenian Sea (Libeccio), and western direction over the central part of the Tyrrhenian Sea (Ponente). The directions of the winds are reversed on the Adriatic side. The winds in the northern and central parts prevalently arrive from the north and northeast, while those in the southern part are from the south and southeast. Winds from the south and southeast are frequent in the southern parts of the peninsula. The Ionic coasts are hit by lukewarm and moist Scirocco winds, while the extremely hot and moist African Scirocco wind blows from southeast and reaches Sicily.

4.3 Climate Classification

Classifying climate means defining its characteristics in different places, considering the most important climatic elements.

The most famous climate classification and to which reference is made regularly in climate descriptions is that proposed by W. Köppen (Pinna 1978). It is based on the distribution of mean annual and monthly temperature and rainfall, and distinguishes five main climate groups in the world.

The Italian peninsula falls completely within the Mediterranean climate area, which is part of the meso-thermal type climates and, to be more precise, of subtropical climates with dry summers. In reality, besides the typical Mediterranean climate, there are also areas with other meso-thermal climates, or areas with situations of micro-thermal or altitude climates. A climatic classification based on the Köppen–Geiger scheme (Fig. 4.2) and only referring to thermal aspects is outlined below.

1. *The Ligurian-Tyrrhenian, Middle Adriatic, Ionic and Mediterranean coastal regions* (Cs). Two types of climates can be found within this group:
   (a) *Subtropical temperate*. This climate is marked by limited (almost non-existent in summer) and very irregular rainfall. It affects the hottest areas along a narrow strip of the southern Italian coast and that of the islands. Mean annual temperature >17 °C; mean

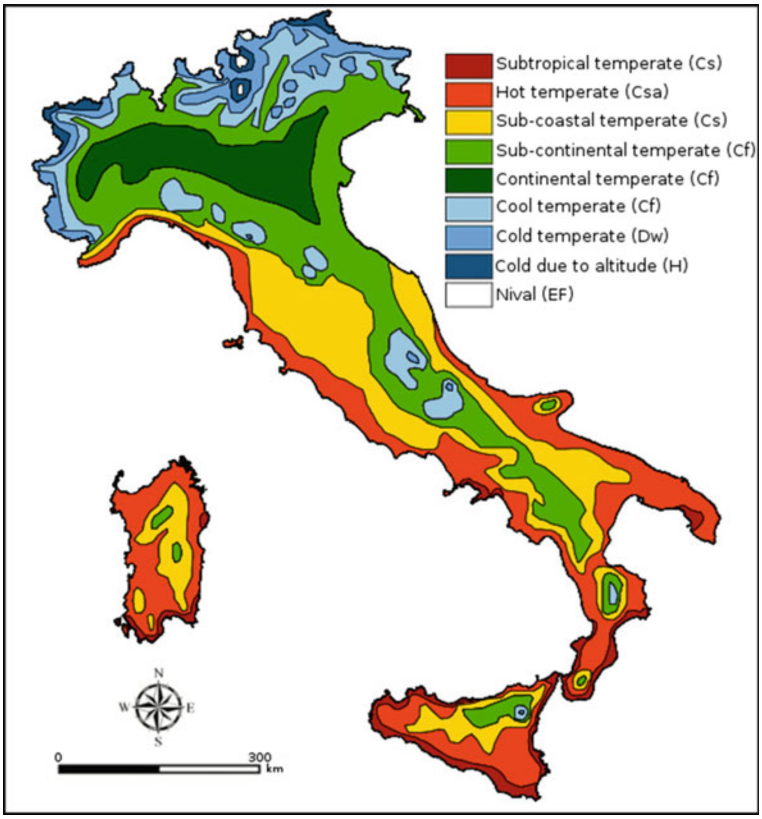

Fig. 4.2 Map of climatic classification by Köppen and Geiger (after Pinna 1978, redrawn by D. Garzena)

   temperature of the coldest month >10 °C; five months with a mean temperature >20 °C; annual temperature from 15 to 17 °C.
   - (b) *Hot temperate*. This climate is usually characterized by summer droughts (Csa), and it affects the Tyrrhenian coastal area from Liguria down to Calabria, the southern part of the Adriatic coast and the Ionic zone. Mean annual temperature from 14.5 to 16.9 °C; mean temperature of the coldest month from 6 to 9.9 °C; four months with a mean temperature >20°C; annual temperature from 15 to 17 °C.
2. *The internal sub-coastal region* (Cs) includes the hilly zones of the Tuscan-Umbrian-Marche pre-Apennines and the lower slopes of the southern Apennines. Mean annual temperature from 10 to 14.4 °C; mean temperature of the coldest month from 4 to 5.9 °C; three months with a mean temperature >20 °C; annual temperature from 16 to 19 °C.
3. *Po and Venetian plains, Upper Adriatic and internal peninsular regions*. Two types and two sub-types can be identified in this climatic region:
   - (a) *Sub-continental temperate* (Cf), which affects part of the Venetian Plain, the Friulian Plain, the coastal area of the Upper Adriatic Sea and the internal peninsular region. Mean annual temperature from 10 to 14 °C; mean temperature of the coldest month from −1 to 3.9 °C; two months with temperature >20 °C; annual temperature from 16 to 19 °C.
   - (b) *Continental temperate* (Cf), which affects all of the Po Plain and part of the Venetian Plain. Mean annual temperature from 9.5 to 25 °C; mean temperature of the coldest month from −1.5 to 3 °C; three months with a mean temperature >20 °C; mean annual temperature >19 °C.

   Two sub-types that show a remarkable extension can be identified within the temperate type of climate: the *hot summer temperate climate* (Cfa) and *lukewarm summer temperate climate* (Cfb).
4. *Pre-Alpine and Middle Apennine region*. A *Cool temperate* (Cf) climate can be identified. This affects the pre-Alps and the axial zone of the Apennines, which sometimes presents sub-continental characteristics. Mean annual temperature of 6 to 9.9 °C; mean temperature of the coldest month from 0 to −3 °C; mean temperature of the hottest month from 15 to 19.9 °C; annual temperature from 18 to 20 °C.
5. *Alpine and Upper Apennine region*. A *Cold temperate* (Dw) climate can be identified. This affects an area of the Alps and the summit areas of the higher Apennine groups. Mean annual temperature from 3 to 5.9 °C; mean

temperature of the coldest month >−3 °C; mean temperature of the hottest month from 10 to 14.9 °C; annual temperature from 16 to 19 °C.

6. *Alpine region*. Two types of climate can be recognized
   - (a) *Cold due to altitude* (H) which affects the highest sectors of the Alps and the summit areas of the higher Apennine groups.
   - (b) *Nival* (EF), which affects the Alpine zone above 3500 m, with the presence of perennial snow.

4.4 Temperature Distribution

In general, the mean temperature throughout Italy decreases in winter as the latitude, altitude and distance from the sea increase. However, this trend shows significant exceptions, above all as a result of the barrier effect of the main mountain chains (Rapetti and Vittorini 1989). It has already been mentioned how, at the same latitude, the Adriatic coast, which is open to winds from the north, is relatively colder than the Tyrrhenian coast in winter. The thermal contrast between the Po Plain (which is covered by a layer of cold air in winter) and the Ligurian Riviera, which is sheltered from the arrival of cold air from the north by the Marittime Alps in the west, is even more accentuated. The annual thermal excursion fluctuates, over most of the Italian territory, between 14 and 25 °C; in general, temperature increases when moving from the coast towards the internal part, and then diminishes passing from the plain to mountains. The lowest values of thermal excursion are recorded over some parts of the western part of Liguria and over some sections of the western coast of Sardinia as well as the southern sections of Sicily. The highest values are instead found in the southwestern sector of the Po Plain (Pinna 1978).

On the basis of the map of mean annual temperatures that are recorded in Italy (Fig. 4.3), mean values of more than 16 °C can be observed over the western part of Liguria, along the Tuscan coastline, along the coast between Abruzzo and Apulia, along the Ionian coast of Basilicata and Calabria, and along all the coastal sections and internal flat areas of Sicily and Sardinia. In the peninsular areas, the isotherm passes locally in a more or less decisive way towards the corresponding hinterland. Most of the Apennine range, the Sardinian mountains, the pre-Alps and the Alpine valleys record mean values ranging between 10 and 12 °C; mean annual temperatures ranging between 5 and 10 °C are instead recorded on the top of Mt. Etna, on the highest summits of the Apennines and on most of the Alpine range, where mean annual values below 5 °C can even be recorded on the highest peaks.

The absolute mean extreme values of the temperature fluctuate between 44 and 45 °C—recorded in July over some locations in southern Italy—and −30 °C, recorded at some locations in the Alps in January.

The highest temperature in Italy, since 1951, was recorded by the Air Force Military meteorological network, which is affiliated with the World Meteorological Organization, and was equal to 47 °C; it was measured by the Foggia Amendola station on 25 June 2007 (Fig. 4.3). The lowest temperature was measured in February 1929, at 4554 metres, at the Regina Margherita hut on Monte Rosa. On that occasion, the temperature dropped as low as −41 °C. Always in the Italian Alps, the −34.6 °C measured at Plateau Rosa on the 6 March 1971 stands out, and this was followed by the −30 °C that was measured at Dobbiaco on 1 January 1953. Whilst for the cities on the plain, the lowest temperatures were recorded in Florence (12 January 1985) and Tarvisio (7 January 1985) with −23 °C.

4.5 Precipitation Distribution

The mean annual rainfall distribution, though generally depending on the latitude, is also influenced by altitude and aspect. The mountainous zones in Italy in fact receive a greater quantity of water than the plains and the coasts, especially when they are exposed to moist currents from the sea. The rainiest areas in Italy (mean annual rainfall between 2500 and 3500 mm) are located in the Carnian and Julian Alps, in the pre-Alpine section between Lake Maggiore and Lake Como, in the eastern Ligurian Apennines, in the Apuane Alps and in the highest sectors of the Tuscan-Emilian Apennines (Fig. 4.4). In general, rainfall is more plentiful along the Ligurian-Tyrrhenian side (which is open to currents from the west and to the perturbations that accompany these currents) than on the Adriatic-Ionian side (see Rapetti and Vittorini 1989). Less abundant rainfall is generally recorded on the plains and along the coasts. Rainfall is particularly scarce (below 500 mm/year) along the coast in some parts of Apulia, Sicily and Sardinia. Low values are also found in the bottom of some Alpine (Aosta Valley, Susa Valley, Valtellina, Pusteria Valley) and some Apennine valleys, which are protected by elevated mountainous ramparts. In the Po Plain, rainfall diminishes from east to west, as it does from the high altitudes to the low plain. The mean annual number of rainy days is higher on the western sides of the peninsula (110–120 days in the Alps, pre-Alps) and in the most elevated areas of the Alps and Apennines. It is lower in the western Po Plain, and along the coastal plains of Southern Italy and the islands. The pluviometric regime presents a remarkable variability

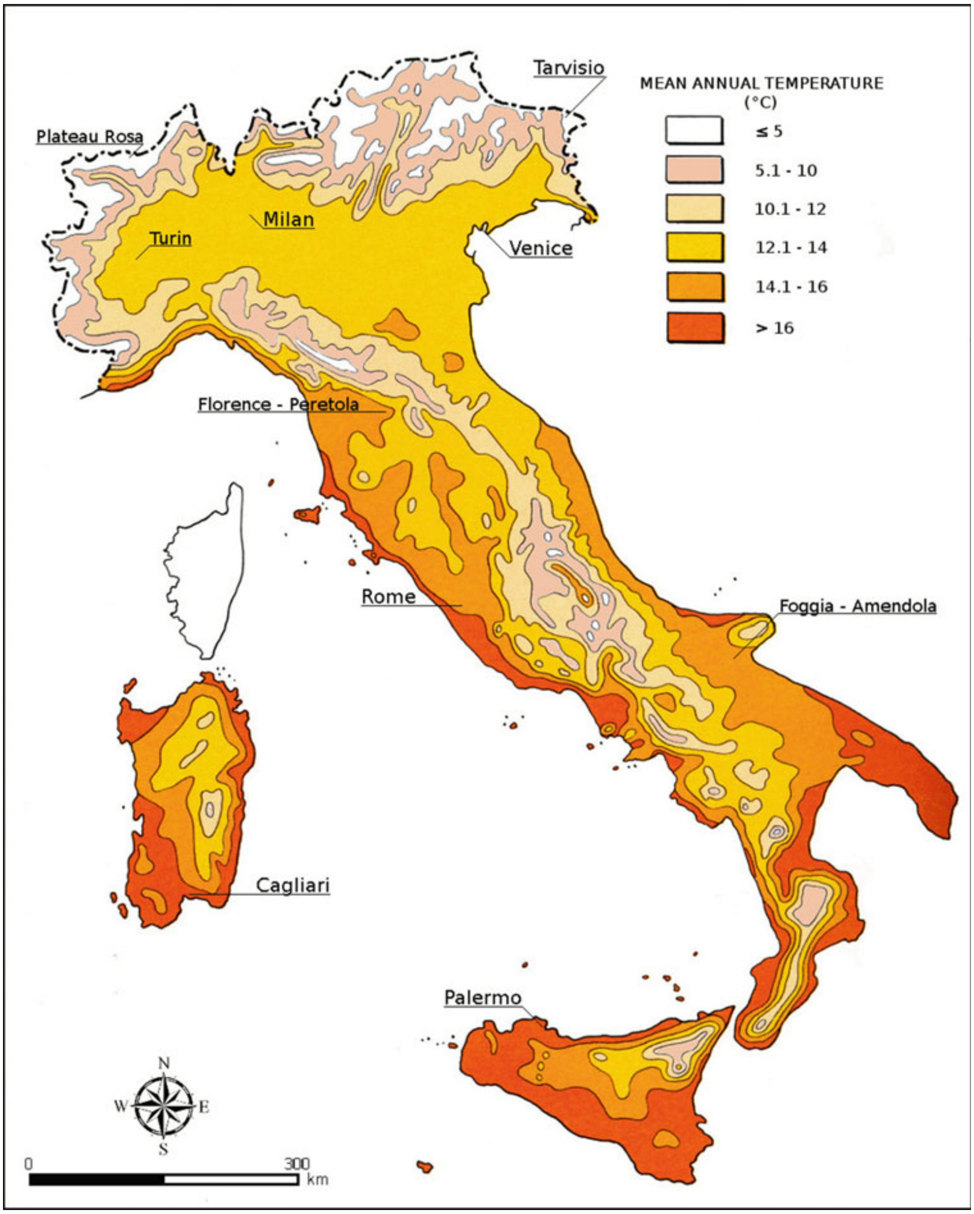

Fig. 4.3 Map of mean annual temperatures from 1961 to 1990 in Italy. *Source* SCIA system by ISPRA (www.scia.isprambiente.it)

(Pinna and Vittorini 1985) and the following main types can be distinguished:

- Continental regime is characterized by an accentuated maximum summer rainfall and an accentuated minimum winter rainfall: it affects some Alpine and pre-Alpine areas.
- Pre-Alpine regime affects almost all of northern Italy and the upper part of Tuscany, with two maximum rain periods in spring and in autumn, and two minimum periods in summer and winter. In some zones, such as in Piedmont, the spring maximum is prevalent, while the autumn one is prevalent in other zones.
- Apennine regime presents a main maximum rainfall period at the end of autumn and a main minimum period in summer; a minor minimum occurs at the end of winter.
- Sub-coastal regime is rather similar to the previous one, with less accentuated minor minimums and maximums which, going towards the south, almost level out.
- Mediterranean regime: this type presents a maximum winter rainfall and a minimum summer rainfall: it affects Sicily, Calabria and parts of Apulia.

The location that shows the highest rainfall in Italy is Musi (633 m) in Friuli Venezia Giulia exposed to the moist and rainy Scirocco and Libeccio winds, thanks to which it

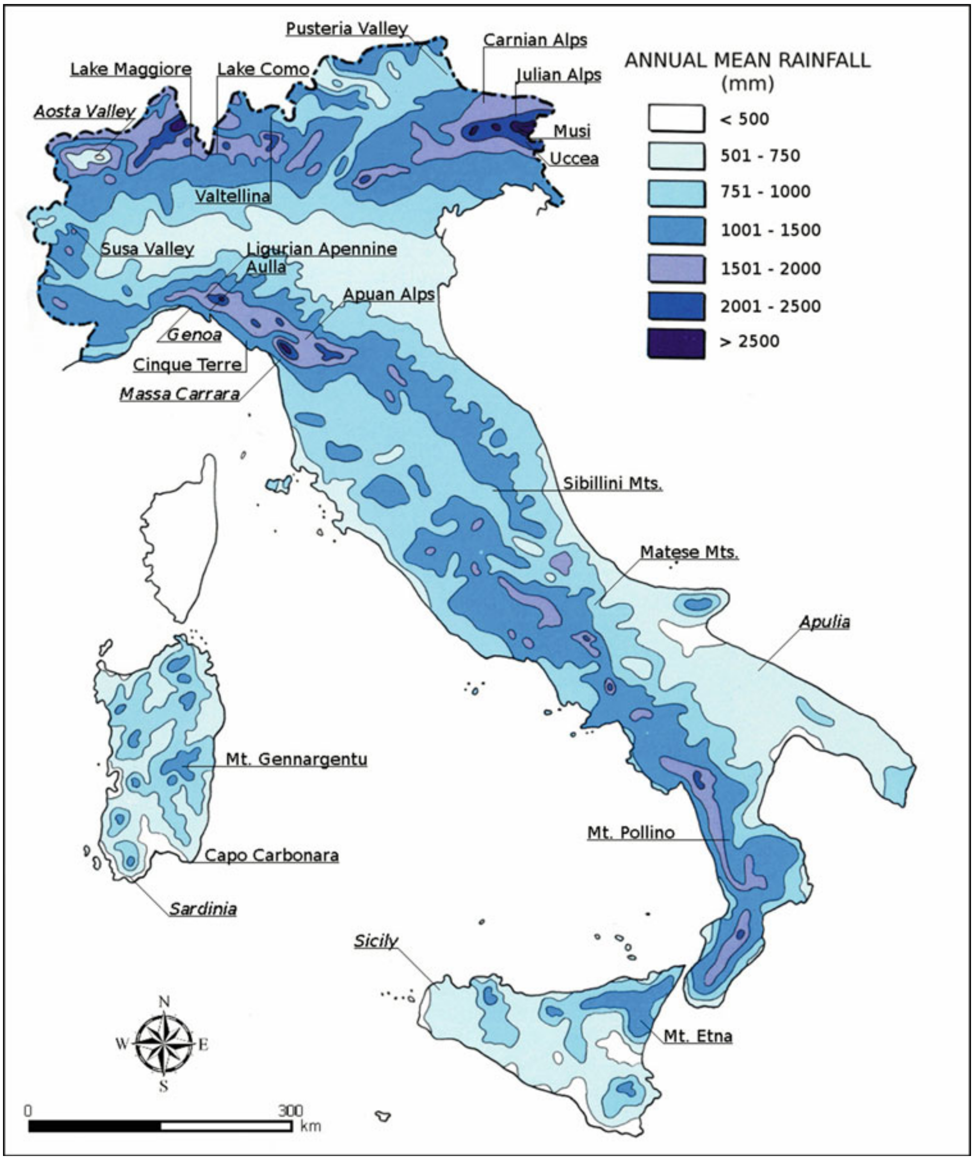

Fig. 4.4 Annual mean precipitation from 1961 to 1990 in Italy. *Source* SCIA system by ISPRA (www.scia.isprambiente.it)

manages to accumulate a total mean annual rainfall of 3300 mm. In this area, the maximum quantity of rain cumulated in a year was recorded at Uccea in 1960 with 6012.9 mm.

The location with the lowest precipitation throughout the entire Italian territory is that of Capo Carbonara, in the municipality of Villasimius, in Sardinia, with a mean yearly rainfall of 237.8 mm in the 1971–2000 30-year period.

As far as snowfall in Italy is concerned, unlike what can be observed for rainfall, precipitation events are particularly abundant on the most internal elevations, and also on the slopes that back on to the sea. This shows that altitude and continental nature of weather are the main factors that determine the rather low temperatures that occur during the winter period.

These events increase over the Po Plain, from east to west. They are somewhat modest at the bottom of the alpine valleys, but increase rapidly towards the top of the valleys, above all in the Western Alps—which are more internal and therefore subject to more continental weather.

Mean annual snowfall between 20 and 50 cm occur on the plains of northwest Italy, in the Alpine valleys, in the plain areas of Emilia-Romagna close to the Apennines, along the coastal section in the first part of the hinterland in the Marche region, and along the whole Apennine ridge at the altitude of transition between the high hills and the mountains; the high hills and low mountain areas of Sardinia also fall into this category. As far as the mountainous areas are concerned, snowfall increases with altitude, and above all with exposition to the moist currents from the Mediterranean and Balkan seas. As far as the Apennines are concerned, the snowiest areas are generally those of the Tuscan-Emilian regions and that of the Adriatic side—in particular between Sibillini and Matese mounts—as well as the areas closest to the sea of Mt. Pollino, Mt. Etna and Mt. Gennargentu.

4.6 Climatic Variations

The analysis of the temperature series gathered throughout the Italian territory makes it possible to point out two sub-periods, since 1961 until 2010, which are characterized by opposite trends. A decreasing trend can be identified from 1961 until the end of the 1970s, while a sudden increase in temperature can be observed from the eighties onwards.

A decrease in the mean temperature of 0.3 °C/10 years has been estimated from 1961 until the end of the seventies (Fig. 4.5a). The most noticeable decreases are calculated on the series of the minimum temperature, where a decrease of −0.84 °C has been identified for the twenty-year period, while a decrease equal to −0.51 °C has been found for the maximum temperatures (Toreti and Desiato 2007). A sudden change in the temperature trend has been observed from the 1980s until today (Fig. 4.5b, c). The maximum and minimum temperatures have begun to increase. The most notable increase, that is of 0.6 °C/10 years, has been calculated on a series of maximum temperatures, and this is followed by the minimum ones with 0.5 °C/10 years. An increasing trend has also been calculated for the temperature range, the summer days and the tropical nights.

A relevant increase of temperature was calculated in particular in the Alps, for locations above 2000 m. For these areas the maximum increase was estimated for minimum temperature of up to 2.8 °C in the last 50 years (Acquaotta et al. 2015).

A stationary trend has been observed in Italy in the period 1961–2010, as far as rainfall is concerned. The cumulated annual rainfall has neither increased not decreased in the north, in the centre or in the south of Italy. A decreasing

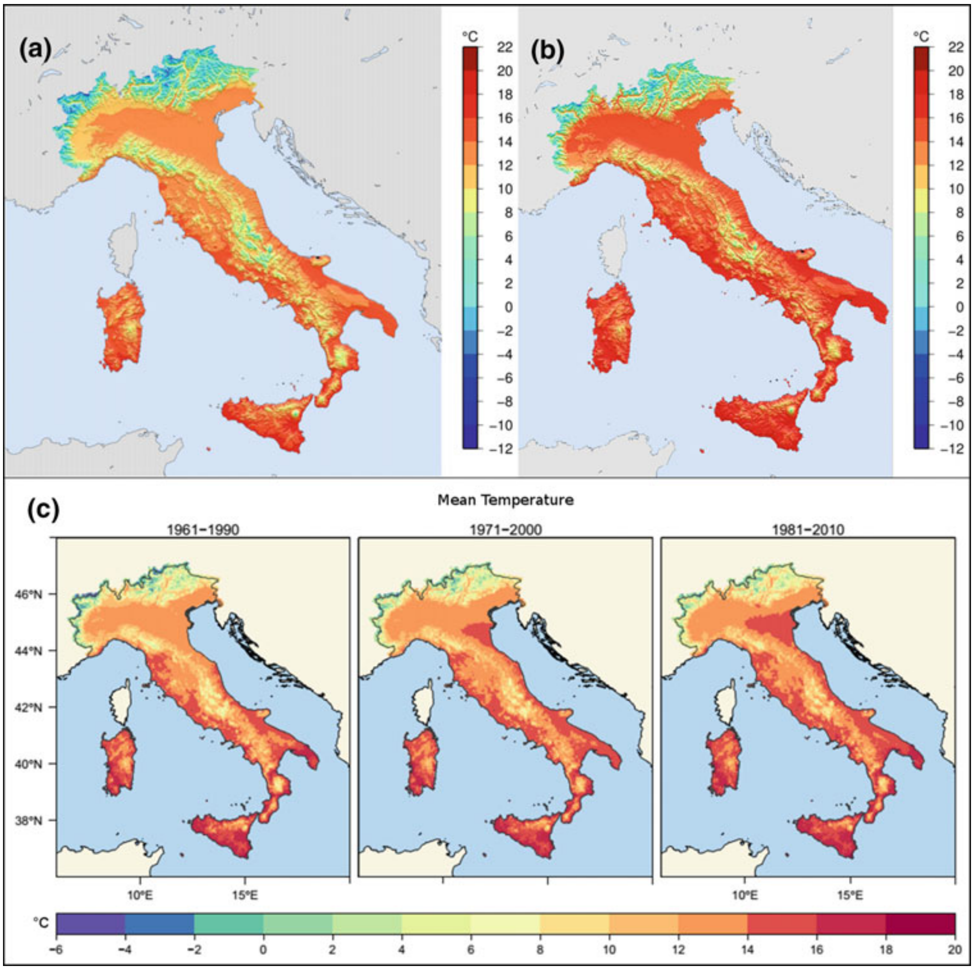

Fig. 4.5 **a** Mean temperature of Italy in 1978; **b** Mean temperature of Italy in 2011; **c** Mean temperature in three different 30 years periods. *Source* SCIA system by ISPRA (www.scia.isprambiente.it) (Desiato et al. 2015)

winter trend has been observed at a seasonal level in the north and centre of Italy. In the north, a decrease of −1.5 mm/year has been recorded, while in central Italy the decrease, which is equal to −7.7 mm/year, has been calculated starting from 1988. More consistent variations have been found for the number of rainy days. The overall number of rainy days throughout the entire national territory has diminished by about 14%, without any significant differences between the northern and central-southern regions (Brunetti et al. 2006). The greatest contribution to the decrease has been calculated for the winter season. This behaviour points out a variation in the occurrence of rainfall events. Heavy rains have increased over the 1961–2010 period and 2011 was characterized by extreme events (Fig. 4.6). The recent flash floods that hit the Liguria (Genoa, Cinque Terre) and North Tuscany (Aulla and Massa Carrara) regions between the end of October and beginning of November 2011 are examples of this behaviour. In fact, on 25 October 2011 nearly 542 mm of rain, a third of the average annual rainfall, fell in six hours. The city of Genoa was rocked by severe flash floods on 4 November 2011, when nearly 500 mm of rain fell in six hours. Six people perished and millions of Euros in damages occurred. The next event occurred in Genoa on 9–10 October 2014, with 188 mm in 24 h, causing one fatality.

A decreasing trend in snowfall has been pointed out in Italy over the Alps from 1961 until the 1970s. An inversion in tendency has been registered from the 1970s onwards,

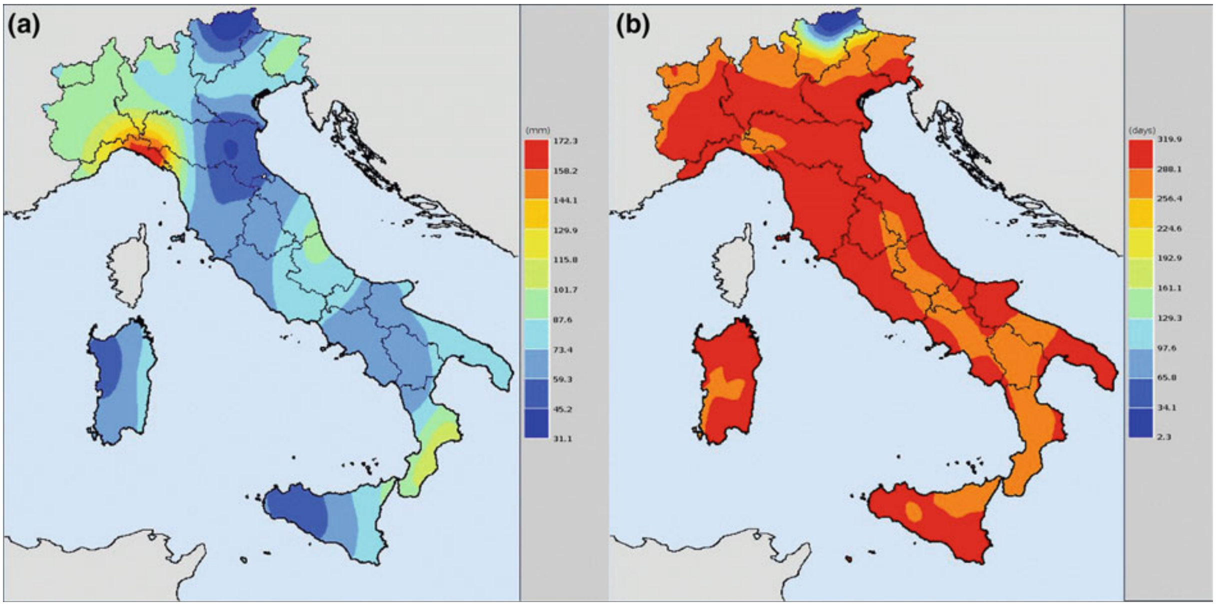

Fig. 4.6 Distribution of heavy precipitation (**a**) and distribution of dry periods in Italy in 2011 (**b**). *Source* SCIA system by ISPRA (www.scia.isprambiente.it)

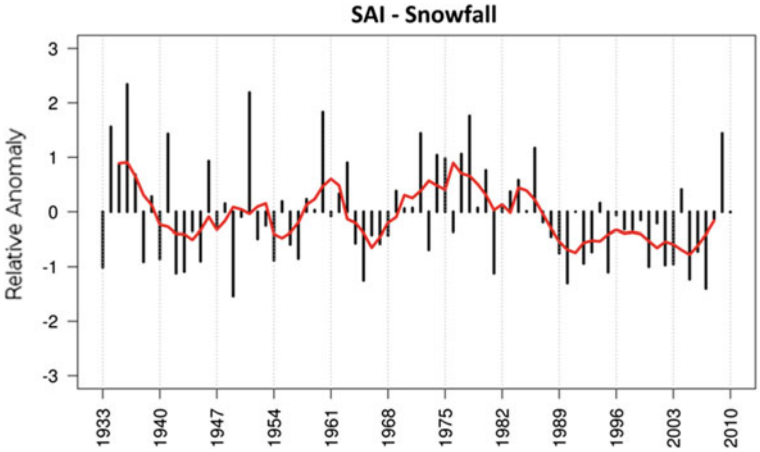

Fig. 4.7 Snowfall Standardized Anomaly Index (SAI) of Piedmont highlighting the greater variations of the variable from his mean value. The snowfall data are calculated using the dataset from all of Piedmont high altitude stations from 1961 to 2010. The *red line* shows the moving mean value for 5 years (reference period from 1971 to 2000)

until and including all the 1980s. Abundant snowfall has been recorded over the entire Alpine range (Fig. 4.7). However, in the last few decades, a decrease has continued to be recorded, although this decrease is more moderate than in the previous years (Auer et al. 2007).

The reduction in the snow cover is more remarkable at lower altitudes, between 800 m and 1500 m, and in the spring season, from March till April. The maximum decrease was recorded in the nineties, with −14 days/10 years, while the decrease over the last decade has been more moderate, −8 days/10 years (Terzago et al. 2013).

As far as snowfall in the winter season is concerned, decreasing trends of between −44 cm/10 years and −4 cm/10 years have been calculated from December to April. The most important decrease has been identified at the end of the 1970s and during the 1990s. Two contrasting trends have been also observed over the Apennines from 1987 until today. In the northern Apennines, both snowfall and snow cover have shown decreasing trends, which are comparable with those of the Alpine chain. The maximum decrease has been recorded for stations located at altitudes below 1300 m. Instead, increasing trends have been calculated for the central part of the Apennines.

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Morphological Regions of Italy

5

Paola Fredi and Elvidio Lupia Palmieri

Abstract

This chapter presents a synthesis of the wide variety of landscapes that makes Italy a very interesting country from a geomorphological point of view. The complex and lively geological history, responsible for the peculiar tectonic arrangement of Italy, the high heterogeneity of outcropping rocks and the distinct distribution of altitudes, together with the different types of climates are the main causes of the landscape varieties. The main natural aspects of the "Morphological Regions" of Italy are described; that is to say those areas of the Italian territory marked by a dominant type of landscape—even though often strongly diversified within themselves—which resulted from both the conditioning of the geological structure and the predominance of given exogenous processes, in relation to climatic conditions.

Keywords

Morphological regions • Morphogenetic processes • Landforms • Landscape • Italy

… il bel paese
ch'Appennin parte, e 'l mar circonda e l'Alpe
(Sonetto XCVI in vita di M.L.)
Petrarca (1304–1374)

5.1 Introduction

"… our world (i.e. Italy) is … immensely rich in natural phenomena and beauties. The beauties and the scientific treasures of the Alps go along with the dissimilar beauties and treasures of the Apennines; and after having described our glaciers, the castle rises and the gorges of the Alps and Prealps, we shall have new worlds to describe: gas emissions, nuée ardente, mud volcanoes, still active or extinct volcanoes, Vesuvio, Etna; and further on, the sea and its islands, different climates and vegetation, from subtropical to glacial, and so on, so that Italy (and I do not stammer saying it) is the synthesis of the physical world."

This is the translation of a text from the essay "Il Bel Paese. Conversazioni sulle Bellezze Naturali, La Geologia e la Geografia fisica d'Italia" (The Beautiful Country. Conversations on Natural Beauties, Geology and Physical Geography of Italy) written in 1876 by Antonio Stoppani, a man of letters and sciences, who had been teacher of Geology for a long period. He derived the title of his book from a sonnet by Petrarca, where the poet defines Italy as the "Beautiful Country that the Apennine divides and the Sea and the Alps encircle". The Stoppani's statements clearly underline the wide variety of landscapes that makes Italy a very interesting country from a geomorphological point of view. Many different causes contribute to the diversity of the landscapes of Italy. The geological background plays

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obviously a decisive role. The complex and lively geological history is responsible for the peculiar tectonic arrangement of Italy, with the Alps and the Apennines, two young and still rising mountain chains that make up the general framework of the peninsula. The different orientations of the two chains—roughly west–east of the Alps, and NW–SE of the Apennines—are the main cause for Italy's geodiversity, as they are a crucial factor of climate variability. Furthermore, the same dramatic geological events have also produced the high heterogeneity of outcropping rocks, often changing on small distances, and the distinct distribution of altitudes (Figs. 5.1 and 5.2). All these peculiarities are sound basis for the development of differentiated landforms.

If we add the varied types of climates occurring in the peninsula extended for about 12° in latitude, we can easily understand the multiplicity of natural landforms of the Italian landscapes. All the following chapters of this volume are by themselves a tribute to the richness of the geomorphological features of Italy.

Indeed, speaking about the causes of diversity of the Italian landscape, to remind the human presence since the most ancient times is also obligatory. In fact, human activities have had and still have an increasingly important role in the modification of natural landscapes, which at present occur only over very restricted areas of the Italian territory. Anyway, it is impossible to go over all the detailed aspects of the Italian landscapes in a single, overview book chapter. Some simplifications and generalizations are unavoidable, which imply, first of all, to neglect the human role in shaping the land.

Therefore, geomorphological descriptions in the next paragraphs will be devoted to the general, main natural aspects of the "Morphological Regions" of Italy. That is to say those areas of the Italian territory marked by a dominant type of landscape—even though often strongly diversified within themselves—which resulted from both the influence of geological structure and the predominance of certain exogenous processes, in relation to climatic conditions. On these bases, and substantially in accordance with previous works (Almagià 1959; Sestini 1963; Franceschetti 1974; Federici 2000), we will describe the overall features of the following morphological regions: Alps, Padano-Veneta Plain, Apennines, Volcanoes, Major Islands and Coasts of the Italian Peninsula.

5.2 The Alps

> *Alpi nevose, che le corna al cielo*
> *e quinci e quindi oltre misura alzate,*
> *e ne l'algente verno e calda estate*
> *orride sète di perpetuo gelo…*
> *(Il Canzoniere)*
> *Matteo Bandello (1485–1561)*
>
> Snowy Alps, that everywhere lift up your horns
> beyond measure
> and in the freezing winter as in the warm summer
> are wild and icy…
> (Translation by G. Luciani)

The Alps are the widest and highest mountain chain of Europe. They extend for about 12° in longitude and 5° in latitude, over an area of 250,000 km^2 approximately, and constitute an imposing rocky rampart that separates ancient, mostly levelled massifs of Central and Northern Europe, from the southern and geologically younger Mediterranean domain. The alpine reliefs are the result of complex and long-lasting events started in the Cretaceous (Coward and Dietrich 1989; Bosellini 2005) that produced a complex chain with double vergence: a N-vergence, towards the European foreland (the Alps s.s.), and a S-vergence towards the Africa-Adriatic foreland (Southern Alps). The two relief systems are linked up with the Insubric Line system (Fig. 5.3).

The Europe-vergence chain is present in the Italian territory with its inner slope that includes the crystalline uplifted basement massifs of the Western Alps, the Pennine nappes (the Alps s.s. which make the arch of Western Alps and its prolongation towards the Carpathians) and the Austro-Alpine nappes (most of the reliefs of Central and Eastern Alps, to the north of the Insubric Line system). The S-vergence chain is represented by the Sudalpine nappes, to the south of the Insubric Line system.

The Italian Alps (about 27% of the entire alpine area) form a wide arch extending for approximately 1200 km from Liguria in the west, to the Dinarids in the east. Orientation of the chain varies along its length: in the westernmost sector it roughly follows the parallels direction (Alpi Liguri and Alpi Marittime); then the meridians direction (Alpi Cozie and Alpi Graie); finally the parallels direction again (Alpi Pennine, Alpi Lepontine, Alpi Retiche, Alpi Carniche and Prealps chain), vanishing with decreasing altitude into the Dinaride arch.

The complex sequence of tectonic events reflects itself in the overall morphological aspect. First of all, it is responsible for dissimilar altitudes, but also for the sharper and narrower landscapes of the western sector and the progressively more rounded and spacious landscapes that prevail moving towards the eastern sector.

Generally speaking, the alpine landscape has very distinctive characters, typified by high and steep-sided reliefs, wide and deep valleys, vegetation cover that changes from woods to grassland with altitude, human settlements on the valley floors or on the gentler sun facing slopes. The landscape changes with seasons: the snow cover dominates during winter partially hiding landforms that become more evident during spring and summer. All these features are

Fig. 5.1 Orographic map of Italy (after Insolera and Musiani Zaniboni 1979)

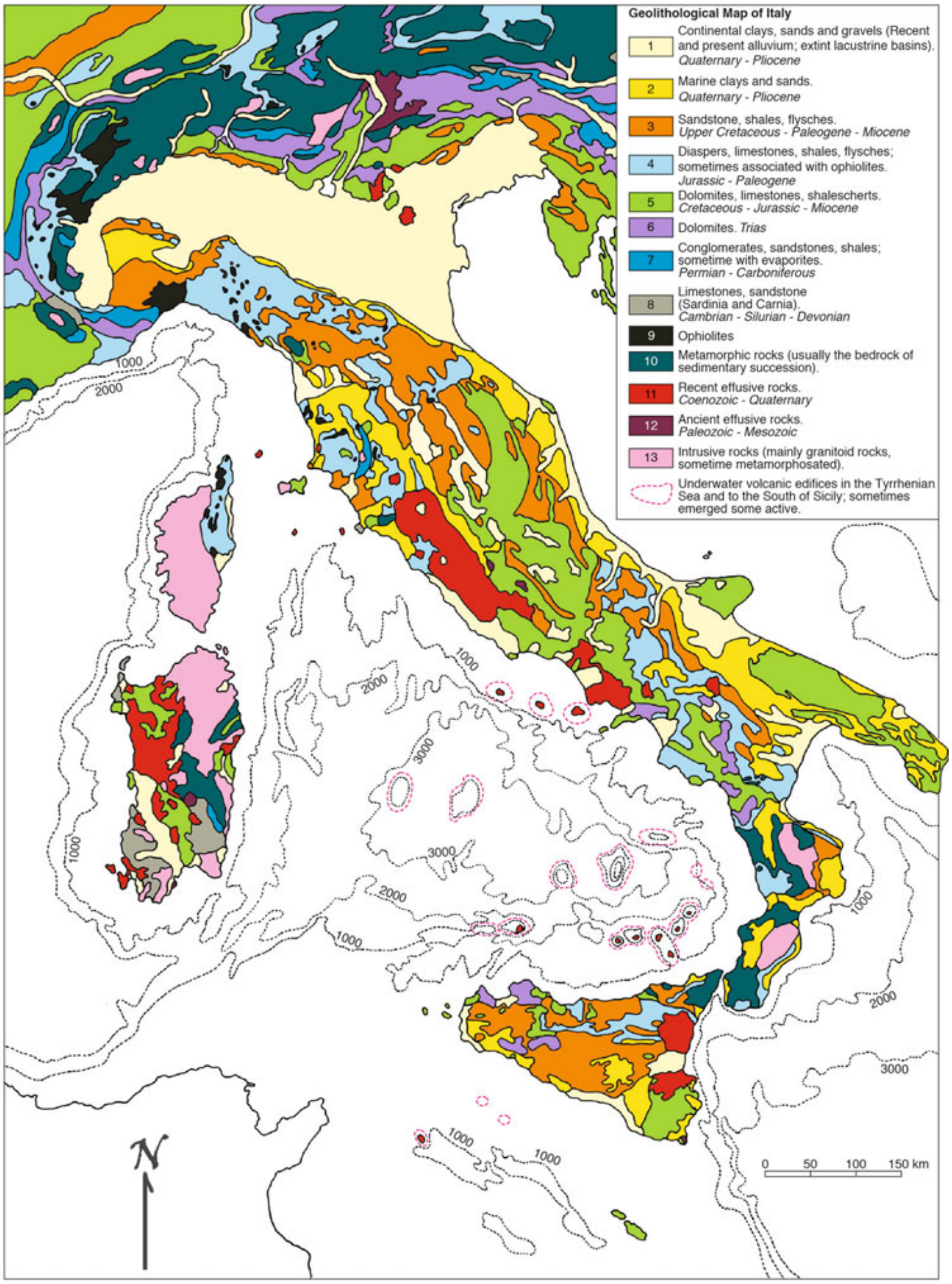

Fig. 5.2 Lithological map of Italy (after Lupia Palmieri and Parotto 2009)

strictly tied to the high difference in elevation between the valley floors and the summits that is responsible, in its turn, for marked climatic and vegetation diversity (Sestini 1963). The Italian Alps share these peculiarities with other geologically young mountain chains, in which tectonic deformations and uplift are still active.

Given the young age of the chain, the alpine landscape clearly shows the dominant effects of endogenous morphogenetic agents; indeed, the constructive activity of such processes still overcome that of the destructive exogenous processes. However, varying morphosculptures, mainly produced by glaciers, surface running waters and gravity, occur on the large morphostructures. The tectonic conditioning goes along with the lithological control that is particularly evident where sedimentary rocks alternate with igneous and metamorphic rocks.

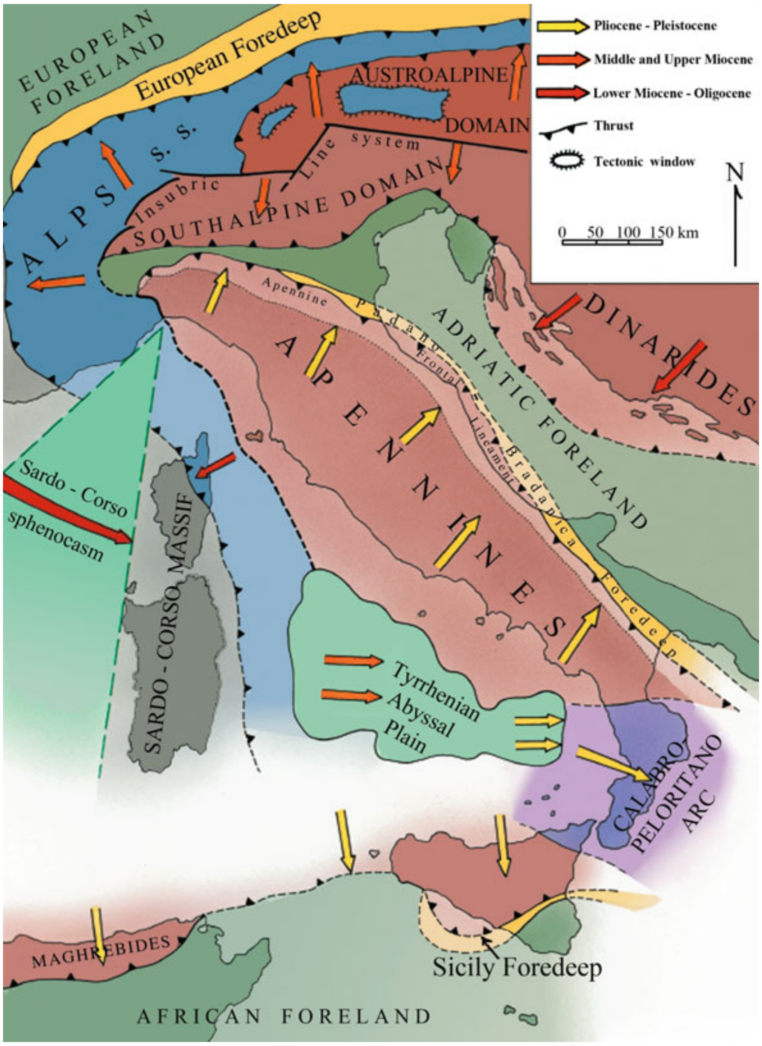

Fig. 5.3 Main structural units of Italy and its surrounding areas. *Arrows* indicate direction and age of large movements connected to the last orogenetic phases, the Sardo-Corso massif rotation, and the Tyrrhenian Abyssal Plain formation (after Lupia Palmieri and Parotto 2009)

5.2.1 The Landscapes of the Italian Slope of the Europe-Vergence Chain (Alps S.S.)

A very distinctive character of this chain is the presence of the imposing “crystalline massifs”.

They are essentially intrusive bodies coupled with belts of metamorphic terrains (para- and orto-schists and gneiss), which represent the highest relief of the alpine system, mostly at the border of Italy. Starting from the western section of the Alps, the most important massifs are the following: Argentera (Alpi Marittime, 3297 m a.s.l.), Gran Paradiso (Alpi Graie, 4061 m), Monte Bianco (Alpi Graie, 4810 m), Cervino (Alpi Pennine, 4165 m), Monte Rosa (Alpi Pennine, 4634 m), Monte Disgrazia (Alpi Retiche, 3678 m), Monte Bernina (Alpi Retiche, 4049 m), Ortles-Cevedale (Alpi Retiche, 3902 m) and Monte Adamello (Alpi Retiche, 3539 m). Monte Bianco and Monte Adamello (actually a post collision intrusive body) are mainly granitic in composition; schistose and gneissic rocks make up the almost continuous massifs in Western and Central Alps and the highest relief of Lombardy. Their landscape is mostly shaped by ice, even if surface waters and gravity have played an important role.

The highest portions of the crystalline massifs—too steep to host glaciers—show the effects of physical weathering clearly. It is mainly due to the repeated freeze-thaw cycles, also favoured by the existence of frequent and differently oriented fractures. Very sharp, irregular and discontinuous crests result from the frost action and gravity; they are often interrupted by saddles from which very narrow, steep-sided canyons originate (Carton 2004).

The summits of Argentera and Monte Bianco are the sharpest and most indented because of their peculiar geological history. These external massifs, in fact, represent the remains of an ancient levelled Hercynian chain that was involved again in the more recent alpine orogenesis. Showing brittle behaviour towards the alpine thrusting, these "nuclei" of the old chain were strongly uplifted and extensively fractured (Franceschetti 1974). Nearly vertical, heavily tectonized rocky slopes were transformed into spectacular notched pinnacles because of physical weathering and gravity processes (Fig. 5.4).

The altitude of the crystalline massifs is above the contemporary snow line of the Italian slopes of the Alps (2850–2950 m); therefore glaciers are often present. Their size is much smaller in comparison with the huge Pleistocene glaciers, and they have receded drastically since the end of the Little Ice Age (1550–1850). In spite of reduction of their size, glaciers can still be considered among the main erosional agents (Fig. 5.5). The shapes of present-day glaciers are markedly varying as a consequence of general morphological arrangement of the massif. Larger glaciers are classified as valley glaciers; but smaller glaciers are often present, generally lacking a well-developed ablation area. The largest glacier (18 km^2) of the Italian Alps occurs in the Adamello massif (see Carton and Baroni 2017). The latter shows a very peculiar morphology resembling a large Norwegian plateau, with glaciers feeding radial valleys. The Forni glacier, in the Ortles-Cevedale massif, is the second larger glacier in the Italian Alps and the largest among valley glaciers. It is an example of a valley glacier with a complex accumulation area, followed down valley by an undersized ablation area which is an evidence of its marked retreat. Miage glacier on Monte Bianco is perhaps the most famous and spectacular glacier of the Italian Alps. Its accumulation area is not a single well-defined depression; steep and narrow lateral valley glaciers feed the main valley where the ice flows are constrained between vertical walls. It is a debris-covered glacier that resembles the Himalayan glaciers (Smiraglia 2004).

On the whole, both weathering and glacial processes are strongly influenced by geological structure that is particularly evident and complex in metamorphic massifs; as a result their landscapes are much more uneven than the landscape of granitic massifs.

As consequence of severe frost and gravity action, wide talus slopes occur at the foot of steep rocky walls of the crystalline massifs. More frost susceptible metamorphic, schistose rocks produce a larger quantity of debris of various sizes in comparison with granitic rocks. The higher volume of debris influence, in its turn, the volumes of talus slopes at the foot of the metamorphic reliefs and the moraine rampart size as well.

The landscapes of the crystalline massifs and their active glaciers are surely the most spectacular and known of the whole Alpine chain. Nevertheless, other landscapes offer equally striking views. This is the case, for instance, of areas where selective erosion acts upon different lithologies of outcropping rocks. In the Western Alps, for example, where variously resistant lithologies of the Mesozoic and Permo-Triassic sedimentary cover crop out, the landscape is quite smooth and relief does not exceed 2500–2600 m in elevation. Moreover, as result of morphoselection, rocky landforms built of Triassic dolomites or high ophiolitic massifs, like the beautiful Monviso (3841 m), rise above the generally mild landscapes shaped on calcareous schists. In the northern-central sector of the Italian Alps (corresponding to the Australpine domain), the crystalline and metamorphic massifs go along with extensive outcrops of Mesozoic limestones and flysch; as a consequence, the landscape shows great variety of landforms.

At the margin of glaciated areas, periglacial landforms are common. Rock glaciers are perhaps the most striking. They consist of detrital bodies, produced by creeping phenomena, and resemble true glaciers (Fig. 5.6). Outside of the areas

Fig. 5.4 Panoramic view of the Italian slope of the Monte Bianco, in the Valle d'Aosta (*photo* M. Giardino)

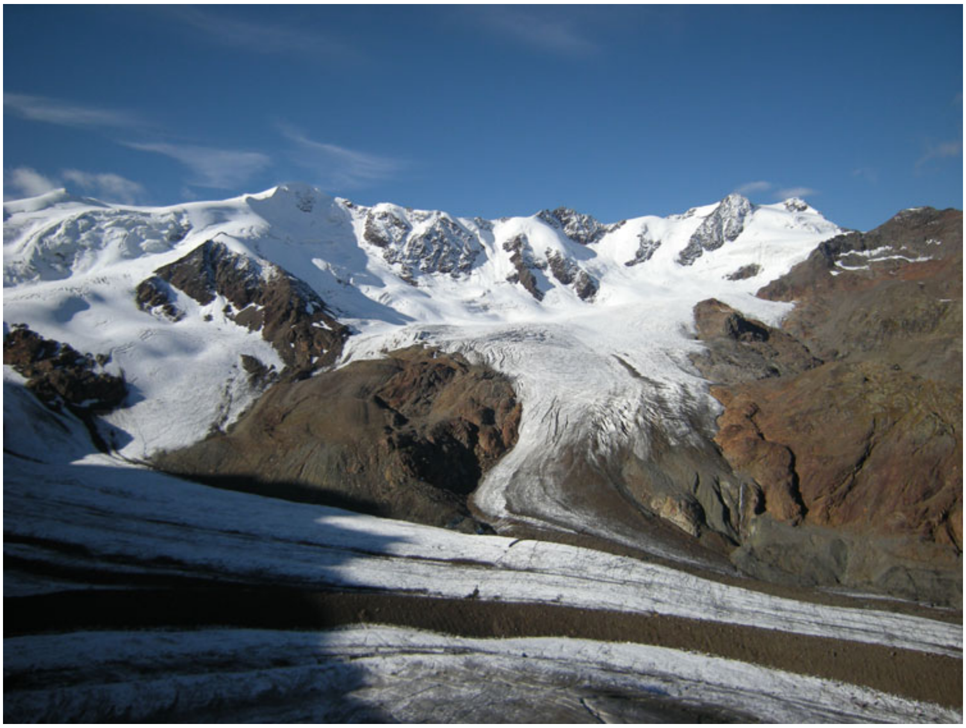

Fig. 5.5 View of the Forni valley glacier, in the Ortles-Cevedale massif (*photo* C. Smiraglia)

presently shaped by glacial processes, the most striking landscapes occur where still recognizable inactive landforms, produced by the large Pleistocene glaciers, were deeply modified by the recent erosional processes due to running waters. Single or coalescent cirques are present at the higher altitudes of deglaciated relief. The sharp crests of *arête* dominate the landscape of the summits; by contrast, glacial striations, grooves and polished surfaces are dominant features of smoothed bedrock below the trimline, marking the maximum upper level of the Pleistocene glaciers.

Valley morphology is very complex, as it is conditioned by landforms shaped by the Pleistocene glaciers that, in their turn, occupied more ancient fluvial incisions. The same drainage network geometry is often influenced by the presence of complex flow directions tied to the frequent glacial transfluences and diffluences. Although often deeply modified, the cross profiles of the present valleys still preserve the U-shape of the glacial troughs (Fig. 5.7). Their longitudinal profiles are irregular and at places contain thresholds (*riegel*) and overdeepened depressions now occupied by series of small lakes (Paternoster lakes) or aggrading streams. High steep steps (hanging valleys) are particularly evident where a secondary stream joins the main valley (Baroni 2004).

The valley arrangement is quite different in the different sectors of the chain. In the western arc they have a radial centripetal pattern verging towards the River Po plain. The Val di Susa (drained by the River Dora Riparia), the Valle d'Aosta, the Val Sesia and the Val d'Ossola are the most important valleys that come from the Pennidic domain. They were once occupied by the Pleistocene glaciers and are now drained by streams that reach the Padano-Veneta Plain, crossing the moraine amphitheatres.

The major valleys of the Central alpine arc end within depressions that host large southern alpine lakes. The tectonic control on the valley arrangement is easy discernible. Long rectilinear stretches of the main valleys follow tectonic directions that are parallel to the chain axes. The Valtellina is the most impressive one; this E–W oriented valley is strongly conditioned by a segment of the Insubric Line system that can be considered as a geological scar at the border between the north-verging chain of the Pennidic/Australpine domain and the south-verging chain of the Southalpine domain. Valleys transversal to the chain are also present; they often follow tectonic lineaments too and make the connection between longitudinal valley stretches possible, thus allowing direct link between the inner part of the chain and the external ones. The northeastern arch is characterized by wide valleys that reflect the highly evolved glacial morphology of this area. The huge glaciers joining the present River Adige valley, in fact, had a higher volume than the glaciers in the Valle d'Aosta.

Active tectonics, as well as the variety of rocks, the morphology of slopes and the climatic characteristics are all factors that make the Alpine arc prone to mass movements, responsible for profound and fast morphological changes.

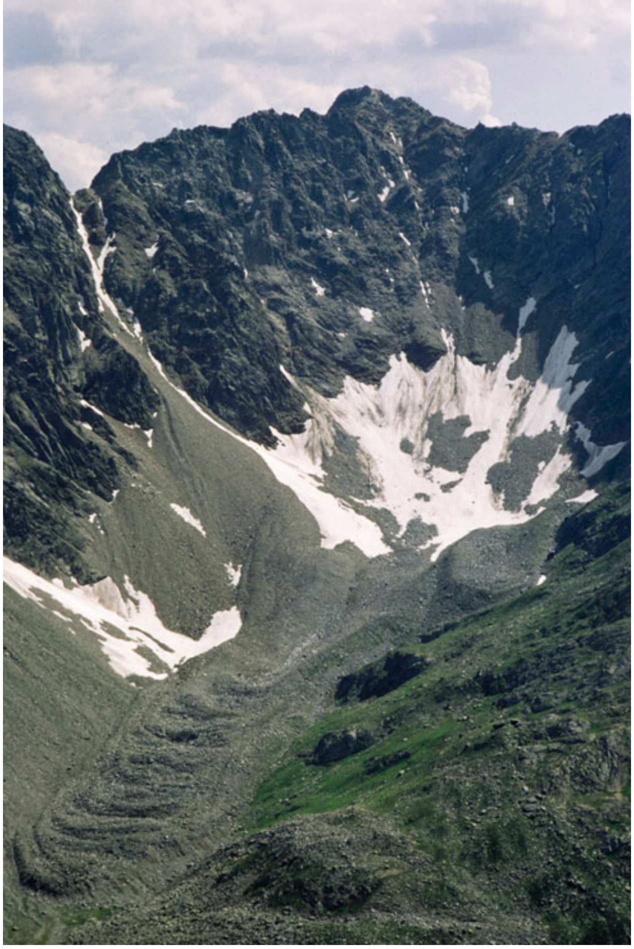

Fig. 5.6 Intact debris-tongue shaped rock glacier with the rooting zone formerly occupied by the Camosci glacier until 1996 (Central Alps, Lombardy) (*photo* R. Scotti)

5.2.2 The Landscape of the South-Verging Chain (Southern Alps)

The Southern Alps are located to the south of the Insubric Line system and represent the Africa verging chain that belongs to the Southalpine domain. They extend eastward for about 700 km from the area to the south of Gran Paradiso and form a wide arc that borders the Padano-Veneta Plain to the north. The relief consists mainly of Mesozoic sedimentary rocks and only subordinately of metamorphic rocks. By contrast with the Alps s.s., the Southern Alps were affected by folds and overthrusting, generally E–W oriented.

The ridges of this chain do not attain high altitudes. Their contact with the Padano-Veneta Plain is generally abrupt because a hilly intermediate belt is often lacking. The landscape of the western portion of Southern Alps, where metamorphic rocks dominate, resembles that of the Alpine chain s.s. Due to lower elevation, glacial erosion was obviously less intense; with the exception of large valleys shaped by glaciers fed by higher altitudes. At present, glacial landforms are more or less modified by stream erosion, depending on different rock erodibility. In the central part of Southern Alps metamorphic rocks give place to the calcareous and dolomitic lithologies. The landscape is dominated by the beautiful Southern alpine lakes and it is one of the most known and celebrated. The lakes Maggiore, Como, Iseo, Idro and Garda occupy the southern stretches of wide valleys that extend up to about 100 km. The lake depressions are the result of a complex geological and geomorphological history in which tectonic events, fluvial erosion and glacial erosion played an important role. The rocky substratum of the depressions is up to 600–700 m below the present sea level and it is overlain by sediments hundreds of metres thick. Cross profiles of the buried rocky substratum suggest that the depressions were initially shaped by streams during the Messinian (late Miocene), when the sea level was far below the present one due to the Mediterranean salinity crisis (Orombelli 2004). These valleys changed into *rias* during the Pliocene marine ingression. Successively they became preferential ways for Pleistocene glaciers that reached the Po Plain and shaped further the morphology of lacustrine basins through erosional overdeepening and damming of the valleys by moraines.

The eastern portion of Southern Alps is characterized by calcareous relief and plateaux that rarely exceed 2000 m in height and show evidence of karst erosion. The correspondence between geological structure and morphology is evident. The landscape is typical of the Jurassic relief, deeply dissected due to action of important rivers such as Brenta, Piave and Tagliamento.

Northward, the Dolomiti, recently declared by UNESCO a World Heritage site, offer one of the most famous and breathtaking landscapes in the world (Panizza 2004; Soldati 2010). Towers, steeples, ramparts and pinnacles of white and pink rocks dominate over gentle and green valley slopes where pastures, woodlands and small towns are present. The Dolomiti landscape tells the fascinating history of this part of the Southern Alps which started about 200 million years ago in the warm tropical waters of the ancient Tethys, where corals and algae (and other organisms) proliferated. Helped by the subsidence of the sea bottom, these organisms raised their buildings up to hundreds of metres, thus originating imposing calcareous and dolomitic reefs. In the meantime, different kinds of sediments, then transformed into marls and sandstone, accumulated progressively in the sea among the reefs. Successively the Alpine orogeny caused emersion of all these rocks that fell a prey to erosional processes. Thick, horizontally layered and fractured dolomite rocks alternate with arenaceous, argillaceous and marly lithologies, and pyroclastics; moreover important tectonic dislocations affect the outcropping rocks. As a consequence, selective weathering and erosion processes (due to glaciers, surface running

Fig. 5.7 This area of the Western Alps (Bousson, Piedmont) is presently shaped by weathering and surface runoff. Nevertheless, the relief shows evidence of processes accomplished by glaciers during the last cold climatic phases. The wide valley that is now drained by a river still preserves the U-shaped cross profile that is typical for the valleys remodelled by glacial tongues (after Lupia Palmieri and Parotto 2009)

Fig. 5.8 The southern slope of Monte Cristallo; this type of relief dominates the landscape of the Dolomiti, close to Cortina d'Ampezzo (Veneto) (*photo* Zavijavah, Wikimedia Commons under CC BY-SA 3.0)

waters and gravity) dismembered the original relief into isolated uneven or massive compartments with low summit relief. Differential weathering resulted in the origin of ledges and steps that interrupt the almost vertical cliffs. Thaw and freeze cycles produced large quantities of loose rock fragments that accumulated in talus cones and talus slopes at the base of the cliffs. Alluvial, lacustrine and moraine deposits filled the valley floors and gave rise to wide flat surfaces (Fig. 5.8).

The Alpi Carniche and the Alpi Giulie close the arc of the Southern Alps to the east. The landscape of the calcareous-dolomitic Alpi Carniche is sharp and limitedly smoothed by glacial processes. However, the presence of frontal moraines at the outlet of the River Tagliamento into the Veneto Plain testifies to glacier action during the Last Glacial Maximum (LGM) Fluvial processes are clearly dominant both in the Alpi Carniche and Alpi Giulie, also helped by abundant rainfall. Finally, the Alpi Giulie slope down seaward in the Carso region, where the landscape is characterized by karst processes that derive their name from this calcareous area (see Cucchi and Finocchiaro 2017).

5.3 The Padano-Veneta Plain

> *... i fiumi colmano le valli e discostano il mare come far si vede al Po colli aderenti sua, li quali prima versavan nel mare, che infra l'Appennino e le Germaniche Alpi si serrava*
> (Codice di Leicester, *f.* 10r and 27v)
> Leonardo da Vinci (1452–1519)
>
> … rivers fill the valleys and push away the sea as the Po does with its tributaries, which once flowed into the sea, that was closed between the Apennines and the German Alps
> (Translation by G. Luciani)

The Padano-Veneta Plain is the largest alluvial plain of Italy. It is roughly triangularly shaped and extends for about 46,000 km^2 between the Alps to the north and the Apennines to the south. The plain gently slopes to the east towards the Adriatic Sea and is crossed by the River Po, the major river in Italy. The altitude of the Padano-Veneta area, which contains the wide plain s.s., ranges from 650 m a.s.l. in the highest western portion to 5 m b.s.l. in the Po Delta (Fig. 5.9).

The coastal belt of the plain stretches for about 330 km. Its central part is dominated by the River Po delta; lagoons prevail in the northeastern reach, the Lagoon of Venice being the most important.

The drainage network of the River Po basin is asymmetric; in fact, the tributaries coming from the Alps and flowing southeastward are systematically longer than the tributaries coming from the Apennine northern slopes that flow north-eastward.

The eastern portion of the plain is drained by large rivers that at present do not belong to the Po drainage basin but were part of it during the LGM, when the plain occupied large part of the contemporary northern Adriatic Sea. The most important are the rivers Adige, Brenta, Piave and Tagliamento (see Surian and Fontana 2017), from the Veneto and Friuli regions to the north, and Reno from Emilia-Romagna to the south.

The Padano-Veneta Plain attained the present configuration in middle Holocene (Gasperi 2001), after a very complex geological and geomorphological history that is strictly connected to the birth of the Alps and Apennines.

During the Mesozoic, the Padano-Veneta Plain area was the foreland for both the chains; starting from the Oligocene it evolved into a strongly subsiding foredeep basin for the Sudalpine nappes first, and then, starting from the Messinian, for the Apennine structures. As a result, the foredeep basin underwent compression from both chains verging in the opposite directions (Gasperi 2001).

During and after the birth of the Alps and the Apennines, and still during the Quaternary, the area now occupied by the plain was a marine basin that extended as a wide gulf as far

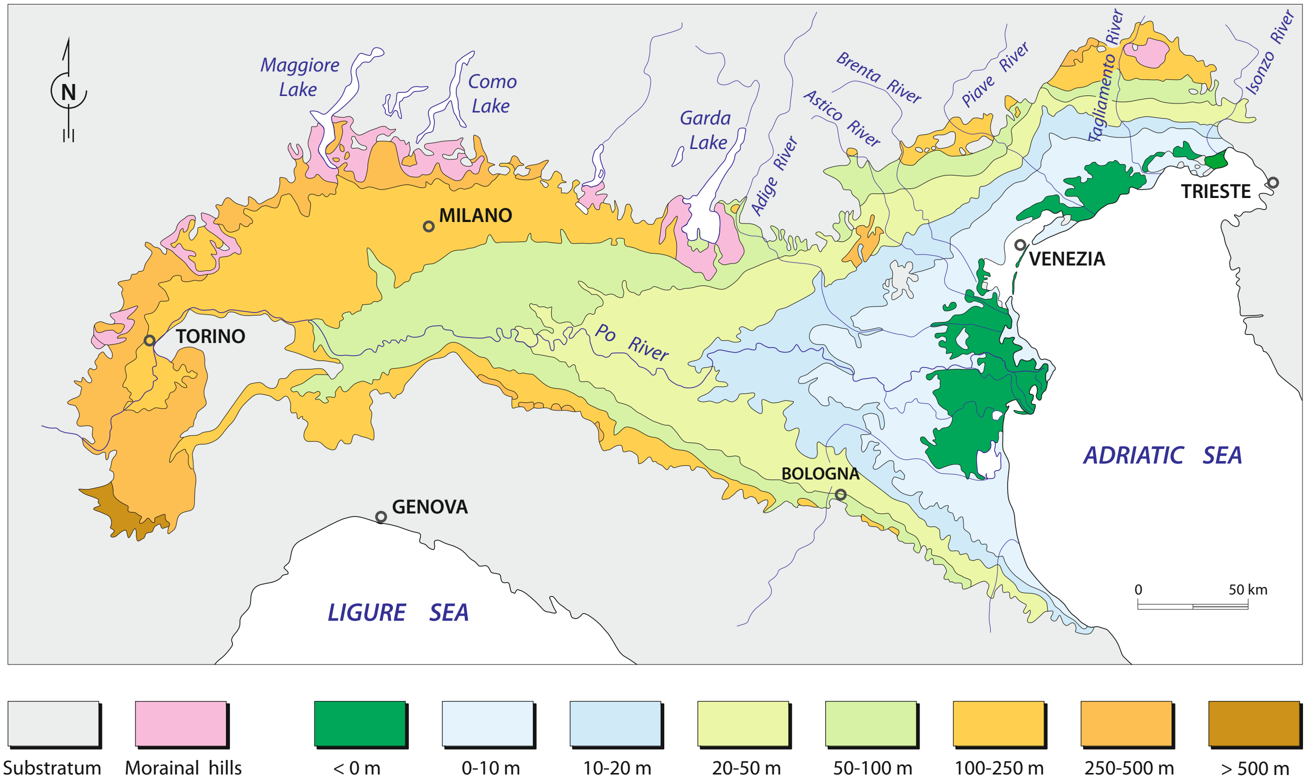

Fig. 5.9 Altimetric map of the Padano-Veneta Plain (*drawing* M. Albano)

as the present Piedmont region. The gulf became gradually smaller due to both compressional forces and thick clastic sedimentation nourished by the abundant solid load that was delivered to the sea by streams coming from both the southern slopes of the Alps and the northern slopes of the Apennines. Wide deltas were built up and the depression progressively changed into a huge valley floor, after complex alternate events differentiated in space and time. In the Lower-Middle Pleistocene continental sedimentation is likely to have prevailed; at that time the area of the present plain, although punctuated by swamps and ponds, was dominated by river dynamics. Streams coming from mountain valleys produced large alluvial fans on the newborn valley floor. Growing in thickness and size, juxtaposing and superimposing each other, the alluvial fans gave rise to an irregular sloping plane.

This apparently simple evolution was strongly complicated by climate changes that allowed the development of glaciers, affected river dynamics, and caused repeated changes of the sea level. The alpine Quaternary glaciers deposited large moraines at the plain borders that were then reworked by the water courses after the end of glaciations. Fluvial depositional phases alternated with erosional phases responsible for the origin of different orders of fluvial terraces and terraced alluvial fans.

Glacial and fluvioglacial deposition led to the formation of two different belts of plain. These are the “high plain” characterized by permeable coarse-grained deposits and the “low plain” where finer-grained and less permeable deposits prevail. The transition zone between the two belts is the line of resurgences locally named “fontanili”. They underline the limits between the high plain and the low plain on the Alpine side and, although discontinuously, also on the Apennine side. The large availability of water and soil fertility is the reason for the successful development of agriculture all over the plain.

The Padano-Veneta Plain evolution was further complicated by intense subsidence phenomena. The weight and consolidation of the sedimentary deposits themselves, as well as tectonics, caused the lowering of the plain up to hundreds of metres. Subsidence was increasing southward, thus explaining the shift of the River Po towards the Apennine chain and the asymmetry of its drainage network. Subsidence in the plain is still active and nowadays natural causes go along with causes due to human activity, consisting mainly in underground water pumping and natural gas extraction.

Many interesting landforms occur at the boundary between the plain and the surrounding higher grounds. In reality, the orographic limits of the present Padano-Veneta Plain do not correspond to the structural boundaries of the Alps and the Northern Apennines that are buried under the thick detrital cover. The plain limit is clearly discernible all along the border of the Alpine chain, where differences in elevation are strong and erosional and depositional processes are very intense. In some other cases transitional, usually hilly, landforms are present that make the boundary of the plain less evident (Tellini and Pellegrini 2001).

Fault scarps and steps, often deeply modified by denudational processes, are among the most widespread types of the margin, especially along the Alps. Sometimes they occur in connection with flexure zones and uplifted or folded areas. The distribution of these tectonic landforms is quite heterogeneous within the plain; nevertheless, they are more frequent at the Apennine and Veneto-Friuli margins, thus testifying to lively tectonic activity witnessed by frequent earthquakes.

In the westernmost sector the limit of the alluvial plain is characterized by planation landforms on bedrock (erosional glacis). In particular, they occur where severe neotectonic uplift prevented the plain margin from being buried under fluvial deposits. Along the Alpine margin alluvial glacis are also found, resulting from the coalescence of complex alluvial fans. These fans extend well downstream and often show evidence of ancient stream courses that are oversized with respect to the present ones, in accordance with high solid and water discharge of glacially fed streams. Their evolution was influenced by Quaternary climatic changes and as a consequence, they usually underwent alternate phases of aggradation during glaciations, and erosion during the postglacial periods. Holocene alluvial fans are also present. They are more frequent at the Northern Apennine border, but they occur also along the Alpine margin. In both cases they do not show clear evidence of dissection.

Moraine hills, sometimes a few hundred metres high, are other typical transitional landforms between the plain and the Alps. In most cases the moraine hills are in morphological connection with the downstream outwash plain and represent the remnants of ancient and wide moraine amphitheatres that testify to the frequent extensions of glacial tongues into the plain marginal areas (Biancotti 2001). The Rivoli and Serra d’Ivrea moraine amphitheatres, at the Dora Riparia and Dora Baltea outlets in the Po Plain respectively, stand out at the western limit of the plain. Moving to the east, the gentle hills of Brianza, to the south of Como Lake, represent an amphitheatre built up by the glacier that was responsible for overdeepening of the depression where the lake is hosted. However, the amphitheatre of Garda Lake, that covers an area of about 760 km^2, is the most impressive. These are only some of the most significant examples, but many other moraine amphitheatres of varying size are spread along the Alps/plain margin.

Other hilly landforms interrupt the apparent flatness of the plain. They are made of pre-Quaternary rocks and rise from the surrounding fluvial, fluvioglacial, lacustrine and moraine deposits. The Colli Berici (made of Mesozoic carbonatic rocks of marine environment) and the Colli Euganei (extinct sub-volcanic reliefs, then exhumed by erosion; Pellegrini 2004), that rise to heights of 300–600 m above the plain are perhaps the most important examples. Both of them are the result of processes that took place well before the origin of the plain.

As a consequence of the alternate depositional and erosional processes, alluvial glacis, single alluvial fans and outwash plain deposits are incised by different orders of terraces that are wider on the Alpine side than on the Apennine one, where they show evidence of neotectonic deformations. Terraces are mainly convergent and they characterize the portions of the plain hanging above the present lower plain level, where the River Po and its tributary flow. The most ancient and highest terraces are connected to the so called "plain main level" through more or less sharp scarps. This level is thought to be the product of fluvioglacial and fluvial aggradational phases that affected the foothill plain in relation with the last glaciation. In turn, this old plain—well extended on the Alpine side from Piedmont to Lombardy—joins the Holocene alluvial plain through a step that resulted from downcutting of the main stream (Franceschetti 1974; Castiglioni and Pellegrini 2001).

The present drainage networks have different characteristics that correspond to the portions of the plain where they are emplaced. The existence of hanging river beds in the low plain is strictly tied to the Holocene prevalence of aggradation over erosion. The result is the origin of typical ribbon-shaped fluvial ridges that extend for tens of kilometres, rising from the plain up to about 2 m. Their persistence is also helped by building of artificial levees which started in the Roman times. The presence of hanging river beds is a crucial factor in flooding events, like the destructive historical one that struck the Polesine area in 1951.

Traces of abandoned river beds are also widespread. In particular, ancient braided patterns are found over the high plain. Old inactive meandering channels occur practically all over the plain (Fig. 5.10). They often consist of single meander, but evidence of shifting of long trunks of streams to other positions (avulsion) are also present. Actually, the present drainage network geometry is greatly influenced by human activities. The high density networks of artificial channels, mainly related to land reclamation and agricultural practices, substantially modify the previous trends of river courses. Close to the coastal belt stream bed patterns are very irregular, also due to the influence of coastal dynamics in the development of river mouth deposits (Bondesan 2001).

Fig. 5.10 The Padano-Veneta Plain in the Cremona District. The meandering bed of the River Po is evident as well as the presence of abandoned meanders (Google Earth—Image © 2016 DigitalGlobe)

The morphological aspects of the coastal belt of the Padano-Veneta Plain allow the identification of three sectors: the southern sector, where wetlands do not exist anymore; the central sector, dominated by the River Po delta; and the northern sector, characterized by a series of lagoons among which the Venezia Lagoon is the most famous. The Holocene evolution of the three sectors was controlled by different factors: subsidence, neotectonic movements, erosional/depositional processes and sea-level changes, together with the very important role of human activities.

The River Po delta history is very long and complex (see Stefani 2017). The most ancient prograding beach ridges are located about 20 km inland in respect to the present shoreline and were built 5000–4500 years ago. Since that time the River Po delta history is a history of progradation that continued until the birth of the modern delta, although with varying entity. The modern delta was established at the beginning of the seventeenth century, after Venetian people shifted the River Po main course to the southeast. Since then, delta development was very fast until the middle of the nineteenth century; progradation in this period has been estimated for 140 ha/year. In more recent times, progradation slowed down and eventually the shoreline retreated, mainly because of anthropic enhancement of subsidence and reduction of solid load in the streams (Bondesan et al. 2001).

5.4 The Apennines

> *Non sono essi (gli Appennini) così belli come le Alpi? … C'è una gran cosa che manca alle Alpi e alle Prealpi, per la quale invece gli Appennini sembrano fatti apposta…la vista del mare.*
>
> *(Il Bel Paese)*
> *Antonio Stoppani (1824–1891)*
>
> Aren't they (i.e. the Apennines) as beautiful as the Alps are? … There is something very important that the Alps and Prealps are missing, which instead the Apennines seem to have been made for … the view of the sea.

The landscapes of the Apennines are not as imposing as the Alpine landscapes. Nevertheless they show very attractive and charming sceneries. They offer perhaps a greater variety of landforms, mainly due to the different outcropping lithologies and climatic variability that affect this long chain stretching for about 6° in latitude.

The Apennine chain, in fact, extends for about 1500 km across the whole Italian Peninsula and along northern Sicily, where it joins the Maghrebides chain of North Africa. Going from the north, it draws initially a southward concave arc that separates the slope facing the Ligurian Sea in the south, from the one sloping toward the western portion of Padano-Veneta Plain in the north. Southeastwards, the Apennine chain becomes concave westward and show its typical NW–SE orientation; it separates the western slope, facing the Tyrrhenian Sea, from the eastern slope facing the Adriatic Sea. Finally, the Apennines are practically E–W oriented on the northern side of Sicily. The highest relief is Corno Grande (2912 m) in the Gran Sasso Massif, Abruzzo Apennines (Central Italy).

The distance of the Apennines' axis from the sea varies. The chain seems to rise directly from the sea in its westernmost stretch (Appennino Ligure). Moving to the south-east it progressively approaches the Adriatic Sea (Appennino Tosco-Emiliano; Appennino Umbro-Marchigiano and Appennino Abruzzese) allowing the existence of a wide Pre-apenninic area on the Tyrrhenian side. Further southward the chain axis moves again towards the Tyrrhenian Sea (Appennino Campano, Appennino Lucano and Appennino Calabro) while an external Pre-appenine area characterizes the Adriatic side.

Sedimentary rocks are dominant along the whole chain and carbonate rocks of the thrust sheets go along with syn-orogenetic terrigenous deposits. Metamorphic rocks of different grade outcropping in the Liguria and Tuscany Apennines are an exception. Finally, crystalline rocks crop out in the Sila and Aspromonte massifs of Calabria and at the Monti Peloritani (Sicily); these terrains, although belonging to the Apennines from a geographical point of view, underwent a different and more complex geological history (see Bosellini 2017).

The topography of the Apennines is characterized by a long-wavelength topographic bulge ~200 km wide, with superimposed ranges ~30 km spaced (Molin and Fubelli 2005). The first one has been interpreted as an effect of deep endogenous processes (D'Agostino et al. 2001). The second ones are made of Mesozoic limestones deformed by Neogene thrusting and bounded by Quaternary normal faults on their southwestern side that show, in some cases, evidence of Holocene activity (Galadini and Galli 2000).

The general morphological setting of the opposite slopes of the Apennines is strongly influenced by the varying tectonic style. The eastern (external) slope has the character of a thrust-and-fold chain that is the result of the northeastward migrating compressive tectonics. The western (internal) slope shows a characteristic horst and graben structure due to the extensional tectonics—northeastward migrating as well—that accompanied the compressive phase starting from the late Pliocene. The origin of the peri-Tyrrhenian depressions and intermontane basins also along the chain axis can be mostly related to this tectonic phase.

Although with different intensity along the chain, both compressional and extensional tectonics is still active; in particular, compression seems to be active in the external part of the northern sectors of the Apennines, while crustal extension dominates in central and southern ones (Frepoli and Amato 1997), which obviously influences their geomorphological evolution.

As a result of the eastward-migrating extensional and compressional deformation belts, the Apennine chain is asymmetrical: the Tyrrhenian slope is generally shorter and steeper in comparison to the longer and gently dipping slopes facing the Padano-Veneta Plain and the Adriatic Sea.

These tectonic styles strongly conditioned the general landscape evolution as well as the arrangement of the present drainage networks that differs greatly on the two sides of the Apennines. In particular, the drainage network pattern in the western portion of the folded chain was influenced by the existence of intermontane basins. These closed tectonic depressions were flooded by the sea and once definitively emerged (Early Pleistocene), they experienced continental, mainly fluvio-lacustrine deposition. Subsequent erosional processes, also driven by intense tectonic uplift, caused the incision of the continental deposits and destruction of thresholds which closed the basins. In this way the intermontane depressions became part of the drainage systems. As a result of this evolution, some trunks of present major rivers joining the Tyrrhenian Sea, as for instance rivers Arno and Tevere, flow longitudinally to the chain and are connected with each other by trunk streams that cut the relief orthogonally, thus depicting a rectangular drainage pattern.

Stream valleys on the Adriatic side show different arrangements: in the Northern Apennines they are usually transversal to the folds originated by compressional tectonics, and join the River Po or the Adriatic Sea being almost one parallel to one another; in the south drainage patterns are much more complex. In fact, the presence of intermontane basins in the chain axial zones favoured the development of longitudinal trunk streams also on the Adriatic side.

Among the main geomorphological features of the Apennines is the existence of low relief palaeosurfaces that are often found along the ridges, but also at lower altitudes within the slopes. They represent very old elements of the Apennines landscape and have been interpreted by many authors (Bartolini 1980; Ciccacci et al. 1985; Boenzi et al. 2004; Della Seta et al. 2008; Schiattarella et al. 2013) as remnants of ancient landscapes that were probably shaped in morphoclimatic systems different from the present one, at the Pliocene–Pleistocene boundary. The subsequent fluvial incision tied to Pleistocene regional uplift processes transformed these old planation surfaces into landscapes hanging high above the present-day lines of erosional incisions. In other words, the geomorphological evolution of most of the Apennine chains can be divided into two phases. The first one dates back to the Pliocene and was characterized by erosional processes that interacted with the chain build-up. The second, Pleistocene phase was dominated by renewal of erosion processes tied to the strong regional uplift and to the complex climatic changes that occurred before the establishment of the present morphoclimatic system (Bosi 2002).

5.4.1 The Landscape of the Northern Apennines

This sector of the chain extends from the Passo di Cadibona (the limit between the Alps and the Apennines) as far as the Val Tiberina, corresponding to the headwater of River Tevere. It attains moderate height, Monte Cimone in the Appennino Tosco-Emiliano (2165 m) being the highest.

The westernmost stretch of the Northern Apennines (Appennino Ligure) can be considered the link between the Alps and the Apennines from both the geographical and geological point of view.

To some extent its tectonic arrangement can be compared to one present in the Alps; relief consists mainly of metamorphic rocks and is not very high (the highest peak is Monte Beigua, 1287 m). Given the short distance from the Ligurian Sea, the southern slopes of this part of the Apennines constitute the steep and beautiful coastal area of Liguria.

Going eastward, the Apennines (Appennino Tosco-Emiliano-Romagnolo) show their typical roughly NW–SE orientation. Nevertheless, the effects of transversal tectonics are evident; as a result the chain is characterized by oriented ridges that on the whole are arranged like a series of theatre wings. The correspondence among drainage divides, highest elevations and the eastern front of normal faulting suggests that the general topographic arrangement is controlled by the eastward migration of normal faulting that lowered the west side of the orogenic belt (Mazzanti and Trevisan 1978; Bartolini et al. 2003).

Streams draining towards the Padano-Veneta Plain are transversal to the chain; however their trending often shows evidence of tectonic controls, tied to the presence of the Apennine Frontal Lineament (a high angle reverse fault system that separates the rising Apennines from the subsiding plain) and tectonic discontinuities (strike-slip faults) that intersect the Lineament itself. On the Tyrrhenian side rectangular drainage pattern prevails (Tellini and Pellegrini 2001).

Generally speaking, the landscape of the Northern Apennines is rather squat and smooth, mainly because of the low resistance of the most widespread outcropping rocks to erosion. The youngest landforms are mainly due to slope processes and to running water, also being favoured by the presence of intensely fractured clayey, marly and arenaceous rocks (Cretaceous–Miocene in age).

Many landslides of different kinds dot the slopes, making this part of the Apennines one of the most hazardous (Bertolini et al. 2017). The most widespread landslides often have complex genesis, as they frequently involve different lithologies. Where clays prevail, flows occur, that are locally named “lame”. In the hill and middle mountain belts, where clays crop out, slope wash gives rise to bare rock surfaces on which badlands and “biancane” easily develop (Vergari et al. 2013a, b; Del Monte 2017).

Given bedrock diversity, selective erosion produced some of the most suggestive landscapes. This is the case of the so-called Pietra di Bismantova (Fig. 5.11) in the northern slope of the Emilia Apennines. Higher erodibility of the underlying marls in respect to the above sub-horizontal calcarenites allowed the formation of a very peculiar relief (1047 m) that rises from the surrounding gentle landscape. This relief was celebrated by Dante in his *Divina Commedia* and it is thought to have inspired the Poet’s description of *Purgatorio*.

Landforms due to fluvial processes are also common. Stream valleys are differently shaped due to varied intensity of fluvial deepening and slope processes that are both controlled by geological structure. The landscapes of the intermontane basins that are now drained by the longitudinal reaches of the main rivers are particularly charming. Considerable stream incision tied to Pleistocene uplift led to the origin of terraces comprising Plio-Quaternary fluvio-lacustrine deposits. The coupled action of streams and slope wash originated the odd “Balze” landscape that is typical of almost all the intermontane basins. In the “Balze” areas rounded clayey hills and steep cliffs shaped on sands and gravel, up to 100 m high, alternate with deep gorges (Fig. 5.12). The beauty of this landscape inspired Leonardo da Vinci who immortalized it in one of his learned sketches and described it in this way: “*…in fra essa terra si vede le profonde segature dei fiumi*” (literally: …within this land it is seen the deep sawing of rivers).

Even if gravity and surface running waters are the dominant morphogenetic agents, other formative processes have also played their role in the origin of the contemporary landscape. On the northern slope of the Emilia Apennines, where Triassic and Messinian evaporites crop out, wonderful and unusual karst landscapes are found.

Quaternary glaciers have left their imprint in the highest slope reaches (Fig. 5.13). During the LGM the headwaters of streams flowing towards the Padano-Veneta Plain were progressively occupied by valley glaciers coming from wide cirques. The southerly unfavourable exposure of the Tyrrhenian slopes, instead, allowed the development of small “vedrette” restricted to the divide areas. In these cases, the presence of glacial landforms has obviously conditioned the postglacial streams. In fact, they show irregular longitudinal profiles, in which steeper stretches alternate with flatter ones, thus revealing the previous morphology of cirques and glacial valleys (Tellini 1994).

The northwestern sector of Tuscany, between the Tyrrhenian coastal plain and the main divide of the Apennines, hosts an amazing, sharp landscape that strongly contrasts with the generally smooth landscape of Northern Apennines. It is the landscape of Alpi Apuane, a mountain chain that is quite distinct from the Apennines s.s. The landscape is characterized by a series of rugged and barred ridges that dominate the surrounding areas. The relief consists mainly of metamorphic rocks among which marbles dominate. Quarry activities, starting about 2000 years ago, are so intense to become the main morphogenetic process. It is to remember that the marbles coming from these areas have been the raw material for Michelangelo’s masterpieces.

Fig. 5.11 The mesa of Pietra di Bismantova in the Emiliano-Romagnolo Apennine. It is a wonderful example of landforms resulting from selective erosion (*photo* P. Picciati, Wikimedia Commons under CC BY-SA 3.0)

Fig. 5.12 The "Balze del Valdarno" (*photo* S. Fabrizi) show the typical landscape of many intermontane basins. Plio-Quaternary fluvio-lacustrine deposits filling these basins were successively incised by stream action, favoured by Pleistocene uplift (see also www.lamiabellatoscana.com)

Fig. 5.13 The Sillara lakes in the Appennino Tosco-Emiliano occupy cirques shaped by glaciers during the LGM (*photo* M. Mendi)

5.4.2 The Landscape of Central Apennines

Geographically speaking, the central sector of the Apennine chain includes the Umbria-Marche Apennines and the Abruzzo Apennines. The highest peaks are in the Abruzzo Apennines (Piacentini et al. 2017) (Fig. 5.14). Given the shift of the chain axis towards the Adriatic Sea, the Tyrrhenian side is much wider and hosts ancient extinct volcanoes of Latium in its westernmost portion, that extend as far as the coastal zone (Fredi and Ciccacci 2017).

The asymmetry of the two slopes of the chain is still evident; furthermore the drainage divide does not correspond

Fig. 5.14 View of the Gran Sasso massif. To the *left* the "Paretone" of the eastern peak of Corno Grande; to the *right* the Corno Piccolo peak (*photo* E. Iannetti)

to the highest peaks that are localized on the Adriatic side. Thus, some of the fluvial systems draining to the Adriatic Sea have their headwaters in the western area subject to ongoing extension. Whether this pattern is caused by stream antecedence on the highest elevations or from regressive erosion by the Adriatic rivers is a matter of a long-standing debate in the geomorphological literature (Demangeot 1965; Mazzanti and Trevisan 1978; D'Agostino et al. 2001).

The presence of Mesozoic calcareous relief along the chain axis, roughly NNW–SSE oriented, is a dominant character that makes the overall geomorphological aspect of this portion of the chain markedly different from that of the Northern Apennines. Given the contrast between the calcareous rocks and the surrounding terrigenous lithologies, the highest peaks of the Central Apennines (Gran Sasso, 2912 m; Maiella, 2793 m; Velino-Sirente, 2486 m) rise abruptly from a generally hilly and smooth landscape.

The development of rivers on the Tyrrhenian slope was strongly influenced by the presence of the intermontane basins that border the chain's western slopes, and by their filling. Most of them were successively integrated in the present drainage patterns and they presently host the longitudinal reaches of the main rivers that are connected through gorges deeply cut into the chain structure. The River Tevere drainage network followed this evolutionary scheme and attained its present pattern only in historical time, when the last swamps were completely dried up. The Trasimeno Lake is an exception: it still exists, although its size has been constantly reduced in time. Some closed basins still survive, as in the cases of Piani di Castelluccio, Colfiorito and Piana del Fucino (Della Seta et al. 2017). They are close to the watershed and their capture by external drainage networks has been probably delayed by both their distance from the sea and active local tectonic subsidence (D'Agostino et al. 2001).

Also favoured by tectonic uplift, the valleys of the Adriatic slope of the Marche Apennines deeply cut the fold–thrust chain through transversal gorges, affording spectacular and wild landscapes (Fig. 5.15). The same arrangement of valleys is found also in the Abruzzo Apennines; however, the presence of intermontane basins at the chain axis makes drainage patterns more complex because of the presence of stream sections that flow parallel to the Apennine structure (Bisci et al. 1994).

Finally, the Adriatic foothills are characterized by parallel drainage pattern that is perpendicular to the NW–SE Apennine trend. This hilly area is characterized by low relief and sub-horizontal plains that slope gently towards the Adriatic Sea. It is shaped on Plio-Pleistocene marine deposits that are strongly affected by gravity-driven processes and erosion due to running water. Striking badland landscapes dominate where argillaceous rocks prevail (Fig. 5.16).

The wide spreading of strongly fractured and tectonized calcareous and dolomite rocks allowed the development of karst processes that affect both the Umbria-Marche and Abruzzo Apennines. In some cases such processes contributed to surface lowering of the intermontane basins, helping the preservation of closed depressions. Karst landforms are present also in the Apennine foothills on the Tyrrhenian side; the landscape of Altopiani di Arcinazzo is a wonderful example (Lupia Palmieri and Zuppi 1977).

Fig. 5.15 The River Furlo gorge cuts transversally the Marche ridge of the Apennines (*photo* Alicudi, Wikimedia Commons under CC BY-SA 3.0)

Fig. 5.16 The suggestive landscape of badlands shaped on the argillaceous hills of Abruzzo, on the Adriatic side of Central Apennines (*photo* Dodo87, Wikimedia Commons under CC BY-SA 3.0)

Besides tectonics and lithological variety, Quaternary climatic changes also had an important role in shaping the Central Apennine landscapes. During the LGM, the snowline in Central Apennines was at altitudes ranging between 1550 and 1900 m (Federici 2004). Therefore, ancient, inactive glacial landforms are present at higher elevations (Fig. 5.17). At present the only existing glacier, named Il Calderone, occurs on the northern slope of the Gran Sasso Massif and extend for about 4.5 ha (Pecci et al. 2000). Some snow fields are present on the Maiella massif, the second highest peak of the Apennines.

Fig. 5.17 Landscape of Monti Sibillini, with traces of past glacial shaping clearly evident (*photo* G. Tassi, Archivio fotografico del Parco Nazionale dei Monti Sibillini)

5.4.3 The Landscape of Southern Apennines

Southern Apennines include the Campania Apennines and the Lucania-Calabria Apennines which have their prolongation in the relief of northern Sicily (Monti Peloritani). However, the Calabrian landscape belongs to the Apennines only from a geographical point of view, as it underwent a markedly different geological history (Bosellini 2005). The chain axis is shifted towards the Tyrrhenian Sea; as a consequence, high relief often hangs over the coastal belt. The celebrated Costiera Amalfitana in the Penisola Sorrentina is a wonderful example (Cinque 2017).

Unlike the Northern and Central Apennines, the typical longitudinal arrangement of the relief is hardly discernible and the mountain chain lacks an overall unity; as a result the divide between the Tyrrhenian and the Adriatic slopes shows a very irregular trend. Furthermore, considering the peculiar outline of the Italian Peninsula, the trend of the divide and streams patterns are made more complex by the presence of the slopes facing the Ionian Sea.

Calcareous and dolomite terrains, often affected by intense and advanced karst processes, predominate. In the inner zones, the carbonatic rocks are often flanked by sandy, marly and clayey rocks, thus favouring processes of selective erosion. The Matese massif, Monte Taburno, Monti Picentini, Monti Alburni, Monte Sirino and Monte Pollino (that includes the highest relief of the Southern Apennines: Serra Dolcedorme, 2267 m) afford some among the most typical landscapes of this part of the Southern Apennines (Fig. 5.18).

The effects of horst and graben tectonics, guided by both NW–SE and NE–SW oriented faults, are clearly evident on the Tyrrhenian side. The coastline of the Campania Apennines, for example, is very irregular because of the presence of bays and headlands which are the consequence of the activity of the differently oriented fault systems. The NE–SW oriented Penisola Sorrentina, with its exiting landscape and the enchanting towns like Amalfi, is a structural high, connected with Plio-Quaternary tectonics that closes to the south the well-known Gulf of Naples. The coastal flat areas of Piana Campana and Piana del Sele (which faces the Gulf of Salerno) have an analogous meaning: they are structural lows deriving from this very same tectonics. The volcanic activity of Monte Vesuvio and Campi Flegrei (Aucelli et al. 2017), that characterizes the landscape of the Piana Campana, is tied to this same tectonic phase.

As in the case of Northern and Central Apennines, extensional tectonics produced also NW–SE and NE–SW trending intermontane basins that influenced the evolution of drainage networks. The largest among these depressions are some tens of kilometres wide and represent morphological elements that separate the carbonatic massifs. Some of these basins hosted tectonic lakes for a long time, as in the cases of the Vallo di Diano, now drained from south to north by the River Tanagro before joining the River Sele, or of the mountain valley of the River Mercure, that drains the eastern slope of the Pollino massif (Gioia and Schiattarella 2006). Some others evolved into poljes and they still host small or temporary lakes (Matese Lake). Generally, the evolution of these depressions was characterized by phases of lacustrine

Fig. 5.18 The landscape of the calcareous monoclinal relief of Monti Alburni. The massif is strongly affected by karst processes (*photo* M. Schiattarella)

and fluvial deposition that alternated with erosional phases; as a result fluvial terraces are common in these areas.

The overall aspect of the carbonatic massifs is by itself evidence of the complex tectonics that affected this sector of the Apennines. The same discontinuous trend of the chain and the usually polygonal shapes of the elevated tracts of terrain are derived from the Plio-Quaternary activity of normal or strike-slip faults. The landscape is generally sharp, due to the low erodibility of the outcropping rocks and karst landscape is dominant. Mountain slopes are generally steep and they often correspond to fault scarps or fault-line scarps. By contrast, flat erosional surfaces are repetitive and easily discernible features of the mountain summits; they represent the remnants of a wide palaeosurface shaped by long lasting karst and fluviokarst processes active at the late Pliocene/Quaternary boundary (Cinque and Romano 2001).

Fluvial landscapes are strongly influenced by the tectonic history and the variety of outcropping rocks. The Pleistocene uplift, together with variations of the sea level due to climatic changes, favoured stream incision. The effects of both past and present fluvial erosion are much more evident where less resistant, marly and clayey rocks crop out. Carbonatic massifs have poorly developed drainage networks and the origin of stream valleys is also affected by karst dissolution. The rare deep gorges that cut these elevations are the result of antecedence or superimposition.

Although it does not belong properly to the Apennine chain, the promontory of Cilento, recently declared UNESCO World Heritage site, is worth mentioning for the beauty of its landscapes (Valente et al. 2017). It separates the Gulf of Salerno from the Gulf of Policastro and has been the object of mythological tales some of which are told by Homer in his Odyssey and in Vergil's Aeneid.

Sandstone and conglomerates laying above less resistant rocks are dominant and the landscape is generally sharp. Streams flowing in very steep, narrow and short valleys deeply cut down the relief that attains maximum altitude of 1898 m at a short distance from the Tyrrhenian Sea (Cinque and Romano 2001). The promontory's coasts are wonderful: sandy beaches alternate with high cliffs that show surprising inlets and caves.

Given their remarkable altitude, also the highest elevations of this sector of the Apennine chain experienced glacial shaping during the climatic cold phases. To the east, the calcareous relief of Campania and Lucania Apennines gently slopes towards a low mountain and hilly area. This area, in turn, gradually declines towards the alluvial plain of Tavoliere, facing the Adriatic Sea, and the Fossa Bradanica (i.e. the more recent foredeep of Southern Apennines) drained by rivers Bradano, Basento and Agri that join the Ionian Sea. Marly, arenaceous and clayey rocks prevail and the landscape is everywhere rather monotonous and smooth. Highest elevations do not exceed 1000 m and are replaced seawards by a large expanse of hills. Ubiquitous spreading of clayey rocks favours the development of badlands and mass movements, thus reminding of the Emilia Apennines.

The extinct volcano of Monte Vulture and the Monte Volturino—the easternmost among calcareous elevations—rise up from these gently rolling areas.

Although they do not belong to the Apennine chain, it is worth mentioning the karst uplands of Gargano promontory (600–1000 m) and Le Murge (400–600 m) where Cretaceous limestones crop out. The landscape is obviously characterized by karst landforms that are much more developed on the Gargano upland. These flat topped plateaux are bordered by steep scarps that in Le Murge are cut by characteristic deep gorges, locally named "gravine".

From a geomorphological point of view, the Pollino massif—at the border between Basilicata and Calabria—represents the southernmost limit of the peninsular Apennines. In fact the Calabrian uplands, to the south, are made of pre-Triassic crystalline rocks that differ greatly from the rocks of the Apennines but show strong analogies with the Alpine rocks. Thus the Calabria Apennines, together with the Monti Peloritani in Sicily, would represent a fragment of the European crust that was pushed and rotated up to get stuck into the Apennine chain (see Bosellini 2017).

The most important elevations making the Calabria Apennines are the Catena Costiera, running close to the Tyrrhenian coast, the Sila and the Aspromonte (Fig. 5.19), where the highest altitude occurs (Montalto, 1956 m). The landscape is quite unlike those of the other sectors of the Apennines. Dissimilarities are mainly due to marked lithological differences but also to the higher uplift rates, as well as to different climatic conditions. All of them influenced past morphological evolution and still guide the present morphogenesis.

The rocks making the Calabrian relief are densely fractured and deeply weathered, also because of the Quaternary hot-wet climatic phases. As a result, a thick debris cover is present that mantles bedrock surfaces and reduces their sharpness. The resulting thick debris cover is often involved in mass movements or removed by the action of running waters.

Although they show their own peculiarities, the general aspect of the Calabria relief is characterized by flattened or gently rolling summits bordered by steep convex slopes. Because of this particular geomorphological arrangement, the steepness of stream valleys increases from the upper to the middle stretches. In the lower reaches—and before reaching the coastal plain—valleys are generally deep and wide and they host the typical "fiumare": streams with high discharge in the rainy periods alternated with long droughts, which derive from the typical distribution of the precipitation in the Mediterranean climate (Robustelli and Sorriso-Valvo 2017). The abundant solid load by some of these particular streams was responsible for the origin of wide coastal plains, like, for example, the fertile and pleasant plains of Sibari (along the Gulf of Squillace) and Santa Eufemia (along the homonymous gulf).

The structural analogies between Aspromonte and Monti Peloritani testify to the continuity between the Italian peninsula and Sicily. In spite of the geological similarities, however, the Monti Peloritani has a more uneven landscape.

Fig. 5.19 The Fiumara La Verde deeply cut the southeastern slope of the Aspromonte massif. The gently waving summit surface is a frequent feature of the Calabrian relief. The typical bed of "fiumare" is also evident (*photo* E. Galluccio)

5.5 The Volcanoes

Questi campi cosparsi
di ceneri infeconde, e ricoperti
dell'impietrata lava
… fûr liete ville e cólti
e biondeggiâr di spiche…
e fûr cittá famose
che coi torrenti suoi l'altèro monte
dall'ignea bocca fulminando oppresse
con gli abitanti insieme. Or tutto intorno
una ruina involve
(La Ginestra Canto XXXIV, 1836)
Giacomo Leopardi (1798–1837)

These fields with barren ashes strown
And lava hardened into stone,
... Were cheerful villages
With waving fields of golden grain…
Were famous cities, which the mountain fierce
Forth-darting torrents from his mouth of flame
Destroyed, with their inhabitans
Now all around, one ruins lies
(Translation by Frederick Townsend)

Considering the geodynamic framework in which the Italian Peninsula evolved and is still evolving, the presence of both active and inactive volcanoes is not surprising. They are mainly located on the dry land along the Tyrrhenian coast from Tuscany to Sicily; others are completely submerged or partially emerged as islands.

Most of them were imposing volcanic complexes that died out some tens of thousands years ago, like Monte Amiata, the Volcanic Complexes of Latium, the Ponziane Islands, the volcano of Roccamonfina (to the southwest of Monti del Matese) and the Monte Vulture (the only one on the Adriatic side). Others are still persistently active, like Monte Etna, the biggest active volcano in Europe, and Stromboli volcano, in the Aeolian Islands, to the north of Sicily. Their existence is related to the basaltic volcanism of southern part of the Tyrrhenian Sea. Finally, some volcanoes, although active, are only temporarily quiescent, like the Campi Flegrei, Ischia and the Vesuvio; all of them belong to the explosive volcanic province of Campania.

The landscapes of active volcanoes are doubtless the most representative for volcanic geomorphology, as the effects of exogenous morphogenetic processes are obliterated by the powerful action of volcanism. Landforms of inactive volcanoes are obviously strongly reshaped and even completely erased by the subsequent erosional processes, but they can tell a lot about the geological evolutionary history of Italy.

Considering the persistently active volcanoes, it is appropriate to start with the geomorphological characteristics of Monte Etna volcano (3340 m), that covers an area of about 1250 km^2 on the eastern coast of Sicily, where it faces the Ionian Sea (Fig. 5.20) (Branca et al. 2017). From a geodynamic point of view, it is located in the collision zone between the Euro-Asiatic plate to the north and the African plate to the south. The basaltic volcanism of Monte Etna is tied to the existence of an important normal fault system that intersects the eastern Sicily crust, thus allowing magma uprising from the mantle. It is a complex volcano edifice that has the character of a shield volcano in the lower part and of a strato-volcano in the upper one (corresponding to a change in magma chemistry). Monte Etna is an imposing, individual feature of the eastern Sicily landscape. On the whole it does not have steep relief. The foothill area, where the most ancient volcanic products crop out, is very gently sloping. Different orders of fluvial terraces are present in its south-western sector, where the River Simeto is incised into the lava flows that repeatedly dammed its valley. Marine terraces, instead, characterize the southeastern sector of the volcano, facing the Ionian Sea (Agnesi 2004).

The Etna morphological evolution is a very fast one, especially at its summit, where eruptions following one another cause repeated changes of crater shape and location, so that also the mount altitude is continuously changing. About 100 years ago there was only one crater at the summit, while today they are as many as four. A peculiar morphological element of Monte Etna is the Valle del Bove: a wide depression on the eastern slope of the volcano that originated about 10 ka ago as a result of a huge gravitational collapse (Calvari et al. 2004), which followed repeated caldera collapses. It is likely that the huge slope failure produced devastating tsunami that affected all the eastern Mediterranean area (Pareschi et al. 2006).

High permeability of volcanic rocks, helped by intense fracturing, favours water infiltration, thus reducing surface runoff. As a result, Etna slopes are mainly drained by rills and gullies that fill with water after intense rainfall. Fluvial landscapes are particularly impressive at the volcano foothills. Rivers coming from the Monti Nebrodi to the northeast lap on the volcano relief and run towards the Ionian Sea in very deep and spectacular canyons that cross the lava flows.

Stromboli volcano, on one of the island of the Aeolian magmatic arc to the north of Sicily, is persistently active too. The morphology of this sub-conical volcano that covers an area of about 12 km^2 and rises up to 924 m is rather simple as it is the result of different activity cycles of the same central edifice. However, the relief relative continuity is visibly interrupted on the northwestern slope, where the large depression of Sciara del Fuoco dominates the landscape; it is the result of a gravitational collapse which occurred about 6 ka ago, recognizable up to a depth of about 750 m below the sea level. Gravity-driven processes related to the instability of the volcanic flanks are widespread. One of the most recent examples is the landslide that affected the northeastern slope of the Sciara del Fuoco during the

Fig. 5.20 Southern flank of Monte Etna showing lateral cones and flow from the 2001 eruption (*photo* Wikimedia Commons under CC0 1.0)

eruptive events of 2002–2003, causing tsunami waves high up to 10 m (Calanchi et al. 2007). Marine processes are responsible for some of the most exciting landforms: beaches with black sands and steep cliffs alternate and testify to the struggle between the constructive action of volcanism and the destructive and reworking action of sea waves.

Alicudi, Filicudi, Salina, Panarea, Lipari and Vulcano are the other volcanic islands of the Aeolian Archipelago. Lipari and Vulcano (the eponym of all volcanoes) can be considered active, even if their last eruptions date back respectively to the seventh century BC and to 1890. Their morphology is much more complex as they are the result of a very complex volcanological history that determined the superimposition in time and space of different eruptive centres (Lucchi et al. 2017). A constant geomorphological feature of all the volcanic Aeolian Islands is the presence of marine terraces. Their sub-horizontal surfaces are the result of sea wave erosion which acted during periods of sea still stand and volcanic inactivity; sea-level low stand or crustal uplift were then responsible for the terrace emersion.

In spite of its 70 years of inactivity (the last eruption dates back to 1944), Vesuvio is perhaps the most famous volcano in Italy (Fig. 5.21). It is also one of the most studied because the consequence of a possible future eruption would be devastating for the about 800,000 people living on its slopes. The Giacomo Leopardi's poetry at the beginning of this paragraph clearly evidences the high risks of Vesuvio's eruptions.

Vesuvio, more properly named Somma-Vesuvio, can be considered the symbol of the Gulf of Naples (Campania region) of which it is surely the most outstanding morphological feature (Aucelli et al. 2017).

The Somma-Vesuvio has developed since about the end of late Pleistocene into an extensional basin that originated in relation to the Tyrrhenian Sea formation (Cinque et al. 1987; Santacroce 1987). It is a double peaked stratovolcano made by an ancient edifice, the Monte Somma, and by the more recent Vesuvio that has developed inside the caldera depression produced by the collapse of Monte Somma summit (about 3.6 ka ago; Rolandi et al. 2004). In spite of more recent modifications, the present overall morphological aspect of the volcano was determined by the very well-known destructive eruption of 79 BC that destroyed the towns of Pompei and Ercolano.

The most impressive volcanic landform of the Somma is the roughly circular caldera (15 km in diameter). Its rim is very asymmetric, with a very steep inner slope. The outer slopes are moulded by well-developed drainage networks. Stream valleys do not show a simple centrifugal pattern; stream piracies and headward erosion, in fact, allowed the development of amphitheatre valleys (Ollier and Brown 1971; Davoli et al. 1999). At elevation lower than 200 m the low slope gradient (about 10°) on lahar deposits allows the development of large flat floored valleys, with gentle slopes, locally known as "Lagni". In the past the Lagni were responsible for repeated floods that contribute to the geomorphological hazards and risks of the Somma-Vesuvio area (Davoli et al. 2001).

The younger Vesuvio is a cone-shaped stratovolcano, with an elliptical summit crater. Streams generally flow following the maximum slope without joining in a more complex network. Gullies are widespread; they often join into "parasol ribbing" networks.

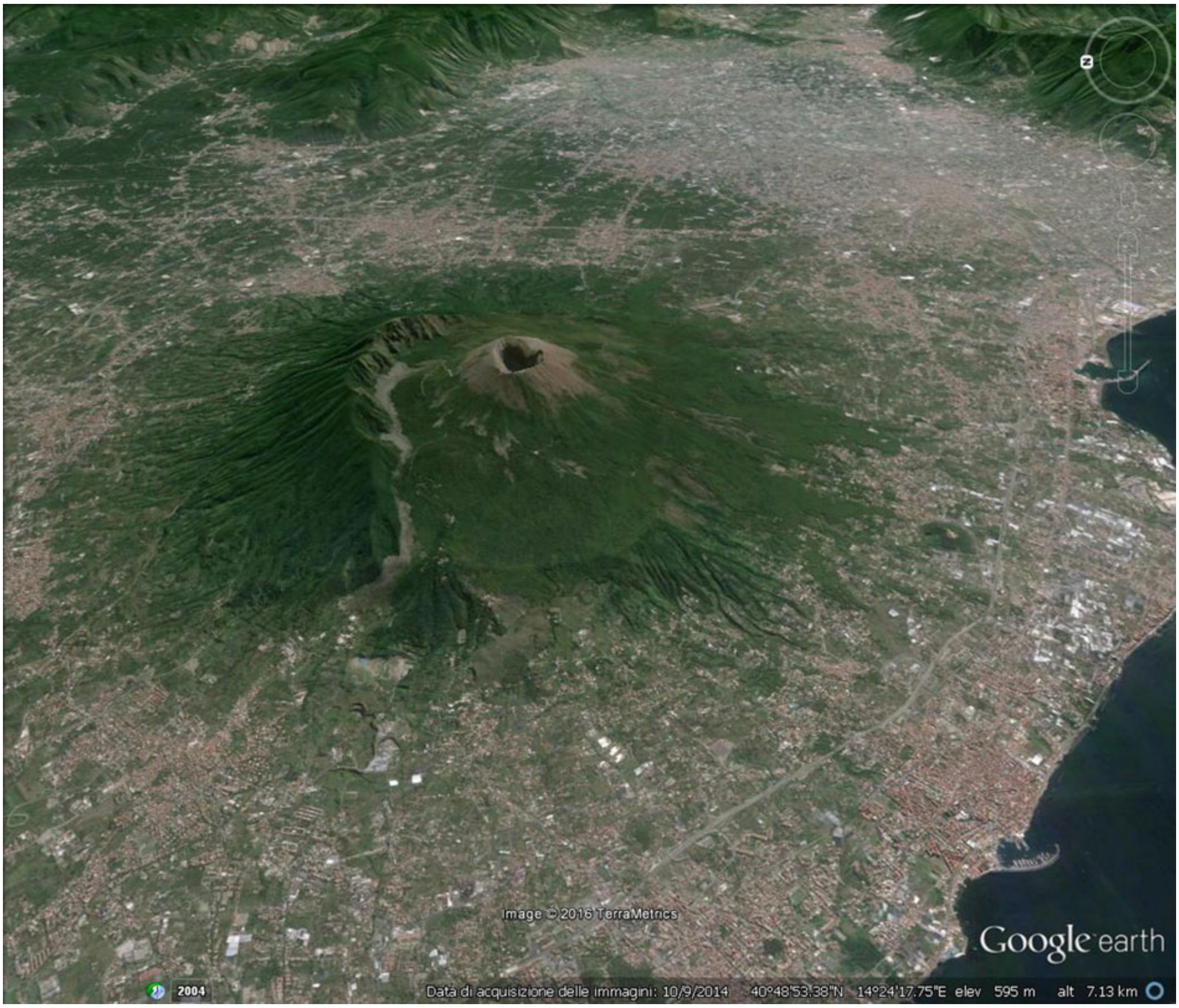

Fig. 5.21 The Vesuvio volcano. The volcanic edifice impends over the city of Naples (Google Earth—Image © 2016 TerraMetrics)

Not far from Somma-Vesuvio, other active volcanic areas exist. The most important is the Campi Flegrei, to the west of the city of Naples, and the Ischia Island, at the northwestern margin of the Gulf of Naples. Both of them belong to the same volcanic district that has been active since about one million years ago.

The volcanic landforms of Campi Flegrei, that also extend below the sea level, characterize the northern sector of the Gulf of Naples. The whole area consists of a volcano–tectonic depression, inside which numerous monogenetic, mainly explosive, eruptive centres have developed chaotically (Russo 2004). The volcanic elevations have gentle slopes and often show wide central depressions of crateric or calderic origins; the scoriae cone of Monte Nuovo—born in the sixteenth century—with its rather steep flanks is an exception. Less important volcano–tectonic collapses affected the area in recent times, too; the resulting depressions, together with the remnants of cones and domes contribute to the typical uneven morphology of the area. The coastal belt too shows evidence of volcanic activity: various promontories and semicircular bays, although deeply demolished by marine erosion, clearly denote their crateric origin.

Even if volcanic landforms are widespread, the landscape of the Ischia Island (in the Campano Archipelago) is dominated by the effects of exogenous processes and by tectonic landforms. The resurgent block of Monte Epomeo (Acocella and Funiciello 1999; Della Seta et al. 2012) is one of the most impressive landforms of the island. Its slopes are drained by dense stream networks that originated steep and deep incisions, whose unstable slopes are affected by frequent mass movements. The northern and western very steep

Fig. 5.22 Outline of the extinct volcano of Monte Vulture (*photo* Generale Lee, Wikimedia Commons under CC BY-SA 3.0)

flanks of Epomeo are, in fact, fault slopes often affected by rock falls and earth flows. The coastline is generally indented; cliffs are prevailing, while beaches are few and instable (Russo 2004).

Striking landscapes characterize also the areas were volcanism extinguished long times ago (Fredi and Ciccacci 2017; Margottini et al. 2017). Monte Amiata, an isolated gently sloping elevation in southern Tuscany (Central Italy), the volcanic Complexes of Latium, the stratovolcano of Roccamonfina (active in Campania from 650 to 50 ka BP; Davoli et al. 1999), the Monte Vulture (active in Basilicata since 730–132 ka BP; Ciccacci et al. 1999) are among the most important examples. With the only exception of Monte Vulture (Fig. 5.22) that developed in a horst and graben structure on the compressive front of the Apennine chain, they owe their origin to the extension along the margin of the Tyrrhenian Sea which followed the compressive tectonics responsible for the formation of the Apennine orogen. The morphology of these areas still reflects their volcanic origin, even if volcanic landforms are more or less modified by the subsequent action of exogenous processes, depending on the time elapsed since the end of the volcanic activity, and masked by the often thick vegetation cover.

It is noteworthy mentioning also the volcanic landforms of Sardinia. They are connected with Oligo-Miocene explosive volcanic events and to the more recent emplacement of basaltic lava flows, Pliocene-Quaternary in age. Basaltic plateaux (locally named “giare”) were successively disarticulated into mesas by fluvial erosion; these mesa landforms are a main morphological characteristic in the landscape of the western-central sector of Sardinia. Lava flows often reached the sea, thus contributing to the wonderful coastal landforms of the island.

5.6 The Major Islands

> *Giusto è che questa terra, di tante bellezze superba, alle genti si additi e tanto si ammiri…*
>
> *(De rerum natura)*
> *Tito Lucrezio Caro (∼ 98–55 BC)*
>
> It is only too fair that this land (i.e. Sicily), splendid for so many beauties, is glorified to all the people in the world and deeply admired…
>
> (Translation by G. Luciani)

> *… io percorsi, o Sardegna, le tue strade*
> *saline di Gallura,*
> *la terra d'Orosei bianca, africana,*
> *la Barbagia granitica e selvosa,*
> *l'Ogliastra rossa…*
>
> *(Sardegna)*
> *Vincenzo Cardarelli (1887–1959)*
>
> I travelled, oh Sardinia, along your routes
> saline of Gallura,
> the Orosei's white African land,
> the woody and granite Barbagia,
> the red Ogliastra…
>
> (Translation by G. Luciani)

Offshore the Italian coasts, many archipelagos exist. Some of the islands are made of sedimentary rocks, some of magmatic rocks, but all of them afford wonderful landscapes that are strictly tied to the different origins of the islands, as well as to climatic conditions and local factors.

The most important group of islands in the Tyrrhenian Sea is the Tuscan Archipelago, located in front of the homonymous region; the granitic Elba Island is the largest (about 234 km^2). To the south the Campano Archipelago includes volcanic islands (Ischia, for example) but also islands made of sedimentary rocks. The wonderful calcareous Capri Island that faces the Penisola Sorrentina and shares with it its geological origin is well known all over the world for its landscape, dominated by "Faraglioni", and its sea caves. The already mentioned volcanic Aeolian Islands, as well as the sedimentary Tremiti Islands (in the Adriatic Sea), the astonishing pink granitic islands of the Maddalena Archipelago, to the north of Sardinia, and the calcareous Lampedusa Island in the Pelagie Archipelago, close to the Tunisian coasts, are other examples of the numerous islands of Italy.

The two major islands of Italy, Sicily and Sardinia, deserve a short, specific description because of the multitude of landscapes they afford.

The statement of Tacito, a famous historian, orator and senator of Ancient Rome, stressed the beauty of Sicily, the widest region of Italy and the largest island of the Mediterranean Sea with a coastline stretching along 1623 km, including its minor islands. The high variety of landscapes, changing from the dreadfulness of Monte Etna to attractive coastal areas, together with the historical and cultural treasures, make Sicily one of the most beautiful regions of Italy. The orography of Sicily shows strong contrasts between high relief of the coastal chain in the northern sector, hilly areas of the southern-central and southwestern sectors, uplands of the southeastern sector and the eastern sector dominated by Monte Etna. Drainage systems reflect this peculiar arrangement of the relief. Streams draining northward flow in short and steep valleys; the longest and more important ones flow southward and southeastward and join the Sicily Channel and the Ionian Sea, respectively. Some of them can be classified as typical "fiumare". Exogenous processes are mainly due to gravity and running waters, and by sea waves in the coastal zones. The result is a great variety of landscapes, in which evidence of past climatic changes is also present.

The relief of the coastal chain that faces the Tyrrhenian Sea is the main morphological feature of the Sicily landscape. From a geological point of view (see Bosellini 2017) they belong to the Calabro-Peloritano arc (Monti Peloritani) and to the Maghrebian chain of North Africa (Monti Nebrodi, Madonie, Monti di Palermo, Sicani and Egadi Islands). As a whole, the coastal chain is the result of compressive tectonics that caused folding and emersion of the area during Early and Middle Pliocene; successively, extensional tectonics and uplift played a key role in relief evolution.

The Monti Peloritani, the easternmost elevations, are made of metamorphic rocks, often affected by intense weathering. Their tops are generally sharp, even if the presence of deeply weathered rocks allows at places the development of rounded summits. The steep slopes, especially those facing the Tyrrhenian Sea, are drained by impetuous "fiumare". To the west, the landscape of Monti Nebrodi (1847 m) is gentler as a whole. The relief is made of pelitic-arenaceous flysch. Their summits are often rounded off; by contrast, slopes are generally abrupt and cut by narrow valleys that become wider towards the Tyrrhenian Sea. Landforms due to selective erosion are widespread (Regione Sicilia 1996).

Further to the west, the landscape is dominated by the massif of Madonie (Fig. 5.23), the highest (Pizzo Carbonara, 1979 m) and largest relief after the volcanic complex of Monte Etna. The summit area of the Madonie is a wide karstic plateau underlain by carbonatic rocks. The detrital sedimentary piedmont belts of the massif and the surrounding argillaceous hilly areas are mainly affected by gravity and surface erosion processes. Rill and gully erosion are common and badlands are widespread (Agnesi et al. 2004).

Moving westward the coastal chain loses its identity and vanishes into the Monti di Palermo and Monti di Trapani to the north, and the Monti Sicani to the south. They are generally characterized by abrupt slopes and narrow and steep valleys due to elevated resistance of the outcropping rocks to erosional processes.

To the south of the coastal chain the landscape changes definitely. The southern central sector, to the south of the Madonie massif and to the west of Monti Erei, is characterized by a continuous succession of hills that gently slope toward the Mediterranean Sea. Plio-Quaternary clays, marls and sands prevail. Outcrops of evaporitic rocks, chiefly gypsum, are affected by karst erosion and provide very peculiar landscapes. The smooth and sometime tabular relief of Monti Erei connects the northern coastal chain to the Monti Iblei. These mounts constitute the southeastern portion of Sicily that corresponds to the northernmost sector of the Maghrebian chain foreland. They constitute tabular unfolded plateaux, mainly calcareous in composition, that are deeply cut by fluvio-karstic gorges, locally named "cave" (Regione Sicilia 1996).

The most important alluvial plains are located in the southeastern coastal areas; the Catania Plain and the Gela Plain are the widest. The coastal landscapes of Sicily differ greatly from one another. The presence of the coastal chain along the Tyrrhenian side determines the prevailing steepness of the northern coasts. High and rocky cliffs alternate with sandy beaches that represent the edge of the "fiumare" alluvial plains. In the sharpest coastal landscape of the

Fig. 5.23 View of the Madonie massif (*photo* MoritzP, Wikimedia Commons under CC BY-SA 2.0)

western sector, high rocky cliffs alternating with wide gulfs prevail (Amore and Giuffrida 2011).

The northern sector of the Ionian coasts is dominated by the Monti Peloritani and Monte Etna reliefs. Narrow pebbly beaches grade into the jagged coast at the Monte Etna feet, where inlets in the lava flows alternate with basaltic cliffs. By contrast, low sandy and calcareous beaches exist in the southern sector, where Monti Iblei faces the sea.

The coasts along the southern Mediterranean Sea are a belt of wild, wide sandy beaches, bordered at places by low white cliffs and interrupted by rocky promontories. In the northwestern stretch, wet coastal flats are the site for the development of salines. They represent a very characteristic landscape where natural and human aspects merge into a harmonious unity.

Sardinia is a world apart. From a geological point of view, it deeply differs from the rest of Italy, so that it can be considered as a fragment of the European continent (see Bosellini 2017). Its Palaeozoic rocks, the oldest found in Italy, outcrop mainly in the eastern, Tyrrhenian sector of the island and, subordinately, in the southwestern corner. They are highly deformed granitic, metamorphic and sedimentary rocks that show evidence of the Hercynian orogenesis and even of the Caledonian one. In other words, they represent the remains of an old Hercynian chain, successively levelled into a peneplain by erosional processes. This erosional surface is still well recognizable in the landscape of the central eastern sector of the island (Federici 2000), where it constitutes a wide plateau deeply cut by streams. Mesozoic and Cenozoic sedimentary rocks overlay the Palaeozoic basement; their outcrops are dominant on the western side of the island. Since Sardinia was not involved in the Alpine orogenesis, the post-Palaeozoic rocks are sub-horizontal, although they are displaced by fault systems. Moreover, volcanic rocks are present. They are related to three subsequent Cenozoic explosive and effusive volcanic cycles, each of them referred to different phases of the island geological history (Bosellini 2005).

Since the orogenic processes ceased long time ago, exogenous morphogenetic agents could easily reduce the resultant relief. The Gennargentu massif (1834 m), in the central eastern part of Sardinia, is the highest relief of the island, with a mean elevation of about 400 m.

It is self-evident that the variety of rock types, their different grades of tectonic deformation and their peculiar distribution, are important factors that influenced the exogenous morphogenetic processes shaping the Sardinia landscapes. Granitic rocks crop out mainly in the northeastern sector and especially in the Gallura area, where they support the wonderful and indented coast that contains the very famous Costa Smeralda (Emerald Coast) and the striking islands of the Maddalena Archipelago. The landscape is rather wild and sharp. Tower shaped hills, pinnacles and uneven mountain crests are frequent even if they alternate at places with dome-like elevations that were rounded by exfoliation, also favoured by intense fracturing of the rock (Melis et al. 2017). Rocks with unusual cavernous

Fig. 5.24 This granitic rock of the Spargi Island (Maddalena Archipelago, Sardinia) has been shaped by exogenous processes into a surprising "Witch head" (*photo* Mattia.dipaolo, Wikimedia Commons under CC BY-SA 3.0)

Fig. 5.25 The "tacco" Texile, in the Barbagia region (central Sardinia), has been officially recognized as Natural Monument (*photo* Mario 1952, Wikimedia Commons under CC BY-SA 3.0)

landforms (tafoni) often result from weathering and erosional processes (Fig. 5.24).

The landscape is less sharp where metamorphic rocks prevail. In fact, the lower resistance to erosion of these rocks has allowed the development of generally smooth reliefs. One of the most peculiar landscapes of the whole island is present where Mesozoic sedimentary rocks crop out. The different erodibility of the strongly deformed Palaeozoic formations and the overlying horizontal sedimentary rocks is a key factor for the development of some peculiar landforms, locally named "tacchi" (Federici 2000). They are Jurassic sub-horizontal summit calcareous slabs that were isolated by erosional processes; they are typically bordered by steep scarps that contrast strongly with the gentler slopes, shaped on the more ancient underlying rocks (Fig. 5.25).

The Hercynian peneplain, the characteristic “tacchi” and the already described basaltic “giare” are not the only flat horizontal surfaces of the Sardinia landscape. In fact, one of the main characteristics of the landscape is the low land of Campidano that extends from NW to SE in the southwestern corner of the island. It is a narrow-graben depression, about 30 km wide and 100 km long, that originated as consequence of extensional tectonics, tied to the opening of the Tyrrhenian Sea, and was successively filled with Quaternary alluvial deposits.

The coasts of Sardinia are certainly among the most scenic of Italy, so that they attract a high number of tourists during summer. They extend for 1879 km, including the minor islands, and consist mainly of gently sloping rocky sections or steep cliffs, at places interrupted by small beaches; large beaches are few. Altogether, rocky coasts and sandy-pebbly beaches represent, respectively, about 76 and 24% of the entire coastal perimeter.

The scenery varies greatly, depending on the type of outcropping rocks. The landscape of the granitic coasts in the northeastern sector is surely one of the most spectacular. Numerous promontories alternate with many small sandy inlets and rare cliffs that face the sea dotted by many islands and stacks. The peculiar morphology of this *rias* coast resulted from drowning of previous fluvial valleys, as a consequence of sea-level rise that followed the end of the LGM (Ginesu 1999).

The landscape of the coasts where sedimentary rocky cliffs dominate is as much attractive as that of the *rias* coast. On the eastern Tyrrhenian side, the Orosei Gulf is practically a continuous cliff, shaped in the Jurassic limestones, interrupted by isolated small beaches (Marini 2011). The type of outcropping rocks favours the development of karst. Caves often open at the base of the cliffs, thus contributing to the spectacularity of the landscape.

The western coast shows different morphological characteristics, also depending on the variety of rocks. Cliffs shaped in the Cambrian limestones, Mesozoic ones, or in volcanic rocks represent a true heritage not only from the aesthetical point of view, but also from the geological one, as they show the complex history of Sardinia (Marini 2011). High steep cliffs are poorly represented in the southern coast, where low gently sloping rocky cliffs or beaches prevail.

Long beaches are rare in Sardinia. In the lack of important streams capable of delivering abundant load, the existence of these beaches is tied to tectonic and glacio-eustatic events. They are located in areas affected by Miocene horst and graben tectonics and by Plio-Pleistocene uplift, that allowed the emersion of abundant sands from the before sea bottom. Climate changes also played an important role. The low sea-level stands of the cold periods, in fact, helped the emersion of these sands that were blown inland, giving rise to wide dune fields, especially along the western coasts (Marini 2011).

The same causes were also responsible for the formation of beach ridges and lagoons lying behind them, still present at the back of the present shoreline. These wet areas represent true heritage from naturalistic point of view, as they are important resources for scientific and tourist reasons, as well as precious reservoirs of biodiversity.

5.7 The Coasts of the Italian Peninsula

In tutto il mondo, per quando si estende la volta celeste,
la regione fra tutte più bella è l'Italia... per le coste ricche
di porti, il soffio benigno dei venti...
(Naturalis Historia)
Plinio il Vecchio (79–23 BC)

All over the world, as far as the vault of the heaven extends, the most beautiful country is Italy… for its coasts rich of inlets, the mild breath of winds…

The coasts of Italy stretch for about 7500 km, including the islands, and constitute the majority of the country’s boundaries. Considering only the peninsula, the length of the coastal belt of the Tyrrhenian, Ionian and Adriatic sides is about 4000 km. Coasts are a very important feature of the landscape and have played a primary role in the development of human activities.

The present morphological aspect of the Italian shores is the result of a long evolution in which variable geological histories of the various slopes facing the Italian seas shared a fundamental role with alternating climatic phases and the following sea-level changes. The evidence of this complex evolution is recorded in the frequent presence of marine terraces and notches on the rocky cliffs. The shore aspects greatly differ: sandy beaches alternate with rocky cliffs, deltas, swamps, pools and lagoons; large gulfs and small inlets alternate with more or less projecting promontories (Morandini 1957; CNR-MURST 1997). Either the Ligurian or the Tyrrhenian, or the Ionian or the Adriatic coasts offer great varieties of landscapes, even if each of them has its own peculiarities. As a whole, the Ligurian and Tyrrhenian sea coasts are more irregular that the Adriatic and Ionian sea ones.

Starting from the Ligurian Sea slope and going along the peninsula counterclockwise, the coast of Liguria is found. The Ligurian coasts extend for 350 km and show high variety of landscapes. They are traditionally divided into two sectors: the “Riviera di Ponente” (Western Riviera) and the “Riviera di Levante” (Eastern Riviera) related to the geological evolution of the Alps and the Apennine chain. They correspond, respectively, to the seaward slopes of the Alpi Marittime and the Appennino Ligure. As a result the landscape is characterized by the dominance of rocky cliffs that

Fig. 5.26 The wonderful coastal landscape of Cinque Terre, on the Tyrrhenian side, at the boundary between Liguria and Tuscany (*photo* M. Firpo)

are particularly steep and continuous in the Riviera di Levante. Cliffs often host small sandy or gravelly pocket beaches at their foot, fed by mass movements from the cliffs and marine depositional processes. Only in rare cases larger beaches represent the boundaries of alluvial plains built by the sedimentary load delivered by short and steep streams (Corradi 2011). It is a very striking landscape: the mountain slopes jut out over the deep sea and are refined by the blooming Mediterranean woodlands, also favoured by a particularly mild climate (Fig. 5.26).

Given the shifting of the Central Apennine chain towards the Adriatic Sea, it is easy to understand why the Tyrrhenian coasts of Tuscany (442 km) and Latium (290 km) show wider beaches with shallower sea bottoms. These beaches constitute the seaward edge of the alluvial plains of rivers like Arno, Ombrone and Tevere which have large drainage basins and carry sediment load abundant enough to replenish the shore. The Versilia beaches in Tuscany, with the wonderful Alpi Apuane in the background, are among the most known for their tourist value. Dune ridges are often present landward of the shoreline and they allow the existence of coastal ponds and lakes. The lakes of southern Latium (Fig. 5.27), limited to the south by the Circeo promontory, are an interesting example. The shape of these lakes and the sea bottom morphology suggest that a *rias* coast has originated because of the sea-level rise since the end of the LGM. Successively, the formation of the beach and dune ridges (locally called "tumuleti") cut off a sea sound and caused lake formation (Caputo 2011). These widespread coastal ponds and lakes represent the remains of wider and reclaimed old swamp areas; the Tuscan Maremma and the Latial Piana Pontina, between Monti Lepini-Ausoni and the sea, are the largest and perhaps the best known.

The continuity of the mainly sandy Tyrrhenian shoreline is interrupted by the presence of projecting landforms: they are the rivers Arno, Ombrone and Tevere cuspate deltas and some rocky promontories with rather high cliffs. Monte Argentario, that limits to the south the Tuscan Maremma, and Monte Circeo are the most evident promontories. They share a common origin in that both of them were islands subsequently connected to the mainland by more or less developed "tomboli" and "tumuleti". At present, Monte Circeo is completely linked up with the Pianura Pontina, while a wide lagoon still exists between Monte Argentario and the main shoreline.

Rocky cliffs generally made also the coasts of the islands of Tuscan Archipelago. Elba and Giglio islands are the most known because of the beauty of their cliffs alternated with small and wonderful sandy beaches that are a preferred destination for bathing tourism (De Pippo 2011).

Moving southward along the Tyrrhenian coast, the three wide gulfs of Gaeta, Napoli and Salerno and the Cilento promontory draw the general outline of the Campania shoreline that stretches for about 480 km, containing also the northern portion of the Gulf of Policastro. The Apennine chain is again close to the sea, even if not so markedly as along the Ligurian coast. Sandy shores alternate with inaccessible high rocky cliffs, shaped in calcareous, terrigenous

Fig. 5.27 The coastal lakes of southern Latium. In the *foreground* the calcareous promontory of Circeo (*photo* Parco Nazionale del Circeo)

and volcanic rocks. This is the case of the Capri and Ischia islands in the Gulf of Napoli, or of both the beautiful "Costiera Amalfitana" that limits the Gulf of Salerno northward and the rugged shores of Cilento (Cinque 2017; Valente et al. 2017). The aspect of the coastal belt clearly reflects the structural arrangement of this area. The presence of rocky cliffs of the promontories, in correspondence with structural highs, reveals the control exerted by the Apennine tectonics. Sandy shores are located mainly at the edges of the fluvial plains built by rivers like Garigliano, Volturno and Sele inside the coastal tectonic depressions that were originated by the Plio-Quaternary extensional tectonics affecting the Tyrrhenian slope of the Apennines (GNRAC 2006).

The coast of Gulf of Policastro, to the south, belongs to three different Italian regions: Campania, Basilicata and Calabria. The shoreline is strongly indented and characterized by a succession of promontories and inlets. Gravitational, fluvial and marine processes favoured local deposition of coarse-grained sediments, thus favouring the formation of small and mainly pebbly pocket beaches. The prevailingly calcareous outcropping rocks allowed the development of karst caves that have been flooded by the sea and reworked by marine processes after the end of the LGM (Schiattarella 2011).

Southward, the arrangement of the Tyrrhenian shore of Calabria is influenced by the proximity of the Apennines to the sea. The coastal belt is rather narrow and bordered by sandy-pebbly beaches that are limited inland by poorly developed dune ridges and locally interrupted by more or less projecting promontories. Delta plains occur at the mouths of major streams. However, the main features of the Calabria Tyrrhenian coast are the wide gulfs of Sant'Eufemia and Gioia Tauro, divided by the striking rocky promontory of Capo Vaticano. The two gulfs correspond to wide alluvial plains that are bordered landward by a ring of mountains and hills. The existence of many orders of marine terraces is clearly evident along the coast of Calabria (Fig. 5.28). Their origin is mainly tied to the episodes of strong uplift that has affected this region, and its southern sector in particular, in very recent times. The presence of fossil beaches at different elevations is a further evidence of these marked vertical movements. High cliffs and small beaches dominate the southernmost coasts as far as the opening of the Messina Strait, that represents the limit of the Tyrrhenian shore.

The Ionian shore of the Italian peninsula is marked by the large gulfs of Squillace and Taranto, divided by the large promontory corresponding to the Sila massif and its eastern foothills.

The Gulf of Squillace and the shore to its south, entirely belonging to Calabria, are lined by beaches that show rectilinear trend. Deltaic coastal plains are lacking, in spite of the presence of locally wide drainage basins along this coastal stretch. The main reason to explain this peculiarity is scarce solid load delivered to the coast by streams, as a consequence of their intense embanking and damming. However, the sea bottom configuration has an important role too; in fact the rather narrow continental shelf is incised by

Fig. 5.28 Marine terraces along the Tyrrhenian coast of Calabria (*photo* Bultro, Wikimedia Commons under CC BY-SA 3.0)

deep submarine canyons that carry the detrital load far offshore (Pugliese 2011).

The wide Gulf of Taranto shows a great variety of landscapes. Along this gulf, in fact, different geological arrangements follow one another: the Apennine chains, the foredeep and the foreland. Complex deltas are important elements that stretch out into the sea along sandy shores of the southern side of the gulf. They are the result of depositional processes driven by streams coming from the eastern slopes of the Apennines. Alluvial plains are present only in some cases; in others the typical braided channels of “fiumare” flow directly into the sea giving rise to fan-shaped delta flanked by low rocky cliffs (Schiattarella 2011).

The landscape changes on the northern side, along the calcareous Penisola Salentina that represents the foreland of the Apennine chain (Mastronuzzi and Sansò 2017). Rocky coasts are dominant. High steep cliffs shaped on fault surfaces or gently seaward sloping rocky beaches, in places corresponding to bedding surfaces, are the most common morphological features. Sandy beaches are less widespread; they are usually rather narrow and their landward edges are often bordered by belts of dunes that dam back swampy areas.

The Canale d’Otranto marks the beginning of the Adriatic Sea. The height of the shoreline is generally low; flat or gentle surfaces slope towards the sea that has very shallow bottom. Straight stretches of sand extend for many kilometres forming an almost continuous beach that can be considered the longest in Europe (Pennetta 2011). Moving northward from the Canale d’Otranto, the continuity of the Adriatic sandy shore is interrupted by the jagged headland of Gargano (built of Mesozoic limestones) that shows bluffs and cliffs on its southern side and sandy-clayey beaches on the northern one, where the coastal lakes Lesina and Varano are present.

A practically uninterrupted succession of sandy or pebbly beaches extends northward along the Abruzzo (Fig. 5.29) and Marche shore. Their width becomes narrower where the eastern, and often terraced foothills of the Apennines approach the coastline and reach it at the Conero promontory. Its cliffs are shaped on mainly calcareous substratum and are the highest of the Adriatic Italian coast.

Long sandy beaches, also fed by important rivers coming from the Northern Apennines, characterize the landscape of the Emilia-Romagna shores. Tourism along these beaches is so developed that it has become a first rank economic activity in Europe. Towns, like the well-known Rimini and Riccione, extended in time and eventually coalesced into a single seaside resort stretching for more than 50 km (Simeoni and Corbau 2011).

To the north, the Adriatic shore is dominated by the Po Delta that covers an area of about 400 km^2 and is bordered by a wide submerged prodelta (Stefani 2017). The delta shore is characterized by systems of beach ridges and bars that enclose wide and densely inhabited lagoon areas (Corbau and Simeoni 2011).

The northernmost Italian shores of the Adriatic Sea (belonging to Veneto and Friuli Venezia Giulia) are

Fig. 5.29 The beach of Cerrano (Pineto) along the Abruzzo coast (*photo* C. Bosica)

essentially sandy and clayey and represent the seaward edge of the wide alluvial plains of rivers Adige, Brenta, Piave, Tagliamento and Isonzo. Really the entire shore is a complex system of deltas and lagoons, among which the Venice Lagoon stands out. This lagoon has originated since the end of the LGM and was due to the parallel progradation of the shoreline caused by deposition of clays and muds delivered by the rivers Po, Brenta, Sile, Piave and Tagliamento. Nowadays the lagoon extends for about 550 km^2 and is characterized by a thick channel network of different depth. It hosts the worldwide famous city of Venice (Corbau and Simeoni 2011; Bondesan 2017). Moving northeastward of the Venice Lagoon the landscape does not change. The shore is still a system of deltas (of rivers Piave, Tagliamento and Isonzo) and lagoons (Marano and Grado) that strongly contrast with the rocky and steep coast of the Gulf of Trieste dominated by the Carso Massif (Brambati 2011).

5.8 Final Remarks

The physical landscapes of Italy have a great variety of landforms, hardly found in other countries with a similar small size of about 301,000 km^2. Well-developed landforms that derive their origin from the processes accomplished by glaciers, slope wash, streams, sea and wind, or more strictly tied to weathering and gravitational processes, occur in a very limited space. And they are paralleled by landforms produced by tectonic movements and volcanism. Furthermore, everything is framed into a territory that is geologically young and very active, rather heterogeneous from a lithological point of view, and with climatic conditions that change in time and in the different geographical zones. Italy, in fact, is not only one of the regions of the world characterized by the typical Mediterranean climate, as it is frequently thought, but it is also affected by other climatic types and each of them comprehends different varieties, like, for example, the Mediterranean sub-arid climate of the southernmost areas of Sicily or the cold climate of the Alps (Fratianni and Acquaotta 2017).

The evolution of the geomorphological regions of Italy is made still more complex by human communities that have been present in this country since the most ancient times. Nowadays the presence of people and their activities is widespread over most of the territory, excluding the most internal and highest areas. This human presence deeply modified the natural equilibrium, enhancing the probability for hazardous geomorphological processes to happen or triggering new ones, thus also causing an increase of risks. One of the most impressive examples in Italy is provided by widespread erosion that has affected the Italian beaches in the last decades (Caputo et al. 1991; Table 5.1). The erosional processes can be related not only to natural causes (sea-level rise, subsidence of sedimentary basins, climate change etc.) but also, and perhaps chiefly, to human interventions (inland stream damming, harbour structures, quarrying, dune levelling etc.).

In the light of the above considerations, the Italian territory appears like an extraordinary “geomorphological laboratory”, where it is possible to study the complex relationships between the endogenous and exogenous geodynamic forces, including the increasingly powerful human action in the latter.

Table 5.1 Types of coasts and beach erosion in Italy (modified after GNRAC 2006)

Italian regions	Shore total length (km)	Cliffs (km)	Beaches (km)	Retreating beaches	
				(km)	(%)
Veneto	140	0	140	25	17.9
Friuli Venezia Giulia	111	35	76	10	13.2
Liguria	350	256	94	31	33.0
Emilia-Romagna	130	0	130	32	24.6
Tuscany	442	243	199	77	38.7
Marche	172	28	144	78	54.2
Latium	290	74	216	117	54.2
Abruzzo	125	26	99	60	60.6
Molise	36	14	22	20	90.9
Campania	480	256	224	95	42.4
Puglia	865	563	302	195	64.6
Basilicata	68	32	36	28	77.8
Calabria	736	44	692	300	43.4
Sicily	1623	506	1117	438	39.2
Sardinia	1897	1438	459	165	35.9
Italy	7465	3515	3950	1671	42.3

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Part II

Landscapes and Landforms

6

The Glaciers of the Valle d'Aosta and Piemonte Regions: Records of Present and Past Environmental and Climate Changes

Marco Giardino, Giovanni Mortara, and Marta Chiarle

Abstract

Glaciated mountains of the Valle d'Aosta and Piemonte regions are described in relation to the geological, geomorphological and climatic settings of the Western Alps. A comprehensive view of the present-day Alpine regional cryosphere is offered, and links to regional and local examples of its evolution through the Quaternary are provided. Pleistocene moraine amphitheatres (Ivrea and Rivoli-Avigliana) of the piedmont area recall the development stages of Alpine glaciology. Major glaciers (Lys, Miage, Belvedere, Rutor and Sabbione) of the highest peaks of the Western Alps (Mt. Bianco, Mt. Rosa) are analysed for their specific scientific, environmental, cultural and economic importance. The distinctive dynamic nature of the glacial landscape is illustrated by examples of active glacial landforms and related slope instability, whose sensitivity to climate changes can increase hazards and risks.

Keywords

Glacier • Moraine amphitheatre • Quaternary • Glacial risk • Western Alps

6.1 Introduction

The Valle d'Aosta and Piemonte regions are geologically diverse and include a great number of landforms and deposits related to glaciation and deglaciation processes. In this chapter, we first outline the physical setting and the present-day cryosphere of these regions; then we offer a virtual geomorphological journey through the glaciated Western Alps through time and space, from southeast to northwest.

In order to reach the present-day glaciers from the Po Plain, one has first to cross the piedmont area, onto which glaciers spread out during Pleistocene glaciations. Here, the moraine amphitheatres are the first stop on our journey. Then, as we travel along the major Alpine valleys, we can "feel" the extent of glacial erosion marked by trimlines and steep valley sides. After that, as we approach present-day Alpine glaciers we encounter

- glacial and paraglacial landforms and deposits, and postglacial slope instabilities;
- panoramic views of active glaciers and trails crossing recent moraines and glaciers themselves, for a living illustration of glacial processes and their historical fluctuations.

In relation to the present-day glaciation, our journey includes also a selection of "iconic glaciers", i.e. glaciers of particular relevance for their scientific, environmental, cultural or economic value, with some insights into the rapid loss of ice, related risks and possible future scenarios. We conclude with some remarks on interactions between people

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of the Valle d'Aosta and Piemonte regions and on future adaptation strategies to climate change.

6.2 Physical Setting of the Western Alps

Mountains of the Valle d'Aosta and Piemonte regions are located in the core of the Western Alps (Fig. 6.1) along the boundaries between Italy, France and Switzerland. According to the new classification system of the Alps (Marazzi 2005), the Western Alps extend from the Savona-Bocchetta di Altare-Montezemolo-Mondovì line to the Rhine—Splügen Pass—Como Lake—Lecco Lake line; they are divided in 14 sections and include some of the highest peaks in Europe. From north to south, the most noteworthy are: Mt. Leone, 3552 m a.s.l. (Lepontine Alps); Mt. Rosa, 4634 m (Pennine Alps); Mt. Bianco (Mont Blanc), 4810 m, Gran Paradiso, 4061 m and Uja di Ciamarella, 3676 m (Graian Alps); Pierre Menue, 3506 m and Monviso, 3841 m (Cottian Alps); Argentera, 3297 m (Maritime Alps) (Fig. 6.1a).

From the geological and geomorphological points of view, the Western Alps are an arc-shaped, double-verging orogenic belt composed of diverse lithological, structural and tectonic units. They include three main structural sectors (Fig. 6.1b), partly corresponding to paleogeographic realms (Dal Piaz et al. 2003):

(A) An internal sector belonging to the upper ("African") plate of the collisional system comprising Hercynian and pre-Hercynian basement rocks with lower continental crust, upper mantle rocks and inner molasse units.
(B) An axial composite sector (the orogenic prism with the metamorphic collisional belt), which includes Hercynian and pre-Hercynian continental crustal rocks, metasedimentary cover rocks, oceanic lithosphere and flysch. This sector is bounded by two crustal discontinuities: the external Penninic frontal thrust and the internal Insubric Line.
(C) An external sector belonging to the lower plate of the collisional system ("European" plate) consisting of intrusive rocks of Hercynian massifs (e.g. Mt. Bianco), Mesozoic sedimentary cover and flysch. This sector is bordered outward by the Jura frontal thrust and contains Prealps and outer molasse units.

The tectonic framework of the Western Alps is complex. Extensional, contractional and strike-slip tectonics dominate the internal sector, whereas coeval contractional kinematics has affected the external zone. The Western Alps have an asymmetric cross-profile: the internal (Eastern, "Italian") flank is shorter and steeper than the external one. The internal front range shows a marked step from the Po Plain (elevation 200–300 m a.s.l.) into the mountains (elevation 1000–4800 m, rising from the piedmont to the crest of the range).

Alpine valleys of northwest Italy spread radially around the Western Po Plain. Major valleys (Susa, Lanzo, Aosta, Sesia, Ossola) are deeply incised in bedrock, their slopes being marked by up to 3000 m of relief. Valley incision dates back to the Messinian (late Miocene), according to Bini et al. (1978). Pliocene marine deposits and a regressive continental sequence of Middle Pliocene to Lower Pleistocene age fill the terminal parts of the valleys. During the Pleistocene, large glaciers repeatedly sculpted the Western Alps, producing the present landscape with U-shaped valleys, moraine amphitheatres and lakes at their mouths (Carraro and Giardino 2004) (Fig. 6.2; locations 2 and 5 in Fig. 6.1a). Locally, Holocene gravitational and fluvial processes have modified glacial landforms and deposits (Soldati et al. 2006).

6.3 Contemporary Glaciers

The climate of the Western Alps is conditioned by moderate to low oceanic moisture supply; mean annual precipitation is about 900 mm, a value lower than that of northern and eastern Alpine regions (Biancotti et al. 1998). In fact, the Alpine chain is a barrier to the Atlantic storms that bring heavy precipitation in winter; the Italian side of the Alps can thus only partially benefit from them, with the exception of northern Piemonte.

Due to limited moisture and the exposure to solar radiation, the glaciers of the Italian Western Alps are smaller than those in the rest of the Alps (Williams and Ferrigno 1993). The heads of the valleys are preferentially oriented towards the NE, E and SE (Fig. 6.3; see also location 3 in Fig. 6.1).

As a result, more than 80% of $\sim$300 present-day glaciers in the Western Italian Alps have areas of less than 1 km^2 (Smiraglia and Diolaiuti 2015). They are unevenly distributed in the Alpine sectors (Table 6.1). The Graian Alps host 60% of the glaciers and the same percentage of the overall glaciated area. About 35% of the glaciers are in the Pennine Alps and the other 5% are in the Lepontine, Cottian and Maritime Alps (Salvatore et al. 2015). The largest and most numerous glaciers are located in the Valle d'Aosta, which also hosts the highest massifs of the Italian Alps. The glaciers of the Valle d'Aosta account for two-thirds of the Western Italian glaciers and for 80% of the overall glaciated area (about 166 km^2). The two largest glaciers of the Valle d'Aosta are Miage Glacier (10.6 km^2) and Lys Glacier (9.5 km^2). Glaciers cover 4% of the Valle d'Aosta, but only 0.1% of Piemonte. The contemporary ice cover is less than half of the glaciated area during the Little Ice Age (LIA; see Table 6.1). Glacier shrinkage since the end of the LIA in the Western Italian Alps has been more evident in the south rather than in the north, due to a combination of climatic and topographic factors and latitude. The striking loss of

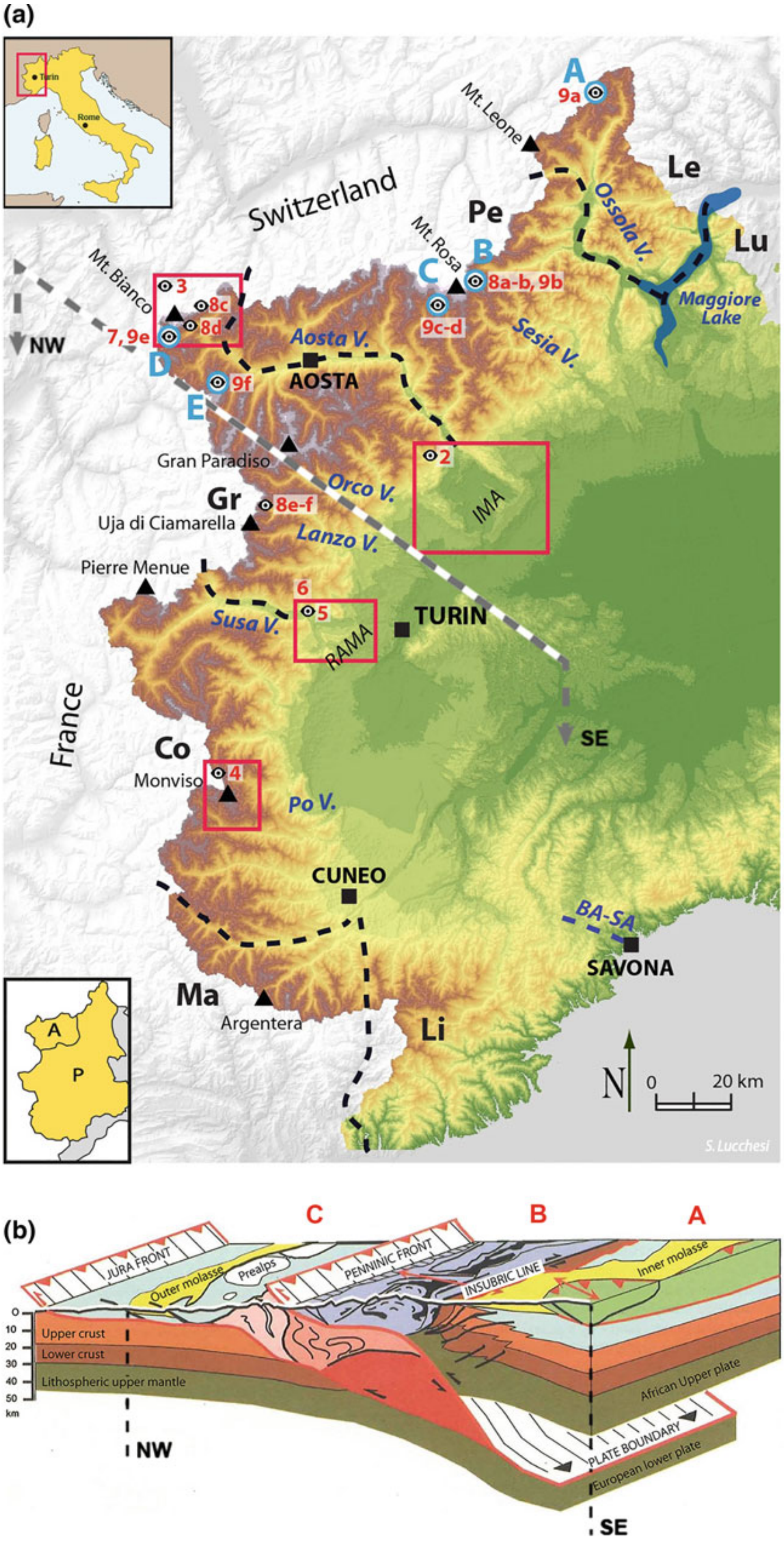

Fig. 6.1 Orography (**a**) and geology (**b**) of the Western Alps **a** The Italian side of the arc-shaped Western Alps with locations of the places and features described in this chapter. *Dashed lines* separate sections of the Alpine subdivision, from NE to SW: Lugano Prealps (Lu), Lepontine Alps (Le), Pennine Alps (Pe), Graian Alps (Gr), Cottian Alps (Co), Maritime Alps (Ma) and Ligurian Alps (Li). Ba–SA is the Savona-Bocchetta di Altare-Montezemolo-Mondovì line, separating the Western Alps from the Apennines. IMA: Ivrea Moraine Amphitheatre; RAMA: Rivoli-Avigliana Moraine Amphitheatre. *Black triangles* indicate major glacierized massifs; *blue circles* are some "glacier icons" (*A* Sabbione; *B* Belvedere; *C* Lys; *D* Miage; *E* Rutor); *red squares* and *black dots* are locations, maps and numbered photographs. Box at the *bottom left* borders of the Piemonte (P) and Valle d'Aosta (*A*) regions (*graphics* S. Lucchesi). **b** Block diagram of an ideal geological NW–SE cross-section of the Western Alps, including three main structural sectors (and related plate tectonics features): *A* internal ("African" upper plate); *B* axial composite sector (orogenic prism with metamorphic collisional belt); *C* external (European, Lower plate). See text for explanations (modified after Polino et al 2002)

Fig. 6.2 The internal depression of the Ivrea moraine amphitheatre (SW to NE view), at the mouth of the Aosta Valley (*left*) with the 20 km long "Serra d'Ivrea" moraine; the Pennine Alps are in the *background* (*photo* F. Gianotti)

Fig. 6.3 The much larger extent of glaciers on the northern (French) flank of the Mt. Bianco than on the southern (Italian) flank. This difference clearly illustrates the unfavourable conditions for the development of glaciers on the Italian side. *Data source* Glariskalp Project, Alcotra Program 2007–2013, www.glariskalp.eu

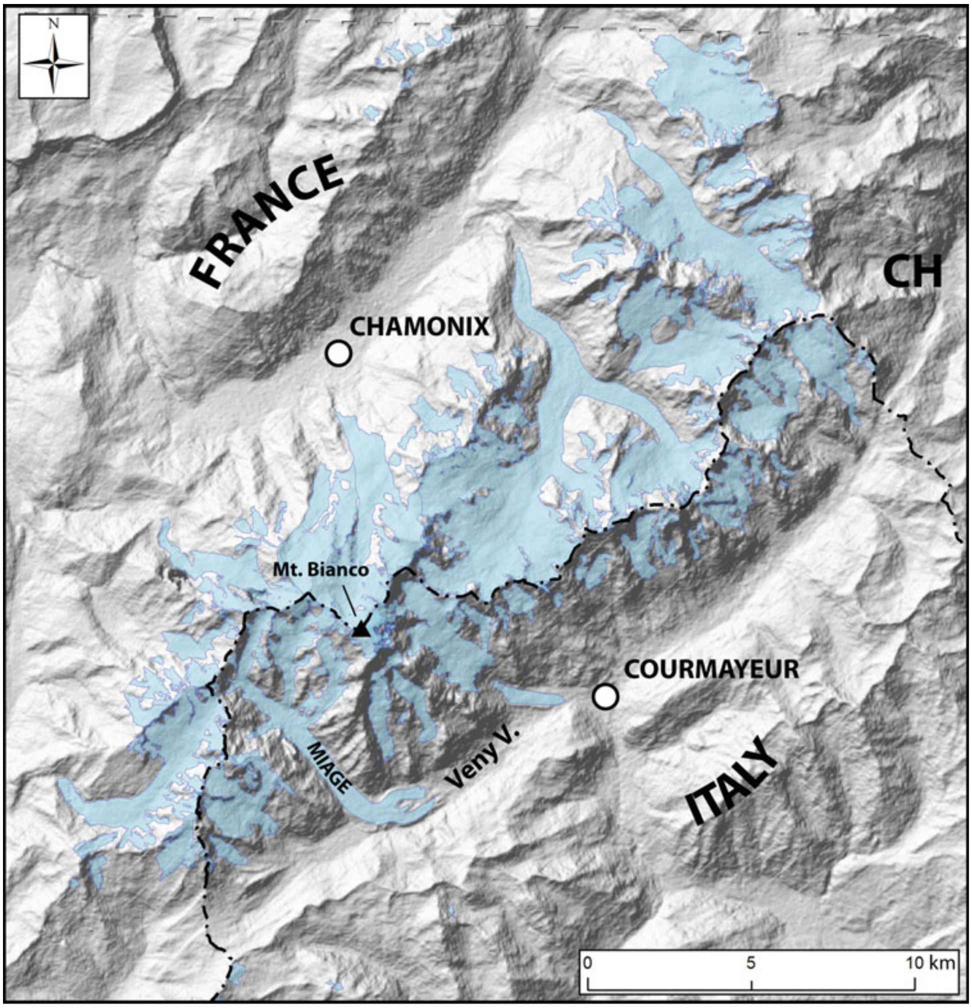

Table 6.1 Number of glaciers and extent of glaciated areas in the alpine sectors of the Western Italian Alps at different times

Alpine sector	2006–2007 (1)			LIA (2)		1958 (1)		1989 (3)	
	N.	Area (km^2)	Area (%)	N.	Area (km^2)	n.	Area (km^2)	N.	Area (km^2)
Lepontine Alps	22	6.95	4.2			26	14.36	26	10.72
Pennine Alps	91	57.31	34.5			93	83.92	77	66.22
Graian Alps	198	101.73	61.2			180	136.65	198	123.83
Cottian Alps	5	0.22	0.1	20	6.13	14	3.39	12	0.87
Maritime Alps	1	0.04	0.0	20	3.27	7	1.05	5	0.19
Total	318	166.25	100.0			320	239.37	318	201.83

Data sources (1) Salvatore et al. (2015), (2) Lucchesi et al. (2014a), (3) Ajassa et al. (1997)

glaciated areas is evident in the Monviso Massif, where glaciers almost disappeared in the last 150 years (Fig. 6.4).

Glacier shrinkage is usually quantified in terms of areal loss, as this is the easiest parameter to measure. In reality, the volume loss of the glaciers, in percentage, has been much larger than the areal loss because of glacier down-wasting (Paul et al. 2004). Many glaciers now have flat surfaces and few crevasses, which are indicators of low activity. In addition, the surfaces of glaciers are becoming more and more dark due to the release of debris from melting ice and rock falls and rock slides onto ice surfaces. In the Western Italian Alps, only the highest glaciers (i.e. above 3500 m a.s.l.) are at the moment escaping this trend.

6.4 Moraine Amphitheatres of the Po Plain

Our geomorphological journey of the glaciated mountains of the Piemonte and Valle d'Aosta regions starts from the Po Plain, by approaching the piedmont area of the Western Alps from southeast. Here, the moraine amphitheatres are the main geomorphic evidence of Alpine glaciers spreading out in the plains from major valleys during the Pleistocene glacial periods (Fig. 6.2).

During the 1800s, before the glacial theory was proposed in the Alpine region, the origin of moraine amphitheatres and related deposits was debated by the scientific community. Disputes among Catastrophists and Uniformitarians arose over relict glacial features of the Piemonte Region, culminating in the definitive studies of the Serra d'Ivrea moraines (Studer 1844) and the Ivrea and the Rivoli-Avigliana moraine amphitheatres (Martins and Gastaldi 1850; Figs. 6.2 and 6.5).

The major moraine amphitheatres of the Piemonte Region are among the most spectacular examples of Pleistocene end moraine systems in the entire Alps (Lucchesi et al. 2014b):

- The Ivrea Moraine Amphitheatre, 500 km^2 in area, at the outlet of Aosta Valley, is a spectacular landscape with a marked contrast between the internal subglacially moulded rocky hills of Ivrea, and the outer surrounding moraines with relief of up to 700 m. It is a product of repeated glaciations ranging from about 900 to 20 ka old.
- The Rivoli-Avigliana Moraine Amphitheatre, 100 km^2 in area, at the outlet of Susa Valley, is today part of the intensively urbanized area of Turin, but still it contains well-preserved Pleistocene glacial landforms, including moraines, spill-way channels, roches moutonnées and erratic boulders.

After the development of Alpine glaciology at the great peri-alpine moraine amphitheatres, the interest of naturalists, geologists and topographers shifted towards the heads of the valleys, driven by the emergence of mountaineering. The Italian Alpine Club, founded in Turin in 1863, understood the importance of studying glaciers and in 1895 established a special commission, which in 1914 became the Italian Glaciology Committee (CGI). A century of uninterrupted study of hundreds of glaciers and participation in numerous projects (International Geophysical Year, International Hydrological Decade, World Glacier Inventory and the Global Land Ice Measurements from Space) have provided an extraordinary body of historical scientific data. This body of data now serves as a valuable reference for understanding the current marked transformation of glacial and periglacial environments. The drastic reduction in the volume of glacier ice is also stimulating additional and more detailed studies, thanks also to the availability of modern investigation tools (Ajassa et al. 1997).

6.5 Pleistocene Glacial Phases and the Evolution of Major Valleys at the Transition to Holocene

The onset of Pleistocene glaciation in the Western Alps led to the formation of a large ice sheet, nunataks and major valley glaciers. Sequences of erosional and depositional landforms, trimlines and steep valley sides witness the extent of glacial phases along the Aosta and Susa valleys.

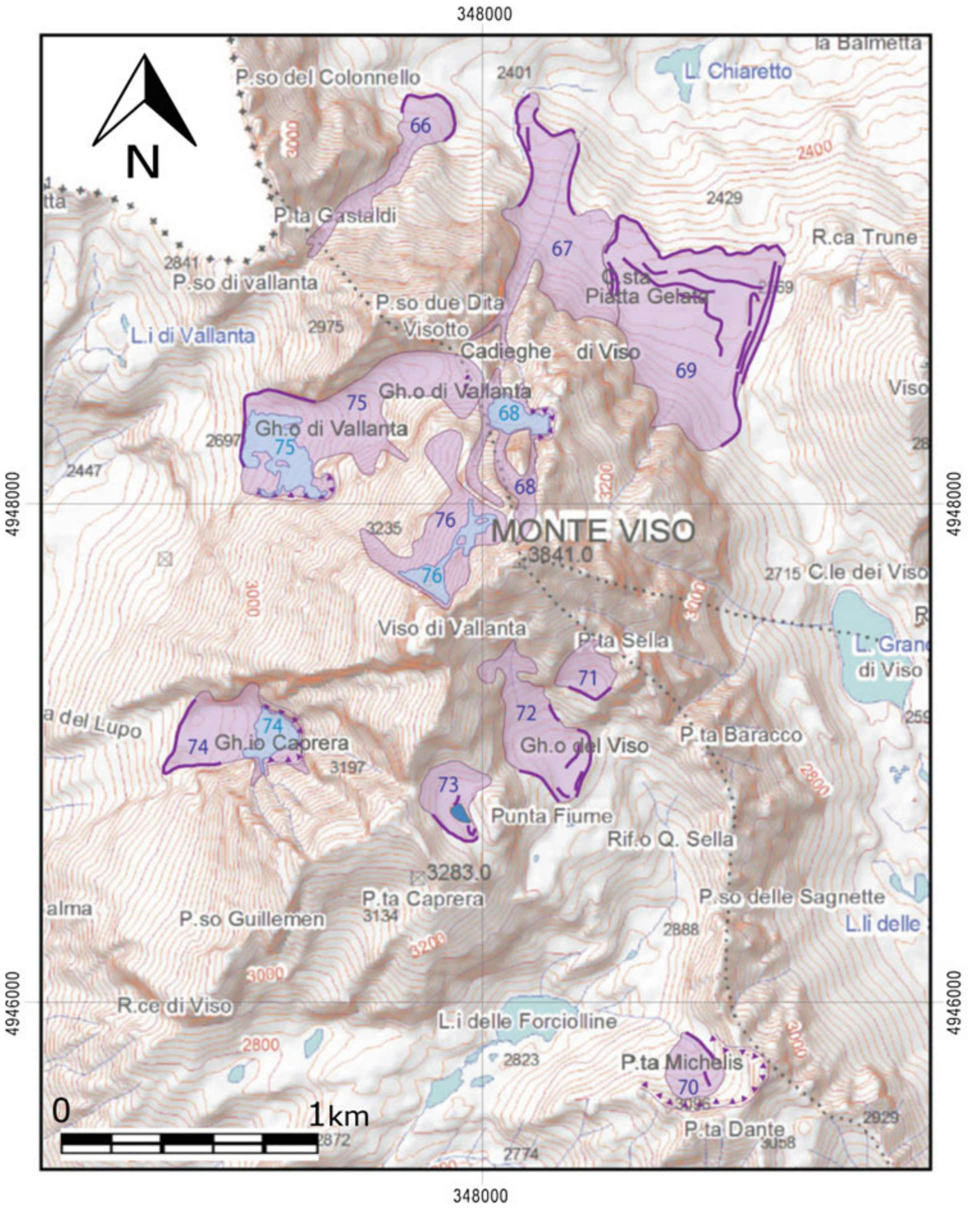

Fig. 6.4 Glacier shrinkage in the Monviso massif (Cottian Alps) since the end of the Little Ice Age (LIA), where glaciers have almost disappeared in the past 150 years. The maximum extent of LIA glaciers is indicated by the *purple colour* (*dark purple lines* are LIA moraines; lines with triangles are glacial cirques); present glacier outlines are in *blue*. Numbers correspond to the glaciers as catalogued by Lucchesi et al. 2014a, from which the present figure has been derived

A distinctive geomorphological feature at the mouth of Susa Valley is Mt. Musinè (Fig. 6.6; see location 6 in Fig. 6.1, close to the Rivoli-Avigliana Moraine Amphitheatre). Here the traces of two distinct glacial phases can be easily recognized along the southern slope on Mt. Musinè: a more recent one (MIS4) is represented by a well-preserved moraine ridge (bold white arrows in Fig. 6.6), whilst an older one (MIS6) is recorded by isolated erratic boulders higher up the slope (Carraro and Giardino 2004).

The evolutionary stages in the development of a major Alpine valley are well documented in the higher part of Valle d'Aosta Region, along the tributary Veny Valley, bordering the southern slope of the Mt. Bianco massif (Fig. 6.7; see location 7 in Fig. 6.1). Here, the U-shaped cross profile of the valley sculpted by Pleistocene glaciers shows distinct geomorphological discontinuities. On the Mt. Bianco side, (right in Fig. 6.7), an upper trimline separates the steep, glacially sculpted slopes from craggy non-glaciated areas above. The terminal moraines (early Holocene to LIA) of the Brenva and Miage glaciers block the mouths of tributary valleys and the lower slopes of the valley are mantled by imposing talus, landslide and avalanche deposits.

Other significant landforms related to the interaction between glacial and gravitational processes are found on the vegetated southern slope of Veny Valley (left in Fig. 6.7). They relate to a complex setting of post-glacial deep-seated gravitational slope deformations and other shallow slope

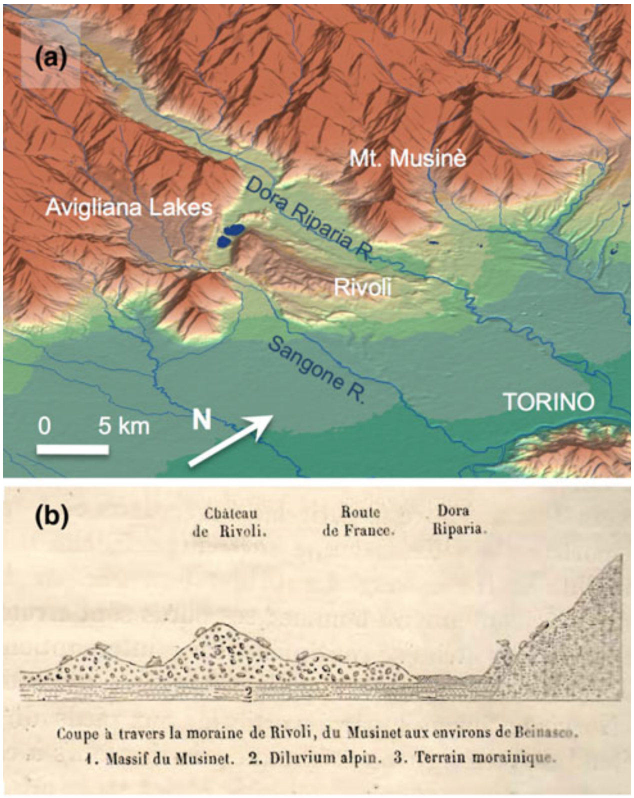

Fig. 6.5 The Rivoli-Avigliana moraine amphitheatre at the Susa Valley mouth: **a** digital elevation model showing major physiographic features and **b** the historical cross-section interpreting the glacial origin of the Rivoli hills (Martins and Gastaldi 1850)

instabilities, which originated as paraglacial landforms and deposits (i.e. produced by geomorphic processes acting during the transition from glacial to postglacial conditions).

Similar phenomena occurred all over the Western Alps at the transition to Holocene. Major Alpine valleys underwent remodelling either by slow/gradual and/or by rapid/impulsive processes, often related to permafrost degradation.

6.6 Iconic Italian Glaciers and Glacial Dynamic Landscapes

The geomorphological, structural, lithological and climatic diversity of the Western Alps gives each glacier its own individuality. Some glaciers, however, have characteristics of particular relevance and therefore can be taken as "glacial icons". Among them are four major glaciers of Valle d'Aosta and Piemonte regions that have specific scientific (Lys Glacier), environmental (Belvedere Glacier), cultural (Rutor Glacier) and economic (Sabbione Glacier) importance. The Miage Glacier and the Veny Valley are also included here as symbols of the glacial dynamic landscapes, which contain significant examples of ephemeral landforms, such as glacial lakes, particularly sensitive to climate changes.

Glaciers are extremely dynamic bodies, which can generate ephemeral landscapes not only in response to climate variations, but also in consequence of slope instabilities, which may cause rock and debris accumulation onto glacier ice, affecting its dynamics (Fig. 6.8). Landscape changes can occur on a time scale of years (glacier fluctuation due to climate variations, see Fig. 6.9c, d), weeks (growth of a supraglacial lake, see Fig. 6.8a), or minutes (collapse of a rock spur or an ice front, or moraine breaching and debris accumulation due to a glacial outburst flood, see Fig. 6.8b–f). Whenever ice and/or water are the main component, these morphological features are transient and will change or disappear rapidly (in years or even in hours).

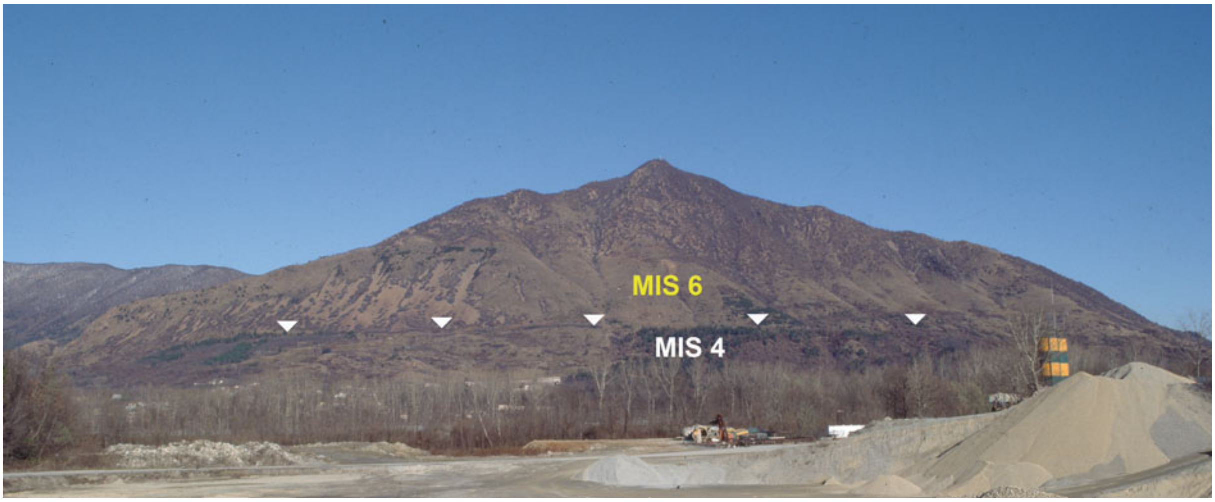

Fig. 6.6 North flank of the Susa Valley. Traces of two separate glacial phases (MIS4 below *white arrows*; MIS6 upslope) are recognized at the foot of the Mt. Musinè (*photo* F. Carraro, 2004)

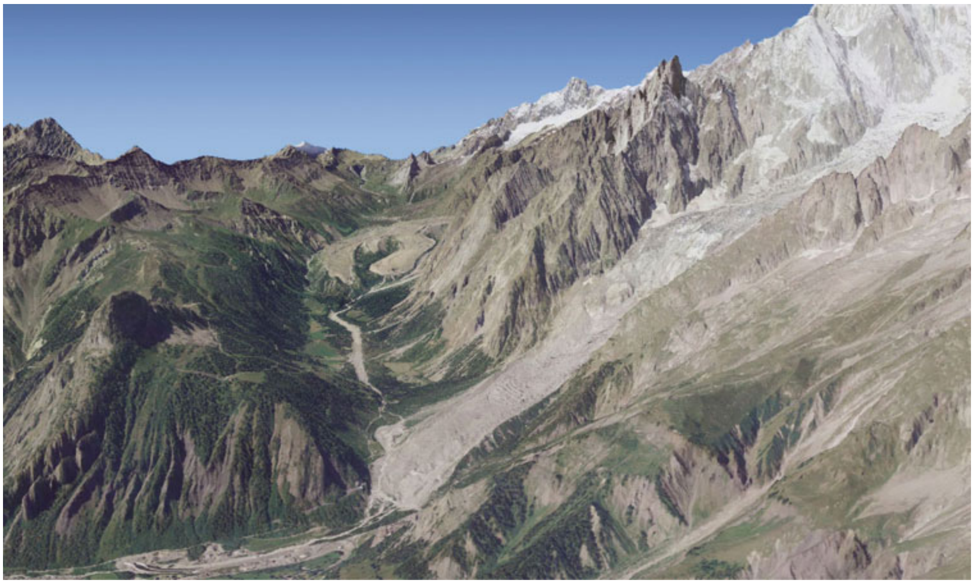

Fig. 6.7 3D model (DEM and orthophoto) of Veny Valley at the margin of the Mt. Bianco. The Brenva Glacier (*foreground*) reaches the valley bottom at the Mt. Bianco tunnel entrance (Courmayeur). Debris-covered Miage Glacier (trilobate terminal moraines in the *background*) is the longest glacier in the Italian Alps (11 km; Fig. 6.3)

6.6.1 Sabbione (Hohsand) Glacier (Ossola Valley, Lepontine Alps)

Alpine glaciers are considered a reservoir for European countries because they are an important reserve of fresh water in the solid state (“white gold”: “oro bianco” in the Italian language, “houille blanche” in French). For this reason, many dams have been built in the main glacierized drainage basins for hydropower, irrigation and flood control. In the Italian Western Alps, most dams are located in the Piemonte Region, in particular in the Orco Valley on the southern flank of the Gran Paradiso massif (Graian Alps) and in the Ossola Valley (Lepontine Alps). Dams in the Ossola Valley have a combined capacity of more than 170×10^6 m^3.

The glacier–dam coupling is well represented by Sabbione glaciers (south and north), which coalesce at the front and terminate in a proglacial lake (A in Fig. 6.1; Fig. 6.9a). The lake formed in 1952 when a dam was constructed a short distance from the glacier front. The artificial lake is still a valuable source of hydropower, but has also had an effect on the dynamics of the two glacier tongues. The glacier fronts have been subjected to intense calving, which accelerated glacier retreat and forced the separation of the two tongues (1850 m of retreat from 1940 to 2009).

6.6.2 Belvedere Glacier (Mt. Rosa, Anzasca Valley, Pennine Alps)

Belvedere Glacier is the largest glacier in Piemonte (4.5 km^2). It flows from the foot of the magnificent northeast face of Mt. Rosa (B in Fig. 6.1; Fig. 6.9b). The glacier is debris-covered and has been admired and studied since the end of the eighteenth century. At the beginning of the present millennium, it gained notoriety following an exceptional surge that greatly changed its morphology. The formation of a large supraglacial lake (3×10^6 m^3) led to an emergency response to mitigate the risk of a destructive outburst flood (Tamburini and Mortara 2005). The surge ended in 2005, however the entire basin is still experiencing geomorphic activity that is unparalleled in the Alps. It includes ice and rock avalanches, collapse of LIA moraines and debris flows (Tamburini et al. 2013). Belvedere Glacier can be considered a geosite of international importance.

6.6.3 Lys Glacier (Mt. Rosa, Aosta Valley, Pennine Alps)

Lys Glacier (C in Fig. 6.1; Fig. 6.9c, d) is one of the largest glaciers in Italy (about 10 km^2) and one of the most studied. Historical observatories at high elevation (Capanna Margherita, 4554 m and Institute “Angelo Mosso”, 2901 m) gave impetus to much research in the field of glaciology, geomorphology, climatology, topography, atmospheric physics, environmental sciences, physiology and medicine. The glacier was visited by H.B. de Saussure in 1789 and J.D. Forbes in 1840 and measurements of its frontal variations span two centuries, starting in 1812. Retreat of its front since the end of the LIA is estimated to be over 1700 m. Important stratigraphic, climatological and environmental information have been provided by deep ice drilling campaigns by Italian and Swiss researchers since 1976 at Colle Gnifetti (4452 m) and at Col du Lys (4248 m) (Smiraglia et al. 2000).

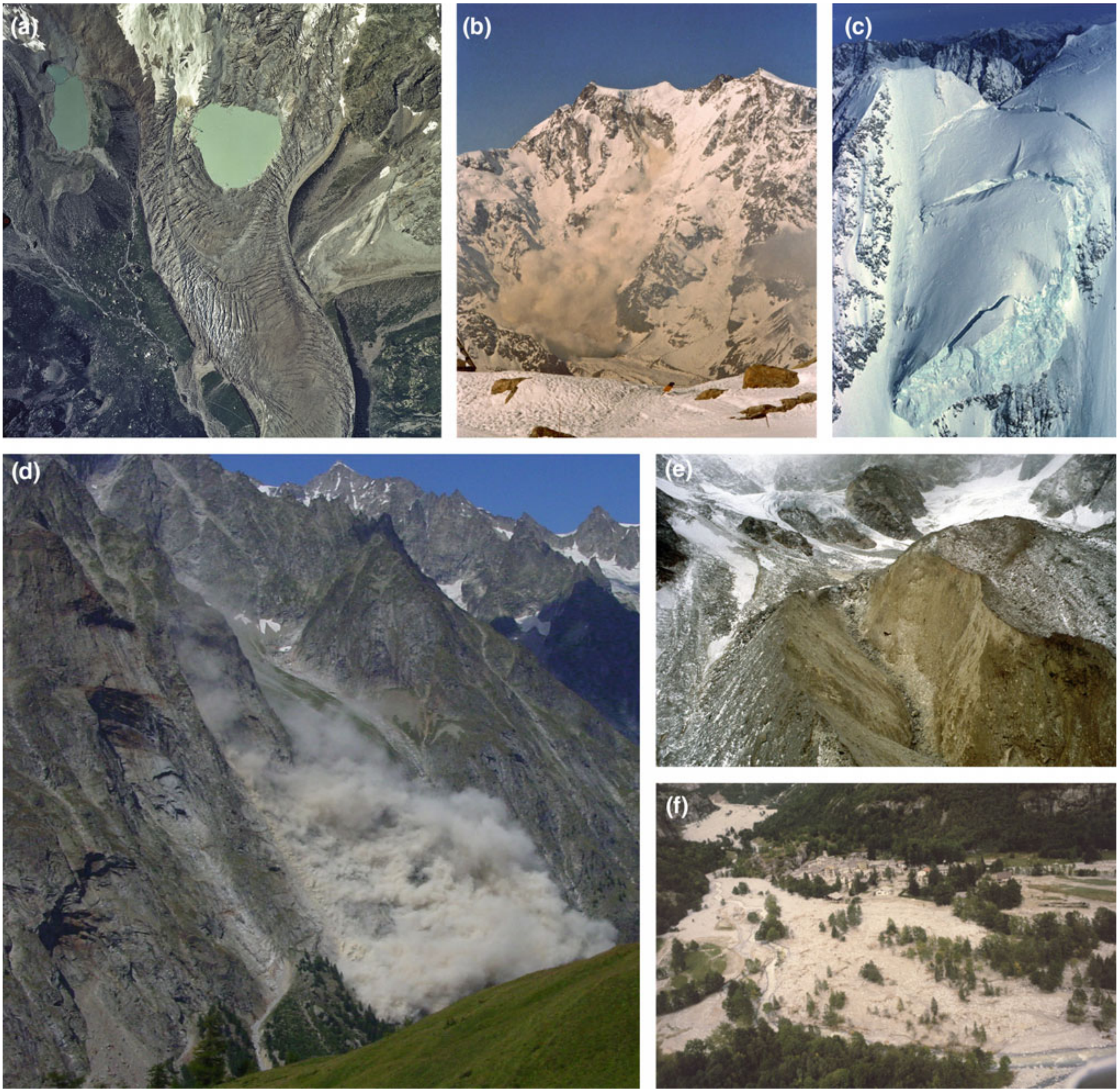

Fig. 6.8 Example of "dynamic landscapes" and related glacial risk case studies of the Western Italian Alps: **a** Effimero Lake at Belvedere Glacier (2002; aerial view, IRPI archive); **b** rock-ice avalanche from the Mt. Rosa NE face (2007; *photo* F. Bettoli); **c** Grandes Jorasses hanging glacier, subject to periodic detachments of its frontal seracs (1996; RAVA archive); **d** "Live" rock falland landslide scarps at the Aiguille Rouge de Peteurey (2009, Aug. 13; *photo* A. Franchino); **e** moraine collapse (*photo* G. Mortara) and **f** depositional area of a debris flow at the Mulinet Glacier proglacial area (1993; *photo* G. Mortara)

6.6.4 Miage Glacier and the Veny Valley (Mt. Bianco, Graian Alps)

Two main geomorphological features dominate the ephemeral landscape of the Veny Valley: the Miage debris-covered glacier and steep rock slopes of the Mt. Bianco. The Miage Glacier is the third largest Italian glacier and the longest one, fed by four tributary glaciers and snow avalanches (D in Fig. 6.1; Fig. 6.9e). From historical data we know that the surface of Miage Glacier was free of debris until the end of nineteenth century. Nowadays almost all the ablation tongue shows a cm- to m-thick debris cover, originated mostly from rock falls. Mass movements are very active in the area (Fig. 6.8d): distribution of rock fall events in the Veny

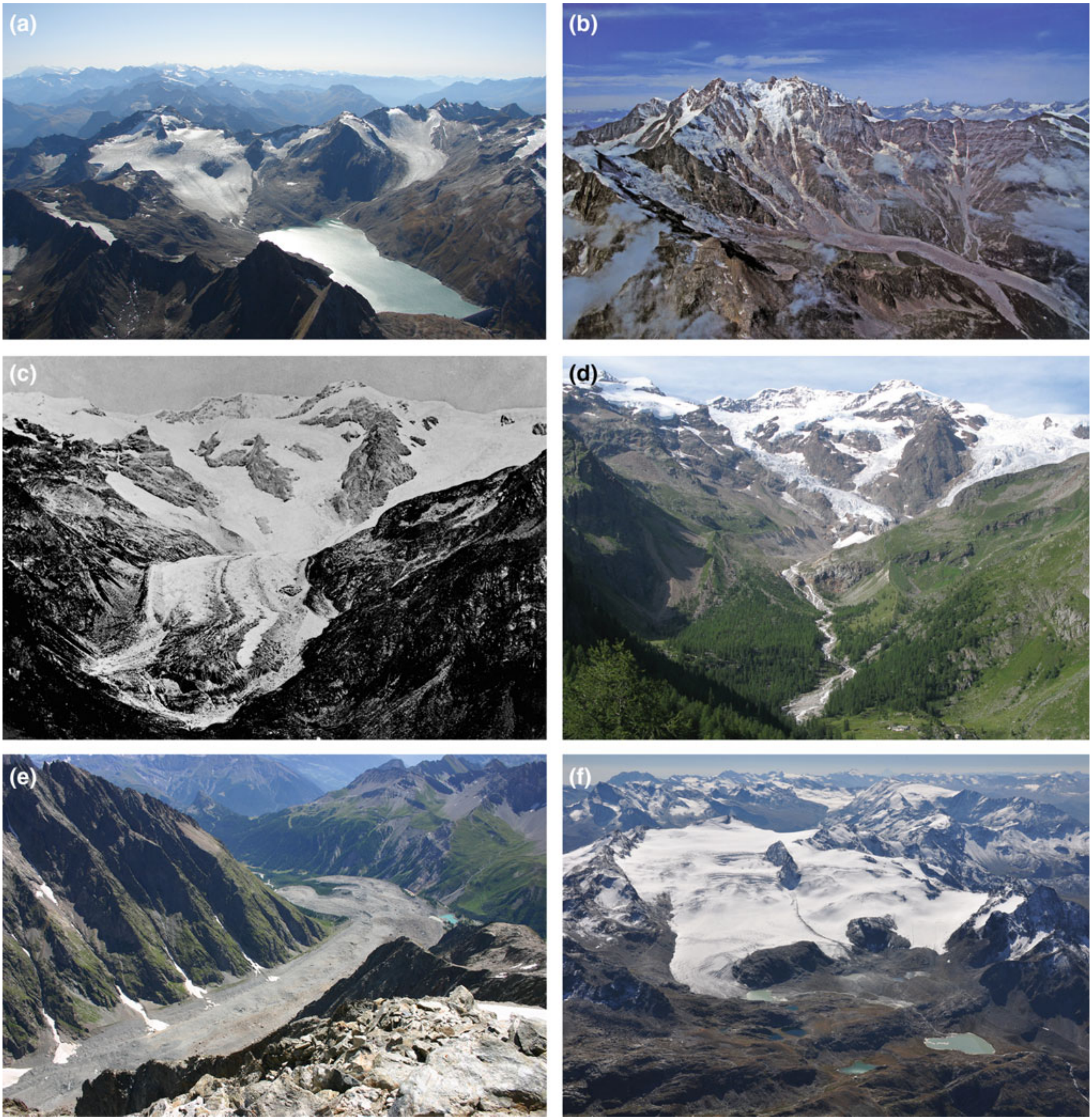

Fig. 6.9 “Glacier icons” of the Western Italian Alps: **a** Sabbione Glacier and its proglacial lake and reservoir (2006; *photo* G. Kappenberger); **b** Belvedere Glacier and the Mt. Rosa NE face (1999; *photo* G. Gnemmi); **c** Lys Glacier (1868; CGI archive); **d** Lys Glacier (2007; *photo* D. Cat Berro); **e** debris-covered Miage Glacier, snow avalanches in the Miage Valley and Miage glacial lake in the Veny Valley (2010; *photo* M. Bacenetti); **f** Rutor Glacier and its proglacial lakes (2012; *photo* L. Mercalli)

Valley is influenced by local geological and geomorphological conditions (such as lithological and structural setting, and related weathering and previous morphogenetic processes producing variable topographic environments) and/or by permafrost degradation induced by climate change (Bertotto et al. 2015).

6.6.5 Rutor Glacier (Rutor Massif, Aosta Valley, Graian Alps)

Rutor Glacier (8.3 km^2) occupies a large basin with a low gradient and has a complex snout bordered by numerous proglacial lakes (E in Fig. 6.1; Fig. 6.9f). One of the lakes

(Santa Margherita Lake) is infamous for its numerous, devastating glacial outburst floods during the LIA. Since 1596, Italian, French and Swiss technicians planned and executed complex and daring interventions (Sacco 1917). This historic cross-border collaboration dealt with an issue—glacial hazards—that the international scientific community became aware of only near the end of the twentieth century (Villa et al. 2008).

6.7 Concluding Remarks

The geomorphological journey through time and space in the Western Alps showcased in this chapter is not intended to be simply a geo-touristic field trip. The glaciers of the Piemonte and Valle d'Aosta regions are impressive indicators of present and past environmental changes in the Alps. We selected some glacial iconic landforms (glaciers, moraines, slopes) and related geomorphological features of the Alpine dynamic landscape (glacial lakes, unstable deglaciated slopes) to illustrate their importance from scientific, environmental, historical, social and economic perspectives.

During their advances and regressions, glaciers explicate an intense morphogenetic action, which is often associated with instability processes like ice falls/avalanches, glacial outburst floods, rock falls/avalanches, moraine collapse and debris flows. These processes can sometimes be extremely hazardous, because of the magnitude they can achieve, the distances that they can travel and, in some cases, because of their unpredictability. The risk is especially high in densely populated mountain areas like the Western Alps and is expected to rise in the future, both because deglacierization and expected climate warming have destabilized steep slopes, as well as due to growth of anthropic pressure.

Societal awareness of past and ongoing glacial processes is the key to developing proper strategies to minimize the impacts of climate change and help decision makers, stakeholders and citizens in mountain communities to make wise land-use decisions.

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7

Landscapes of Northern Lombardy: From the Glacial Scenery of Upper Valtellina to the Prealpine Lacustrine Environment of Lake Como

Irene Bollati, Manuela Pelfini, and Claudio Smiraglia

Abstract

In the region between Valtellina and Lake Como in the Central Italian Alps, one can visit, in a relatively small area, some of the best examples of mountain geomorphological landscapes of Italy. Eight specific sites—showing peculiar glacial, periglacial, structural, gravity-induced and erosional landforms—have been selected to illustrate how different landscapes may originate from geomorphological modelling of different lithotypes in different morphogenetic systems. These eight sites are exemplary cases in which significant evidence of past and current climatic and structural conditions characterising this region is exhibited.

Keywords

Glacial landscape • Periglacial landscape • Structural landscape • Valtellina • Lake Como

7.1 Introduction

The Central Italian Alps and the related Prealpine areas are characterised by different structural domains of the Alpine range and by different climatic conditions. As a consequence, a succession of various landscapes and landforms related to the lithological and structural complexity of the Alpine region characterises this territory. Changes in landforms modelled under different geological and climatic conditions are observable within a region spanning just a few kilometres.

The outcropping lithotypes behave differently with respect to chemical and mechanical weathering and, especially in the Alpine high mountain environment, surface processes are subject to variations in intensity as a consequence of climate change. In this sense, the high mountain environment allows us to directly observe landscape responses to the current climatic trend. The upper sector of Valtellina is characterised by the presence of the most sensitive indicators of climate change—glaciers, some of which are among the most important in the Alps, such as the Forni Glacier, which is the widest valley glacier of the southern side of the Alps. At higher altitudes, the temporal and spatial transition from a glacial to a paraglacial system is documented by glacier shrinkage and widening of proglacial areas. In the meantime, gravity-driven processes, water runoff and periglacial processes are intensifying in the Alpine environment. These changing dynamics are also a crucial for hazard and risk assessment, and for promotion and conservation of geomorphological heritage, especially concerning glaciers and depositional landforms such as moraines (Pelfini and Bollati 2014).

Moreover, in Valtellina the rock–landform relationships are various and peculiar. For example, the Oligocene calc-alkaline rocks of the Masino and Mello Valleys and the ophiolitic rocks outcropping in Valmalenco are modelled to produce relief in significant contrast to each other.

Last but not least, the presence of important structural lineaments (i.e. the Insubric Line) has significantly influenced the trend of the valleys, in particular the main valley, Valtellina, which has a clear E–W trend from Tirano to Colico.

Within the Central Italian Alps, from Upper Valtellina to the Lake Como area, eight sites/landscapes were selected. Some of them are included in the National and/or Regional Database of Geosites and other host cultural,

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Table 7.1 Summary table of the described sites and landscapes. The reference code and the scientific interest are from Geoportale Regione Lombardia (http://www.geoportale.regione.lombardia.it/)

Site		Landscape	Regional Geosites list	
			Code	Type of interest
1	Forni glacier	Glacial	SO0034	Geomorphology
2	Foscagno rock glacier	Periglacial	SO0022	Structural geology
3	Val Pola landslide	Rock avalanche	SO0020	Geomorphology
4	Postalesio earth pyramids	Erosional landforms	SO0010	Structural geology
5A	Val Masino-Bregaglia granitic pluton	Lithological	SO0009	Geomorphology
5B	Malenco-Forno ophiolitic unit	Lithological	SO0016	Petrography
6	Lake Como and Pian di Spagna	Lacustrine	CO0015 SO0030	Geomorphology
7	Karst of the Grigne Massif	Lithological	LC0008	Geomorphology

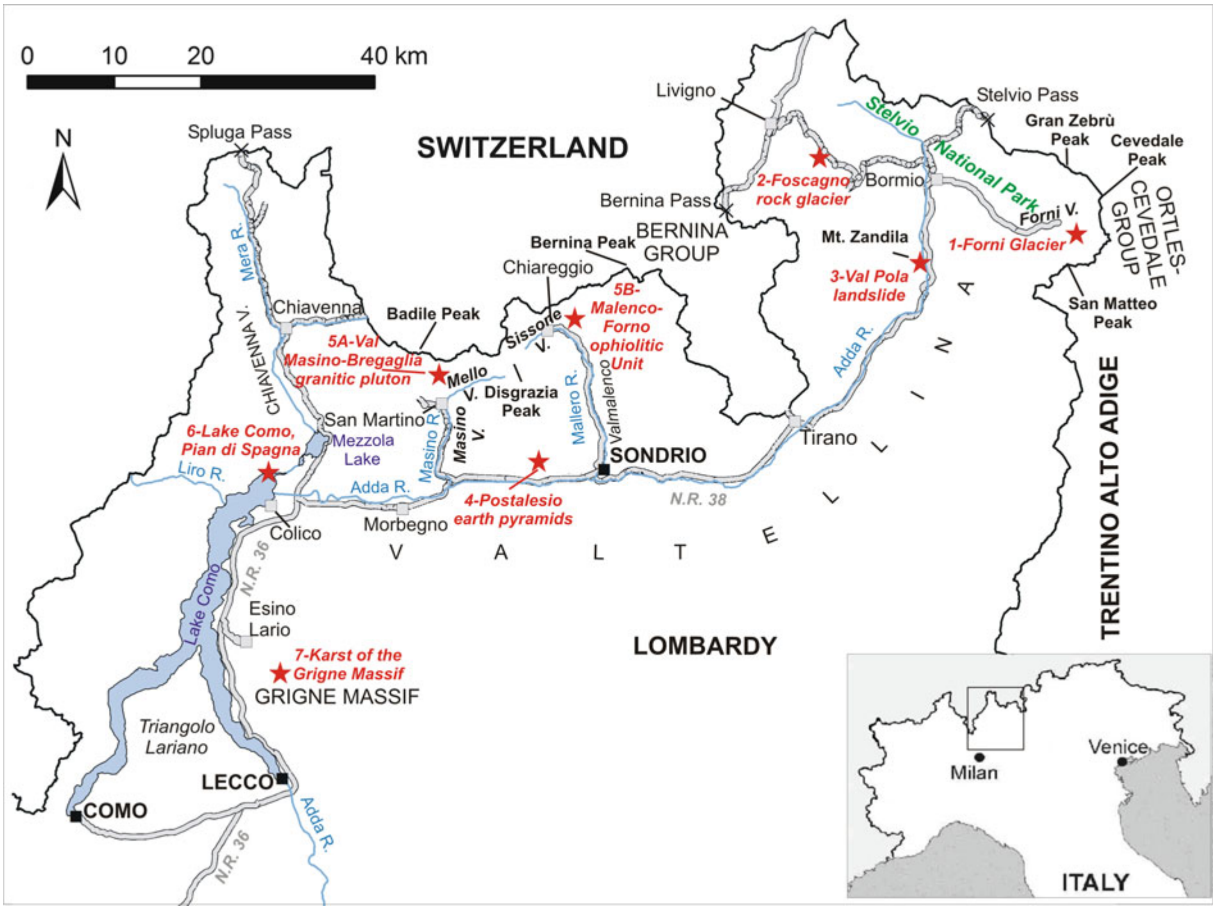

Fig. 7.1 Geographical setting of the Valtellina and Lake Como area and location of the geomorphological sites described

nature or thematic trails. In Table 7.1, codes used in the Geosites list of the Geoportale Regione Lombardia are reported. The sites are numbered following a geographical order from the Upper Valtellina as far as Lake Como and they are presented in the text following a set of geological–geomorphological criteria.

7.2 Geographical Setting

The area is located in the Central Italian Alps (Fig. 7.1), in the Rhaetian sector, principally along the Adda Basin and Valtellina valley, within the provinces of Sondrio, Lecco and Como, generally following National Roads 36 and 38.

The area includes several elevated peaks of the Central Italian Alps, among which are the Disgrazia (3678 m a.s.l.) and the Bernina (4049 m) in the Bernina Group, and the peaks of Gran Zebrù (3857 m), Cevedale (3679 m) and San Matteo (3678 m) in the Ortles-Cevedale Group. In the Upper Valtellina, the inter-regional Stelvio National Park was instituted in 1935, and its Lombardy sector covers a surface area of 593 km^2. It includes one of the most important glaciers of the Italian Alps: the Forni Glacier (Fig. 7.1). Lake Como, which runs along the area between the Alps and the Brianza region, has a surface of 144 km^2. It splits halfway into two branches, the Como and Lecco branches, in the middle of which the Triangolo Lariano region is located (Fig. 7.1).

7.3 Geological and Geomorphological Landscapes

The Valtellina and Lake Como areas belong to various Alpine structural domains: Austroalpine, Pennidic and Southern Alps (Fig. 7.2a). The Upper Valtellina, in the northeastern part, is characterised by outcrops of different nappes of the Austroalpine Domain that represent the remnants of the paleo-African continent. The bedrock of the Valmalenco area, located north of Sondrio, is constituted by rocks belonging to the paleo-African Austroalpine Nappes and to the oceanic and paleo-European Pennidic Nappes. A portion of Sissone and of the nearby Masino and Mello valleys is also characterised by outcrops of the Oligocene pluton of Masino-Bregaglia (Bergell), the emplacement of which is linked to Tertiary magmatic activity, and which developed during the late Alpine orogenesis stages.

The Periadriatic Fault System (i.e. the Insubric Line), with a local E–W trend, marks the contact of the Austroalpine and Pennidic Domains with the Southern Alps Domain, and represents the separation mark between the Alps *sensu* strictu and the Southern Alps region.

Part of the Southern Alps Domain in the area consists of sedimentary rocks such as Triassic limestones and siliciclastic deposits of sedimentary cover that lie above the paleo-African basement. A complete section of this succession is visible along the eastern side of Lake Como, where National Road 36 runs.

The different lithologies have been moulded by different physical agents (e.g. gravity, water, glacial ice, wind) for thousands of years, and structural landscapes are evident in the region. Glaciers are among the most active landscape modelling factors from the highest peak regions as far as Lake Como. During the Last Glacial Maximum (LGM; 30,000–15,000 years BP), the main glaciers flowing from Valtellina and Chiavenna Valley split into different lateral glaciers and reached the Brianza region (Fig. 7.2b), as evidenced by the presence of huge moraine amphitheatres (Bini and Zuccoli 2004). Recent glacial landforms characterise the higher altitudes in the region. The periglacial landscape, symbolised by rock glaciers, is widespread over the Upper Valtellina, and active and well-preserved landforms are common in the Livigno and Foscagno areas.

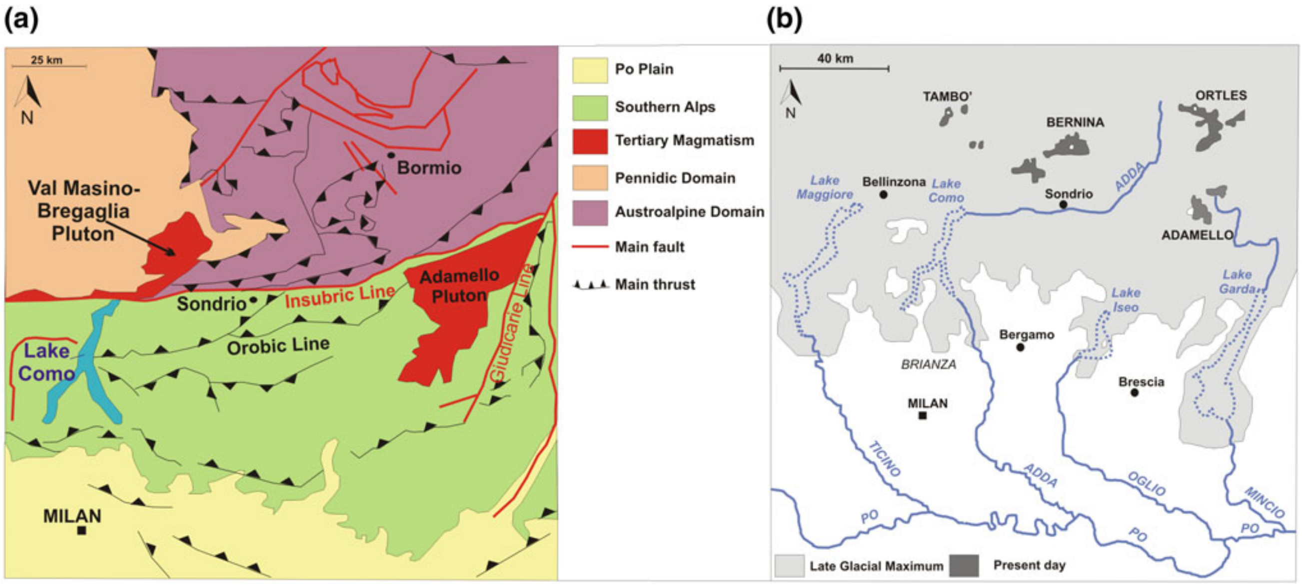

Fig. 7.2 **a** Geological setting and principal structural features of the described area (modified after Montrasio et al. 2012). **b** Reconstruction of glacier extent in the Central Alps during the LGM and the present day (modified after Cavallin et al. 1997)

7.3.1 The Glacial Landscapes of the Forni Valley

In the Upper Valtellina, the most important Italian valley glacier is present: the Forni Glacier (Figs. 7.1 and 7.3), with a surface area, in 2007, of 11.36 km^2 (D'Agata et al. 2014) and an elevation range today between 3670 and 2500 m. It is located in the Ortles-Cevedale Group, within the Stelvio National Park. The area is characterised by an outcrop of low-grade metamorphic basement of the Bormio Phyllades of the Austroalpine Nappe. They are in contact, in the head of the northeastern tributary valley, with limestones and dolomites of the sedimentary cover that forms the pyramid of Gran Zebrù, which stands out prominently.

The Forni Glacier has undergone visible shrinkage, as evidenced by comparison of glacier front positions between the nineteenth and the twenty-first centuries (Fig. 7.3a, b). As quantified recently by D'Agata et al. (2014), the whole glacial surface area of the Ortles-Cevedale Group has undergone surface area changes of −19.43 km^2 ± 1.2%, or approximately −40%, in the interval from 1954 to 2007, with an accelerated surface reduction of approximately 8.7% between 2003 and 2007. This equates to an area loss of approximately 0.693 km^2/year. The glacier thickness, locally covered by debris, is higher as a result of differential ablation. On the glacial surface there are spectacular active medial moraines and active *bédières* that are streamflows draining the surface of the glacier.

The Forni Valley represents a typical glacial U-shaped valley (Fig. 7.3a, b) with huge and abundant *roche moutonnée* and active or relict giant kettles (Fig. 7.3e). The records of several fluctuations are well documented and preserved by the numerous moraine ridges characterising the valley floor and slopes. Along the S and SW facing slopes, the Late Glacial lateral moraines (locally dated 11,000–10,000 years BP; Cavallin et al. 1997) are well developed and conserved, with thick soil coverage. The Holocene and historical moraines are well expressed and are characterised by different levels of development of soil, vegetation coverage and lichen colonisation in relation to their exposure age, and they are easily observable all along the glaciological trails (Fig. 7.3c, d) (Orombelli and Pelfini 1985).

The maximum advance of the Forni Glacier during the Holocene is evidenced by remnants of a terminal moraine that has an age close to that of the Little Ice Age (LIA, 1850). It dams a small peat bog radiocarbon dated to 2670 ± 130 years BP ^{14}C (830–710 cal years BC), which represents the minimum age for the glacier's advance (Orombelli and Pelfini 1985). The main advance and retreat phases of the Forni Glacier tongue after the LIA, evidenced by moraine ridges, happened at the beginning of the twentieth century: 1904 or 1913–1914, 1926. During the next retreat phase, the Forni glacial basin underwent separation into different minor glaciers. The neo-formational moraines resulting from the most recent 1974–1981 advance phase are unconsolidated, dissected by the action of the proglacial stream and largely affected by weathering processes and physical degradation due especially to the melting of their ice core (Pelfini and Bollati 2014).

7.3.2 Periglacial Landscape: The Rock Glaciers of Foscagno Pass

Periglacial features (i.e. rock glaciers, protalus ramparts, polygonal and striated soils) are quite widespread, especially in the Upper Valtellina area, and several examples of these landforms have been studied since the 1980s. In the Foscagno area (Fig. 7.1), periglacial landforms and especially rock glaciers are dominant, providing one of the best expressions of periglacial landscapes. In this climate, the presence of deformed and fractured schist and paragneiss allow for the formation of a great quantity of debris indispensable for the genesis of rock glaciers. The rock glaciers are both active and inactive: in the first case the fronts are generally located at an elevation of 2600 m; in the second case they are located below 2500 m altitude. The quantification of permafrost in the Foscagno area also allowed for recognition of its patchy distribution within the rock glaciers; the active layers range from 1.2 to 1.5 m (N-facing slopes) to almost 10 m (SE-facing slopes) (Guglielmin et al. 1994).

The Forcellina cirque and the below area of Vallaccia are occupied by the Foscagno rock glacier (Fig. 7.4), which is the most important and the most-studied rock glacier of the Italian Alps. It can be approached from National Road 38 (Fig. 7.1). It has a multi-lobed structure and exhibits typical rock–glacier debris zoning. It develops for approximately 1 km and the active zone front is located at a lower altitude than others in this area (2500 m). The ice is considered a relic of glacier ice preserved within a permafrost body that flowed down to the current position from the Forcellina cirque area (Guglielmin et al. 2004).

7.3.3 The Val Pola Rock Avalanche: A Dramatic Change in the Landscape

Gravity-induced processes are very frequent in the upper Valtellina. The most catastrophic event occurred on 27th July 1987 and radically changed the local landscape by burying a small village and damming the Adda River's course.

Fig. 7.3 Glacial landscape of the Forni Valley. Comparison of the Forni Glacier during: **a** Little Ice Age (LIA) (*photo* from Stoppani 1876) and **b** summer 2012 (*photo* I. Bollati 2012). **c** View of the glacial terminus and of the LIA moraine from the left hydrographic valley side (*photo* I. Bollati 2012). **d** View of the vegetation recolonisation process along the proglacial area from the left hydrographic valley side (*photo* I. Bollati 2012). **e** Subglacial giant potholes on the left side of the valley at 2500 m a.s.l. along the upper glaciological trail (*photo* I. Bollati 2012)

During the months of July and August 1987, a serious flood emergency developed, due mainly to intensification of heavy rain. Between 15th and 22nd July 1987 exceptionally warm temperatures and rainfall exceeding half of the mean annual precipitation for this area (i.e. 1200 mm) were recorded (Crosta et al. 2004). Numerous landslides and

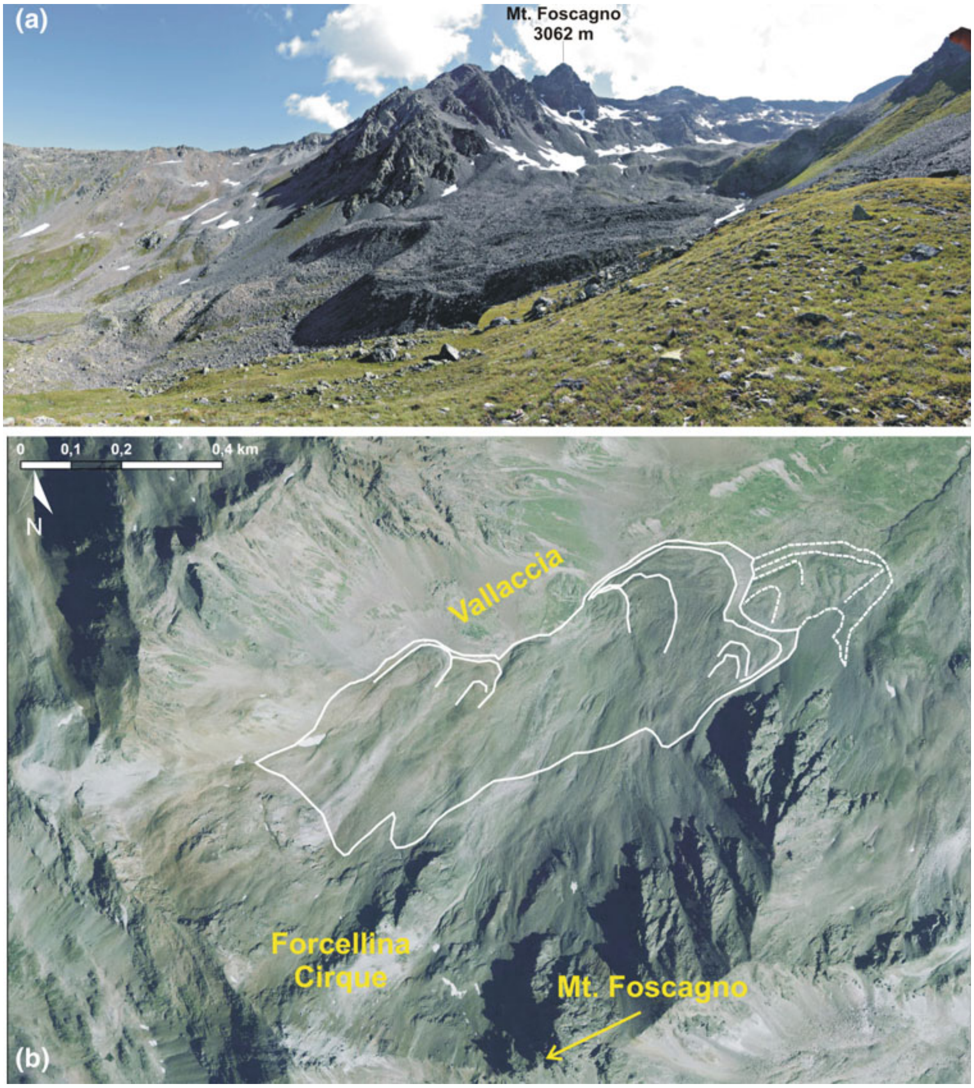

Fig. 7.4 **a** The Foscagno rock glacier. Panoramic view of the northeastern side of Monte Foscagno (*photo* G. Scherini 2010). **b** Aerial *photo* of 2007 (courtesy of Geoportale Nazionale—Ministero dell'Ambiente) in which the Foscagno rock glacier perimeter is shown. The *white line* delimits the active portion of the rock glacier, and the *white dashed line* borders the inactive portion, as identified by Guglielmin et al. (2004)

debris flows occurred during this period in the Upper Valtellina; among these the most dangerous was the Val Pola rock avalanche which is still observable from the older road built to cross the landslide (Figs. 7.1 and 7.5). The landslide deposit has been progressively modified by both natural surface processes and human activities undertaken for risk management and for restoration of safe access.

The Val Pola landslide detached from the eastern slope of Mount Zandila, which consists of Austroalpine Domain rocks such as gneisses intruded by diorite and gabbros, and which was characterised by a prehistoric landslide located at the intersection of two major joint sets. Between 18 and 19 July 1987 debris flows moved down the slope, damming the Adda River and causing the formation of a lake with an estimated volume of 50,000 m^3 and a depth of 1–5 m. In the following days, several fractures along the prehistoric scarp were observed, and on the 27 July, the Val Pola rock avalanche occurred. The landslide volume was estimated at approximately 40 Mm^3. The debris reached as far as 1200 m below the landslide scarp, running 300 m up on the opposite side of the valley, and material was distributed both up- and down-stream along the Adda River (Fig. 7.5). This landslide is considered to be among the most rapid mass movements ever documented (76–108 m/s) (Crosta et al. 2004), and the rock avalanche, entering the debris-dam lake that had formed in the previous days, produced an anomalous water wave. Significant topographic changes occurred, numerous buildings were destroyed and 27 people were killed. The modelling of the Val Pola landslide based on run-out extent, debris profiles, velocities and deposition distributions

Fig. 7.5 The Val Pola landslide viewed from the opposite side of the main valley (*photo* V. Garavaglia 2009)

(see Crosta et al. 2004) provides us with the opportunity to better understand this type of hazard which may significantly affect alpine valleys.

7.3.4 Postalesio Earth Pyramids: The Modelling of Glacial Deposits by Runoff

Coming from the Upper Valtellina, the landscape shows a transition from landforms shaped mainly by glaciers to polygenic landforms generated by mass wasting and fluvial action.

The Postalesio earth pyramids, located a few kilometres west of Sondrio (Figs. 7.1 and 7.6), are famous landforms in Upper Pleistocene glacial deposits, where gneiss and micaschist boulders of the Tonale Units are incorporated and protect the finer portion of the deposit from runoff. Water runoff action is the main process which shapes the deposits of different grain size into spectacular forms. The pyramids have been evolving, and both the formation of new pyramids and the dismantling of old ones are deduced by the presence of fallen blocks at the base of the slopes. In Fig. 7.6, a shot of the pyramids in 1931, as included in the monograph “The Alps” by Federico Sacco (1934), is compared with the current situation, and at least seven pyramids are easily distinguishable. The path that allows a visit along the perimeter of this Natural Reserve has recently been buried by sediment transported during heavy rainfall that occurred during the autumn of 2013.

7.3.5 The Lithological Landscapes of Valmalenco and Masino Valleys

During the Oligocene, a regional tensional regime led to the emplacement of several wide plutons distributed mainly along the Insubric Line. One of the most important plutons is located on the northern side of Valtellina and is known as Masino-Bregaglia or Bergell Pluton (Fig. 7.1). It develops in the area between Valmalenco (Sissone Valley, in the western part) and Chiavenna Valley, with a tail that reaches the Bellinzona area, and covers an area of approximately 280 km^2. The pluton is characterised by elongation along the Insubric Line. The calk-alkaline lithotypes, that characterise the pluton, are of two types, on the southern and south-eastern edges of the pluton, fine grained tonalite is present (locally named “Serizzo”), while the core and the eastern portion of the pluton consist of a large-feldspar granodiorite that, because of the presence of porphyroclasts of potassium feldspar, is known locally as “Ghiandone”. These rock types are largely used for buildings in the Milan area.

Morphology of the granitic pluton has been shaped by advancing glaciers and by their recent retreat, and also by gravity-driven processes, particularly after the LGM which

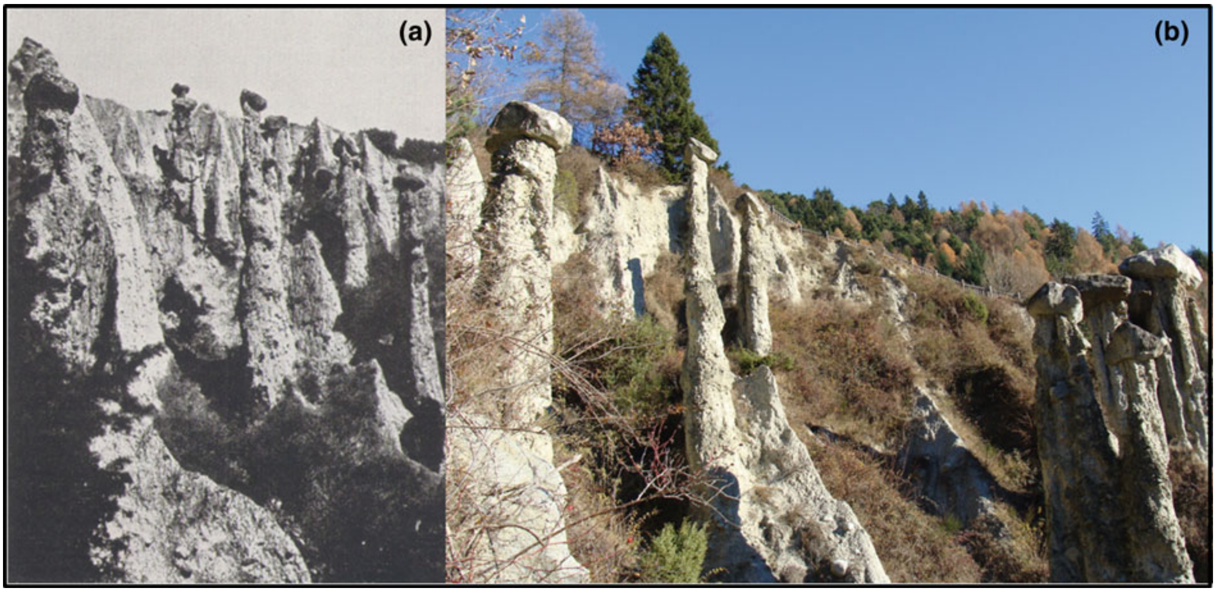

Fig. 7.6 Postalesio earth pyramids. **a** Image extracted from Sacco (1934). **b** View of the pyramids from the lower portion of the tourism path (*photo* I. Bollati 2013)

have produced voluminous rock fall deposits. Running water and fluvial action have been playing an important role in modelling this landscape to a considerable extent as a typical example of a lithological landscape. The Masino and Mello Valley sides are famous for the awe-inspiring rock walls. In the Masino Valley near San Martino, one of the most impressive and famous mega-boulders, the Sasso Remenno, which has a volume of several hundred cubic metres, is present as the result of a huge rock fall (Crosta 1994).

Due to the valley shape and the quality of the granite lithotype, large numbers of tourists and climbers visit the area, especially during summer. Climbing on the rock walls of Mello Valley or on the Sasso Remenno is an appreciated activity, and the granodioritic walls of the Masino and Mello valleys are famous all over Europe as "the little Yosemite". One of the most important mountains in the Masino Valley area, approachable from both the Swiss and Italian sides, is the Badile Peak, a beautiful example of modelling on granitic substrate.

From a geological point of view, the area near Valmalenco is significant because along the valley it is possible to cross the different tectonic units of the paleo-African Austroalpine Nappes and oceanic and paleo-European rocks of the Pennidic Nappes. The importance of Valmalenco is also attributable to mining activity, deriving from the presence of many types of minerals such as chromite, asbestos and manganese nodules that are exported all over the world.

In the mountainsides surrounding Chiareggio village (Fig. 7.1) in the Sissone Valley, the panoramic view of contrasting lithological landscapes is meaningful (Fig. 7.7): the contact is evident between the Oligocene intrusive rocks and the ultramafic rocks of the ophiolitic Malenco-Forno Nappe that makes up the Disgrazia Peak and others. The names of the peaks in the area (i.e. Sasso Nero and Sasso Moro) reflect the dark colour of the unweathered ultramafic lithotypes, and the same naming pattern is evident where the weathering of the ferric serpentinite rocks gives them a very red aspect (i.e. Preda Rossa, Corna Rossa and Corni Bruciati).

Many itineraries and hiking trails allow enjoyment of these spectacular landscapes, which range from lithological to glacial.

7.3.6 The Lacustrine Landscape of Lake Como

Lake Como collects, in the northern sector, the waters of the Mera River flowing from the Chiavenna Valley and of the Adda River flowing from Valtellina (Figs. 7.1 and 7.8). In this region, a wide plain area, the Pian di Spagna, gradually develops and consists of alluvial deposits of both rivers, though the Adda River sedimentation rate has been the most influential one. In fact the advance of sedimentation towards the west led to the progressive separation of Lake Como, in historical times (around the sixteenth century), from the Mezzola Lake located to the north in the Chiavenna Valley. The Pian di Spagna, an internationally recognised wetland, derives its name from Spanish rule during the seventeenth century.

From National Road 36, it is possible to appreciate the Lake Como landscape. The current Lake Como basin shape is an inverted "Y" where the towns of Como and Lecco are

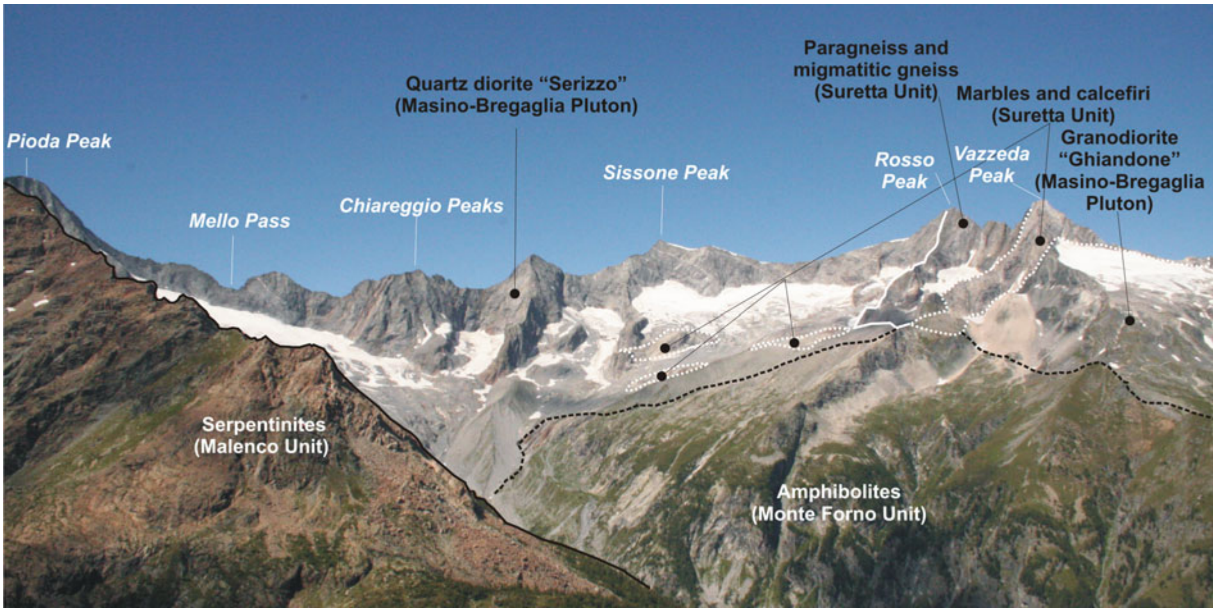

Fig. 7.7 Geological landscape of granites and ophiolitic rocks in the Sissone Valley. The contact between oceanic rocks of the Valmalenco Nappe (serpentinites and amphibolites) and granites of the Val Masino-Bregaglia pluton is very evident, enhanced by the contrasting colours: the *red* of oxidised serpentinites stands out clearly (*photo* M. Lucini 2009)

Fig. 7.8 Panoramic view of Lake Como. The Lecco branch of the lake is visible with the peaks of the Grigna Massif in the background: the Northern Grigna (2399 m) and the Southern Grigna (2181 m), respectively known as "Grignone" and "Grignetta". The *photo* was taken from the Barni village (635 m) located between the two branches of Lake Como (*photo* I. Bollati 2011)

located on the two southern tails (Figs. 7.1 and 7.8). Along the lake sides, from north to south, the change from metamorphic basement to the Permo-Mesozoic sedimentary cover of the Southern Alps is visible.

During the period between the Oligocene and the Middle Miocene, renewed tectonic activity, accompanied by a rapid orogenic uplift, activated the Alps, and in the final phase of the Miocene, during the Messinian (7.2–5.3 Ma BP), the closure of the connection between the Atlantic Ocean and the Mediterranean Sea led to the complete desiccation of the Mediterranean Sea, with the consequent deposition of hundreds of kilometres of evaporite deposits. This episode played a fundamental role in the formation of Lake Como and of the other large Prealpine lakes such as Lake Maggiore and Lake Iseo, for example. This event led to an irregular increase of the incision level of the rivers, mainly N–S oriented such as the Adda River, that tended to reach the new base elevation. The most important consequence of this incision was the formation of deep canyons along the Mediterranean margins. Southern Alpine lakes generally have common features such as N–S orientation, steep lateral slopes and lakebeds that lie below sea level (i.e. cryptodepressions), confirmed by geophysical investigations conducted in both the Po Plain and Lake Como. According to these studies a possible link between lake formation, intensification of erosion and the formation of canyons has been proposed (Bini et al. 1978).

At the end of the Pleistocene, in the LGM phase, the glaciers present in the area were locally up to 2 km thick, leaving only the higher peaks exposed above the ice (Cavallin et al. 1997). These constituted a complex system of valley glaciers continuing south from the main glaciers coming out of the Valtellina and Chiavenna valleys, and forming the piedmont glaciers of Como, Brianza and Lecco (Fig. 7.2b). The glaciers left, as a record of their maximum expansion, a series of concentric moraine ridges referred to as the moraine amphitheatres of Brianza and Lecco. The characteristics of medial and end moraines, together with the positions of erratic boulders and glacial deposits in caves, permitted the reconstruction of thirteen glacial episodes in the Prealpine area since the Late Pliocene (Bini et al. 1996). The erratic boulders dispersed in the area down valley of Lake Como are representative of the outcropping lithotypes in the broad provenance basin of the Adda River, among which the previously described granitic and ultramafic rocks of the Valmalenco and Masino Valley are widely represented. Some of these erratic boulders, which have names linked with local traditions (e.g. Sass Negher, Pietra Luna and Pietra Pendula), are now protected as natural monuments.

Hence, the glacial modelling of the prior canyons, previously proposed as the primary agent for the formation of the U-shaped steep flanks of Lake Como's profile, might have acted only successively, remodelling the canyons and partially re-eroding the sediments pertinent to the Messinian desiccation events and to the successive Pliocene transgression phase.

7.3.7 The Karst Landscape of the Grigne Massif

Approaching the Lake Como area, where calcareous lithotypes become dominant, karst landforms are widespread. One of the most representative and well-known karst landscapes of the Central Italian Alps develops in the Grigne Massif, located on the eastern side of Lake Como (Figs. 7.1 and 7.8). The area is characterised by the sedimentary cover of the Southern Alps which lies above the metamorphic basement outcropping towards the north. The Triassic limestones of the Grigne Massif belong mainly to the Esino dolomitic limestone Platform (Upper Anisian—Ladinian), which forms the two most important peaks: the Northern Grigna (2399 m) and the Southern Grigna (2181 m). The landscape is typically characterised by karst landforms, especially along the Bregai edge: dolines, shafts, hills, flat rock surfaces and karren (micro-karsts) are represented. Snow is present in the area for some months during the year. In the past, the soil coverage must have been very thick, as covered karst landforms are widespread (Santilli et al. 2005).

Different paleo-karst stages led to the formation of a broad and deep karst system that has been successively cut by Quaternary glacial erosion. In fact, the area is renowned from a speleological point of view, and in some of these caves ice is still present, as reported by Leonardo Da Vinci, who was among the first to note this feature. Among the deepest and most famous caverns there is the "Abisso W le Donne" (1160 m deep). The ice from one of these caves ("Abisso sul Margine dell'Alto Bregai", 192 m deep) has been analysed for $\delta^{18}O$ and ionic content relative to depth; the ice is considered to be derived from the crystallisation, from the top to the bottom, of lake water, with partial opening of the system and entry of different sources of water (Citterio et al. 2004).

Also around the Grigna Massif are interesting hiking trails; the one that reaches the Northern Grigna peak from Esino Lario and that crosses the most important cave areas allow observation of the geomorphological features of the area.

7.4 Conclusions

The Central Italian Alps, and in particular the region between Upper Valtellina and Lake Como, permit observation of a varied series of landforms and landscapes by following the retreat path of the glaciers since the LGM. The different structural domains of the Alps are reflected in the various lithological patterns, and the differentiation of geomorphological processes acting through time and space allows us to make inferences regarding the influence of climate change on the intensity and frequency of climate-related processes. The records of the most important evolutionary phases of the Alpine range are present and comprehensible within the current landscapes, as is the glacial evolution from the maximum extent during the Upper Pleistocene until the Little Ice Age, and the current shrinkage phase.

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8 The Adamello-Presanella and Brenta Massifs, Central Alps: Contrasting High-Mountain Landscapes and Landforms

Alberto Carton and Carlo Baroni

Abstract

Adamello-Presanella and Brenta massifs are two distinct and adjacent mountain groups divided by an Alpine structural alignment which separates the Southern Alps into two distinct blocks characterized by different rock types. The Adamello-Presanella Massif is made up of intrusive igneous rocks and shows typical landscapes of high-mountain environments modelled prevalently by the action of glaciers. In the Brenta Massif limestones and dolostones crop out extensively which have been shaped into steeples, pinnacles, vertical rock faces and ledges by selective erosion. In this mountain group subsurface and surface karst landscapes have also developed. Owing to its extraordinary interest and geological-geomorphological value, these massifs are included in the European Geoparks Network and in the World Global UNESCO Network of Geoparks.

Keywords

Alpine landscape • Glacial geomorphology • Karst geomorphology • Nature world heritage • Adamello-Presanella and Brenta massifs

8.1 Introduction

The massifs of Adamello-Presanella and Brenta, located at the easternmost extremity of the Rhaetian Alps, are two mountain groups which differ considerably one from the other, from both geological and geomorphological viewpoint.

The former is mostly made up of igneous rocks of a large batholith formed by several tonalite plutons, granodiorites and gabbros. It is the largest and most spectacular intrusive body of Alpine Tertiary magmatism. Morphology of this area clearly shows typical features of a high-mountain landscape which has been intensely modelled by glaciers, with deep glacial U-shaped trough valleys, laterally flanked by sheer rock slopes and long glacial terraces.

In the Brenta Massif the oldest rocks are Permian volcano-sedimentary deposits but the most widespread formation is Dolomia Principale, a typical carbonate shelf formation made up of a monotonous sequence of typically laminated dolostone layers. The most famous peaks of this group are modelled in this formation which, in its central sector, makes up a majestic landscape dominated by steeples, pinnacles and sheer rock faces. The Brenta Massif is also characterized by glacial landforms, mainly cirques, although karst landscape is the most dominant in this massif. The widespread presence of rocks subject to karst processes makes the Brenta Massif one of the most important karst areas in the Dolomites, with an extremely well-articulated subsurface drainage network.

8.2 Geographical Setting

The Adamello-Presanella Massif lies in the southern sector of the Central Alps (Rhaetian Alps), and covers an area of more than 1100 km^2 (Fig. 8.1). The eastern sector is

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included in the Trentino region, the western one belongs to Lombardy. It is the southernmost massif in this sector of the Alps, with peaks exceeding 3500 m in elevation. Adamello hosts the largest plateau glacier of the Italian Alps: the Adamello or Pian di Neve Glacier. To the north, it borders the Ortles-Cevedale Group, from which it is separated by Val di Sole and the upper Val Camonica. The Brenta Massif bounds it to the east along the Rendena, Campiglio and Meledrio valleys, whereas to the west, beyond Val Camonica, it borders the Orobian Alps. The southern boundary is less marked and the massif gradually gives way to the Lombardy pre-Alps between the Camonica and Giudicarie valleys. The major peaks of the group are Cima Presanella (3557 m), Mt. Adamello (3538 m) and Mt. Caré Alto (3463 m); the southern peaks are no more than 3000 m high.

The Brenta Massif is located some kilometres east of the Adamello-Presanella Group; it stretches entirely within the Trentino territory, between the lower Val di Sole to the northwest, the Meledrio, Campiglio and Rendena valleys to the west, the upper Val Giudicarie to the south, the Val di Non and the Molveno Lake and Banale area to the east (De Battaglia et al. 2013), covering a surface of roughly 400 km^2 (Fig. 8.1). The highest peaks are Cima Tosa (3173 m), Cima Brenta (3150 m) and Pietra Grande (2937 m).

The entire hydrographic network of the Adamello Massif and a great portion of the Brenta flow into Garda Lake and Iseo Lake, therefore within the basin of the Po River, whereas

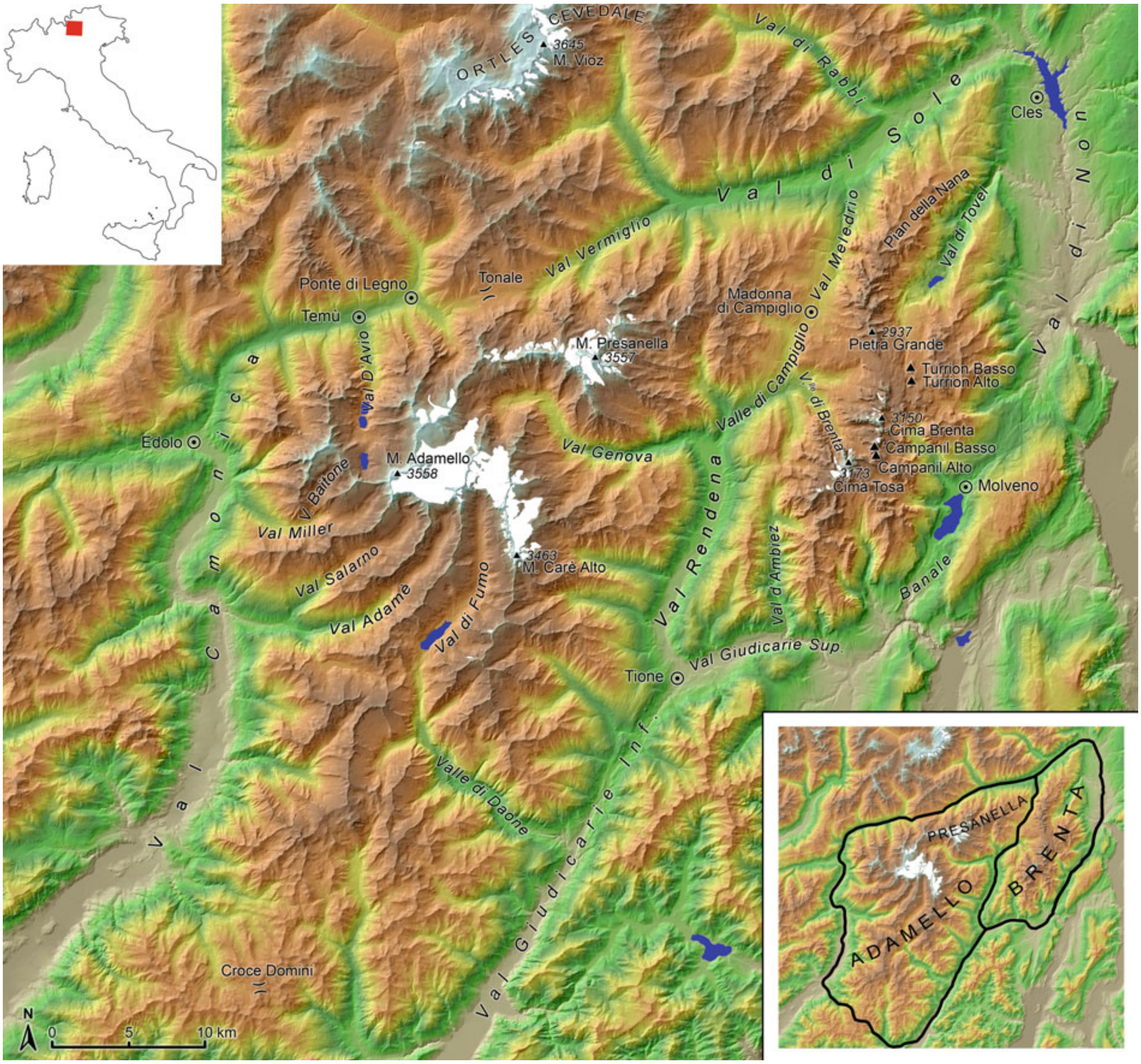

Fig. 8.1 Geographical setting of the Adamello-Presanella and Brenta massifs. The Adamello-Presanella is a rather compact mountain range which stretches nearly symmetrically around the two main peaks (Mt. Adamello and Mt. Presanella). The Brenta massif is instead arranged as a long, narrow ridge with an articulated but practically single N-S oriented water divide in the axis of the group

the northern slope of Presanella and the northeastern ridges of Brenta belong to the Adige River basin.

From the climatic standpoint the Adamello-Presanella and Brenta groups are located at the transition between the southern Alps—characterized by high precipitation (1800–2500 mm/year) concentrated in spring and autumn—and the innermost portion of the Alps, characterized by a more continental climate, with precipitation (including snowfall) mainly occurring during winter and generally not exceeding 1000–1200 mm/year. At higher altitudes, in snowy years, the snow cover remains on the ground until May–June.

These two massifs stretch along an altitude range of over 3000 m; for this reason various vegetation belts are present. There are meadows and pastures, vast extensions of rocky species, sub-alpine shrubs and alpine prairies and sub-nival vegetation. At the highest altitudes vast areas are completely devoid of vegetation and cryonival processes are particularly active.

No carriage road runs completely across these two mountain groups, except a forest road which penetrates for about 20 km into the Adamello-Presanella Massif along the Val Genova.

8.3 Geology and Its Influence on Geomorphology

The Adamello-Presanella and Brenta Massifs cover a key area of the Alps, characterized by the presence of the tectonic border between the Austroalpine and Southern Alps, and by the union of three segments of the Periadriatic Alignment (Bosellini 2017).

8.3.1 Lithology

The Adamello-Presanella intrusive massif is the largest (670 km^2) and the oldest (42–31 Ma) of the intrusive bodies of Oligocene age widespread in the Alps (Brack et al. 2008). Given the great extent of the outcrops of its magmatic rocks (Callegari and Brack 2002), it is considered to be a batholith. The magmatic mass is enclosed in a crustal structural wedge bounded to the north by the Tonale Line, the local name for the Insubric Line, which separates the Austroalpine Domain from the Southern Alps and to the west by the Giudicarie Line (Fig. 8.2). Different rock types can be distinguished (Callegari and Dal Piaz 1973), as the Adamello batholith is made up of many plutons that are more or less differentiated (Fig. 8.2). The main outcropping rocks are tonalite, quartz diorite, granodiorite etc. (Callegari and Dal Piaz 1973). Aplitic and pegmatitic dykes and sills are widespread all over the massif where they cut across the “hosting” rocks.

On the other hand, the geological history of the Brenta Massif is quite different since this massif is made up entirely of sedimentary rocks (Fig. 8.2). The series range from early Palaeozoic to Cretaceous. The volcano-sedimentary succession of the lower Permian shows a very interesting intercalation of volcanic products and fluvial-lacustrine deposits. In the eastern sector of the Brenta Dolomites the higher part of the Dolomia Principale crops out in the central body of this rocky massif and shows spectacular morphostructural (rock towers, steeples, ledges etc.) and morphoclimatic landforms (glacial cirques, roches moutonnées, cryogenic landforms etc.). The back-stepping trend follows with the subtidal limestone of the Calcari Grigi Group. Moving westward all these units are replaced by the Rhaethian basinal deposits. The condensed units of the Rosso Ammonitico Formation and Selcifero Lombardo lie on both the Trento shelf and on the Lombardy basinal facies, witnessing that all the area started developing in a homogeneous way from the late Jurassic onwards (Dal Piaz et al. 2007).

8.3.2 Tectonics

From the structural standpoint, besides the two great regional features which bound it to NNW (Tonale Line) and to the east (Giudicarie Line), the Adamello batholith is affected by the Gole larghe—Val Genova Alignment, which makes up its main tectonic discontinuity. This is a great right-transcurrent E–W trending fault with a throw of about 1 km (Di Toro and Pennacchioni 2004, 2005). On the contrary, the Brenta Massif is affected by a dense network of sub-parallel N-S trending overthrusts (Fig. 8.2).

8.3.3 Geological Control on Landforms

The striking difference between the Adamello-Presanella and Brenta massifs is evident from any aerial view. The first is a rather compact mountain group which stretches nearly symmetrically around the two main peaks (Mt. Adamello and Cima Presanella). On the contrary, the Brenta Massif is arranged as a long, narrow ridge, with an articulated but practically single N–S oriented watershed running on top. These diverse arrangements are perfectly reflected in the hydrographic network which shows different patterns in the two massifs (Fig. 8.1). In the Adamello-Presanella Massif extensive systems of regional faults (Tonale and Giudicarie Lines) have strongly influenced the trend of the peripheral hydrographic network, generating the upper Val Camonica and the Vermiglio, Sole, Rendena and Giudicarie valleys, which may be interpreted as subsequent valleys. On the contrary, the hydrographic pattern developed by Fumo, Adamè, Salarno, Miller, Baitone and Avio valleys assumes a

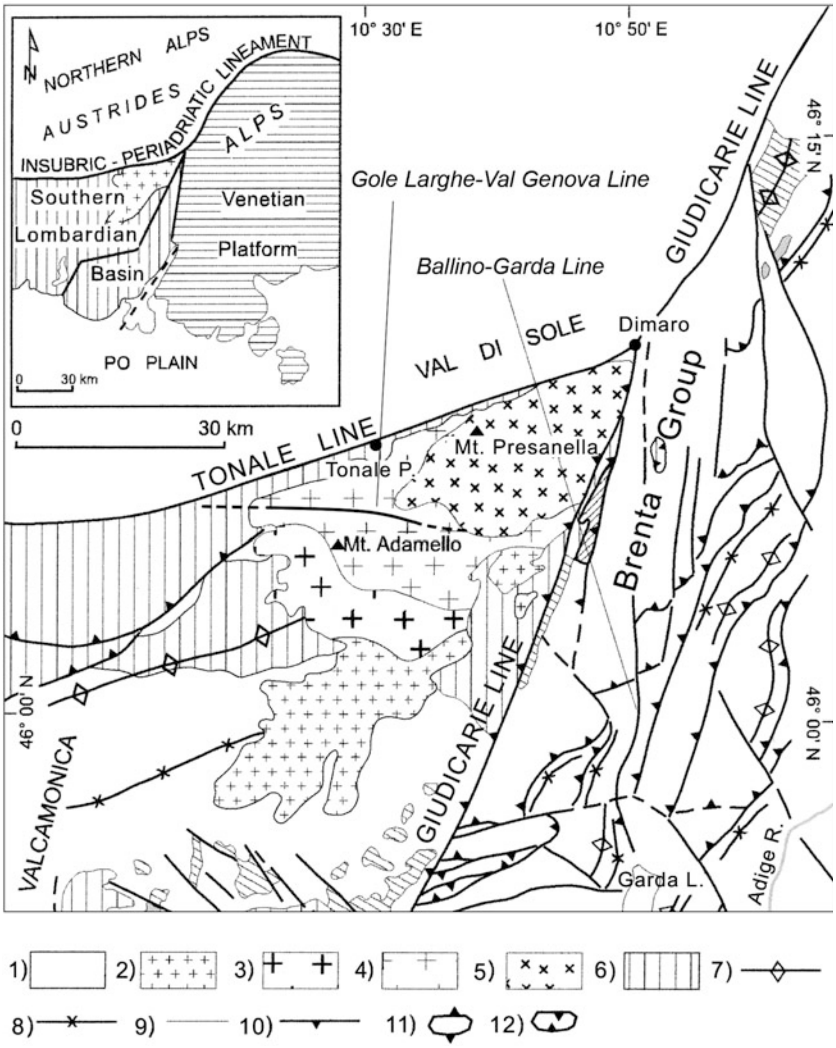

Fig. 8.2 Geological sketch map of the Adamello-Presanella and Brenta massifs. Legend: *1* Sedimentary cover (Upper Permian-Neogene); *2* Re di Castello Tonalite Unit (Middle Eocene); *3* Western Adamello Tonalite Unit (Late Eocene); *4* Avio and Central Adamello Tonalite Unit (Late Eocene-Oligocene); *5* Presanella Tonalite Unit (Oligocene); *6* metamorphic basement rocks; *7* main anticline; *8* main syncline; *9* main fault; *10* main thrust; *11* klippe and summit overthrust; *12* tectonic window (modified after Baroni et al. 2014)

centrifugal arrangement, diverging radially from the top areas of the massif; this is due to the uplift of the Tertiary batholith which has reached its most elevated and eroded point in this area.

In the Brenta Massif the development of valleys is less pronounced and less geometrical. The various geological structures cut across the mountain chain with a dense series of N–S trending faults and thrusts. Along or in proximity of these tectonic features, the main valleys are found, e.g. the Val di Tovel. Structural controls are also found in correspondence with valleys developed along a great normal and trascurrent fault. A set of vertical or sub-vertical faults and joints, which generally cut across the dolostones, usually with sub-horizontal or slightly inclined attitudes, generates a series of pinnacles and rock towers of various sizes (Fig. 8.3) recorded in the local toponymy, as in the case of Campanil Basso and Campanil Alto, and Torre di Vallesinella. These spectacular forms have been shaped in a thick dolostone mass, in particular, the Dolomia Principale Formation which in the Brenta massif forms a single rock body with the underlying Carnian and Ladinian dolostones. In some places the considerable thickness of these rocks is caused also by overthrusts occurring within the dolostones which increase their total thickness. For this reason, the perpendicular faces of many rock towers and monoliths are about a hundred metres high and offer long, vertical rock faces to climbers. Other rock towers are the result of morphoselection processes on rocks of different nature. Spectacular forms of this type are the Turrion Basso and Turrion Alto in the upper Val di Tovel (Fig. 8.4). Selective erosion has also occurred in correspondence with lithological changes or where there are variations of thickness and compactness within the same geological formation. This phenomenon is well represented by narrow ledges sculpted within the Dolomia Principale, which host various alpine itineraries, the most famous of which is the "delle Bocchette" way.

Fig. 8.3 Typical saw-shaped profile of the Brenta Massif caused by a series of faults and sub-vertical joints which cut through the dolostone layers giving origin to pinnacles and towers. Central Brenta: Busa dei Sfulmini. From *left* to *right* Cima Tosa (in the *background*), Cima Brenta Alta, Campanil Basso, Campanil Alto, Cima dei Sfulmini, Torre di Brenta and Cima d'Armi (*photo* P. Calzà)

Fig. 8.4 Spectacular example of morphoselection: Turrion Basso and Turrion Alto. The two towers are interpreted as a klippen (overthrust peak) that duplicates the Rethian succession. The basin (valley) in which they are located is laterally bounded by two faults. The areas near the two faults have suffered more intense erosion than the towers due to a greater jointing of the bedrock (*photo* M. Visintainer)

In the Adamello-Presanella Massif the wide and monotonous outcrops of crystalline rocks lack a network of faults or joints on a regional scale and therefore do not allow the formation of articulated landforms. The slopes are constantly characterized by steep inclinations, sometimes interrupted by glacial shoulders. The rock types found in this group are less subject to frost shattering and, as a consequence, have better preserved the erosional traces of glaciers. For this reason well preserved trimlines can frequently be observed on the slopes, dating back to both the Last Glacial Maximum

Fig. 8.5 Long sharp crests (*arêtes*) characterize the whole Adamello-Presanella Massif originated due to intersection of retreating rock slopes in the glacial valley heads. To the *left* Crozzon di Lares stands above Vedretta di Folgorida, in the *middle* Crozzon di Folgorida with a set of well-preserved Late Glacial moraine ridges at its foot (*photo* A. Carton)

(LGM) and the Little Ice Age (LIA). The flat open spaces found in the central Brenta Massif do not have their counterparts in Adamello, where they are constantly substituted by sharp crests (*arête*), resulting from glacial undercutting of rock slopes and cryogenic processes (Fig. 8.5).

8.4 The Glacial Inprint

The second major control on landforms is ice action. The Adamello-Presanella and Brenta massifs were affected by the great Pleistocene glacial expansions. In particular, they were affected by the LGM expansion, by the subsequent Late Glacial phase and, finally, by the LIA. During the LGM the Adamello-Presanella and Brenta massifs were almost completely covered by an ice sheet from which only the highest peaks emerged. It is estimated that, in the area where the village of Madonna di Campiglio lies (1527 m), the ice sheet surface might have reached an altitude of 2150–2200 m. On the Adamello-Presanella massif the lobes of some of the largest glaciers of the Southern Alps branched out towards the south, such as the Chiese and Oglio glaciers located in Val Camonica. A remarkable lobe came down from Val di Sole to the east. This impressive ice-mass surrounded even the Brenta Dolomites on the east side, along the alignment Val di Non—Molveno—Banale. To the west, a large tongue between the Brenta and Adamello-Presanella massifs was generated along the Meledrio, Campiglio and Rendena valleys.

In subsequent phases of climate warming this "sea of ice" was disrupted. Already in the Late Glacial (*Gschnitz* stage Auct.) numerous valley glaciers, isolated one from the other, were present in the two mountain groups within a network of secondary valleys (Dal Piaz et al. 2007; Brack et al. 2008). However, their successive development and evolution was different, owing to the different orographic conditions of the two massifs. Up to a few decades ago, in the Adamello-Presanella Massif there were well developed valley glaciers. On the other hand, in the Brenta Massif the small Late Glacial valley glaciers soon gave way to a series of cirque glaciers. Even at present this diversity is very evident.

Today the Adamello-Presanella Massif glaciers, including the largest glacier of the Italian Alps, the Adamello Glacier (Fig. 8.6), have an extension of some 53 km^2. More than 140 glaciers developed during the LIA, stretching over an area almost double their present surface; about 90 of the LIA glaciers (extending over some 8 km^2) are at present extinct. The considerable regression of the glacier fronts is marked by withdrawals ranging from several hundred metres to more than 1800 m (Mandrone Glacier) and 2000 m (Lobbia Glacier) (Baroni and Carton 1992, 1996). At present, apart from the Adamello Glacier which is considered a plateau glacier, most glaciers belong to the category of cirque glaciers; only a few of them maintain the characteristics of valley glaciers.

In the Brenta Massif, towards the end of the nineteenth century there were 16 glaciers covering a total area of 4.64 km^2. Now there are about 15 hanging glaciers stretching over an area of less than 1 km^2. They were all cirque glaciers but now they are turning into glacio-nival or debris-covered glaciers. The LIA moraines markedly

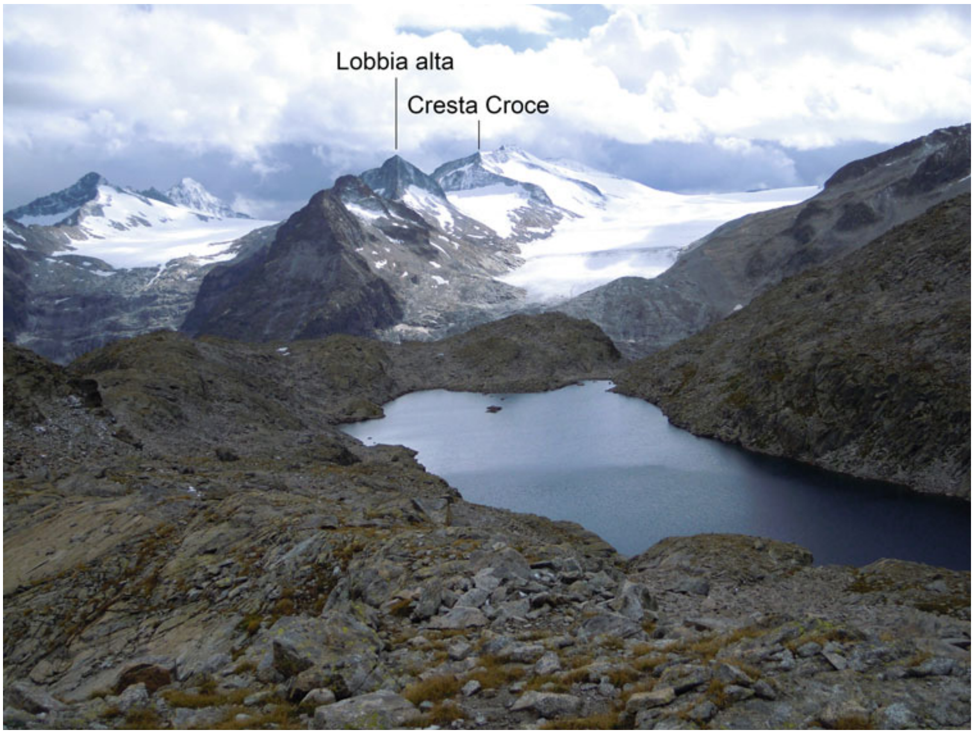

Fig. 8.6 The Lobbia Glacier to the *left* and the Mandrone Glacier (Pian di Neve) to the *right* within the Adamello Massif. In the 1960s they were joined in-between Lobbia alta and Cresta Croce. On the *right* flank of the Mandrone glacier are evident some glacial cirques (*photo* A. Carton, 12 September 2013)

Fig. 8.7 Val di Fumo with characteristic U-shaped section laterally surmounted by glacial shoulders (*photo* M. Visintainer)

characterize the heads and slopes of the valleys (Fig. 8.7). From a glaciological viewpoint, it should be emphasised that in the Brenta Massif glaciers are nearly exclusively fed by avalanches while in the Adamello-Presanella mainly by snow precipitation.

8.5 Landforms

In the Adamello-Presanella Massif the alpine morphology is well-defined, with deep glacial troughs characterized by successions of basins and steps, well-developed glacial shoulders, cirques, *arêtes* and horns. Glacial deposits of the major Late Glacial phases and of the LIA characterize all valleys. The more recent lateral and terminal moraines are found in the vicinity of existing or only recently extinct glaciers. Mass wasting and periglacial landforms are present throughout the massif. This morphogenesis is witnessed by the presence of rock glaciers and by a fair amount of patterned grounds.

On the contrary, the Brenta Massif shows the typical Dolomite landscape, magnificent and unique the world over, which is even more unusual in this area of the Rhaetian Alps dominated by the crystalline massifs of the Central Alps. Intense erosional processes on lithological discontinuities and carbonate and dolomite rocks has generated a landscape rich in rock towers, steeples, ramparts and furrows. In this group glaciation traces are present, although not as widespread as in the Adamello-Presanella Massif, since the materials produced by weathering on the steep calcareous-dolomite slopes have partially hidden the traces of the more ancient morphogenesis. A series of splendid karst and glacio-karst landscapes characterizing the wide upper plateaus compensate this apparent shortcoming. They also show a well-developed subsurface karst pattern. When this pattern emerges in correspondence of the vertical walls, spectacular waterfalls are formed.

8.5.1 Glacial Landforms

The main features characterizing the Adamello-Presanella Massif are glacial valleys. They have been entirely sculpted in the Adamello plutons and have perfectly preserved their typical trough shape. They can attain considerable lengths (up to 20 km) as in the case of Val Genova. The Avio, Miller, Salarno, Adamè and Fumo valleys are shorter but just as spectacular. They preserve the typical U-shape of polycyclic glacial valleys (Fig. 8.8), laterally surmounted by glacial shoulders.

Another common and interesting feature is offered by the steps at the outlet into lateral valleys cutting across the glacial trough (the *righel* of German authors). An example of this type is observed in the upper Val Genova, in proximity of the front of the Mandrone Glacier. Even more spectacular is the series of *righels* found in Val d'Avio, which was already described by Salomon (1908–1910), and in the 1950s was exploited for the construction of a series of artificial reservoirs. A continuous set of outlet steps is recognised in Val Genova in correspondence with the lateral Láres, Seniciaga and Nardis valleys. From this latter step, the melting waters of the glacier bearing the same name create a spectacular waterfall, which is listed among the geosites of the Adamello Brenta Geopark and considered one of the main tourist attractions of the area.

There are also numerous glacial cirques (Fig. 8.6), varying in size and shape but nearly always wide, only partially hidden by debris. In many cases, segments of trimlines—often ascribable to the LGM—are observable in the cirques' inner parts or along the rocky slopes.

Roches moutonnées are just as frequent on the step sills and in the flat areas. They emphasize the joint network in a spectacular manner since they are oriented along these discontinuities. In particular, the roches moutonnées ascribable to the Late Glacial stadial phases are well preserved, although widely covered by lichens.

On the contrary, traces of glacial erosion present in the Brenta Massif are quite different since orographic features of this massif have not allowed the formation of long valleys (the longest one, attaining nearly 12 km in length, is Val di Tovel). All the other valleys are much shorter, orthogonal to the massif extension, and with steeper slopes. The trough morphology can be made out only in a few cases as in Val Gelada since it is devoid of debris and hence its profile appears to be rather distinct. In all other cases abundant ice-shattered material, accumulating from the densely layered calcareous and dolomite slopes, hide the trough profile often buried by debris and talus fans.

8.5.2 Periglacial Landforms

The different susceptibility to frost shattering of the rocks cropping out in the two mountain groups produces larger amounts of ice-shattered material in the Brenta Massif giving origin to voluminous talus, fans and detrital covers. Furthermore, the two mountain groups differ also in terms of the number of rock glaciers. In the Adamello-Presanella Massif a total of 216 rock glaciers have been identified (Baroni et al. 2004). Out of these, 88 are active/inactive and the rest are relict ones. In the group of active/inactive rock glaciers, 59 are considered active and some of these are certainly in motion, as confirmed by two recent topographic surveys (Seppi et al. 2012). At least 30 rock glaciers have been formed since the LIA. The mean elevation of the fronts of active rock glaciers (2527 m) lies well below the estimated altitude of the −1 °C (2740 m) and −2 °C (2910 m) isotherms, suggesting that the reconstructed mean annual air temperature (MAAT) of −1/−2 °C does not coincide with the local MAAT in the entire group or that the rock glaciers studied are in disequilibrium with respect to the current climate conditions of this area.

On the other hand, in the Brenta Massif only seven rock glaciers are found, all of which are relict. The large difference in rock glacier density seems to be related to the different rocks outcropping in the two mountain groups. The most suitable rock types for rock glacier development are, in fact, crystalline rocks; the less suitable ones are carbonate rocks.

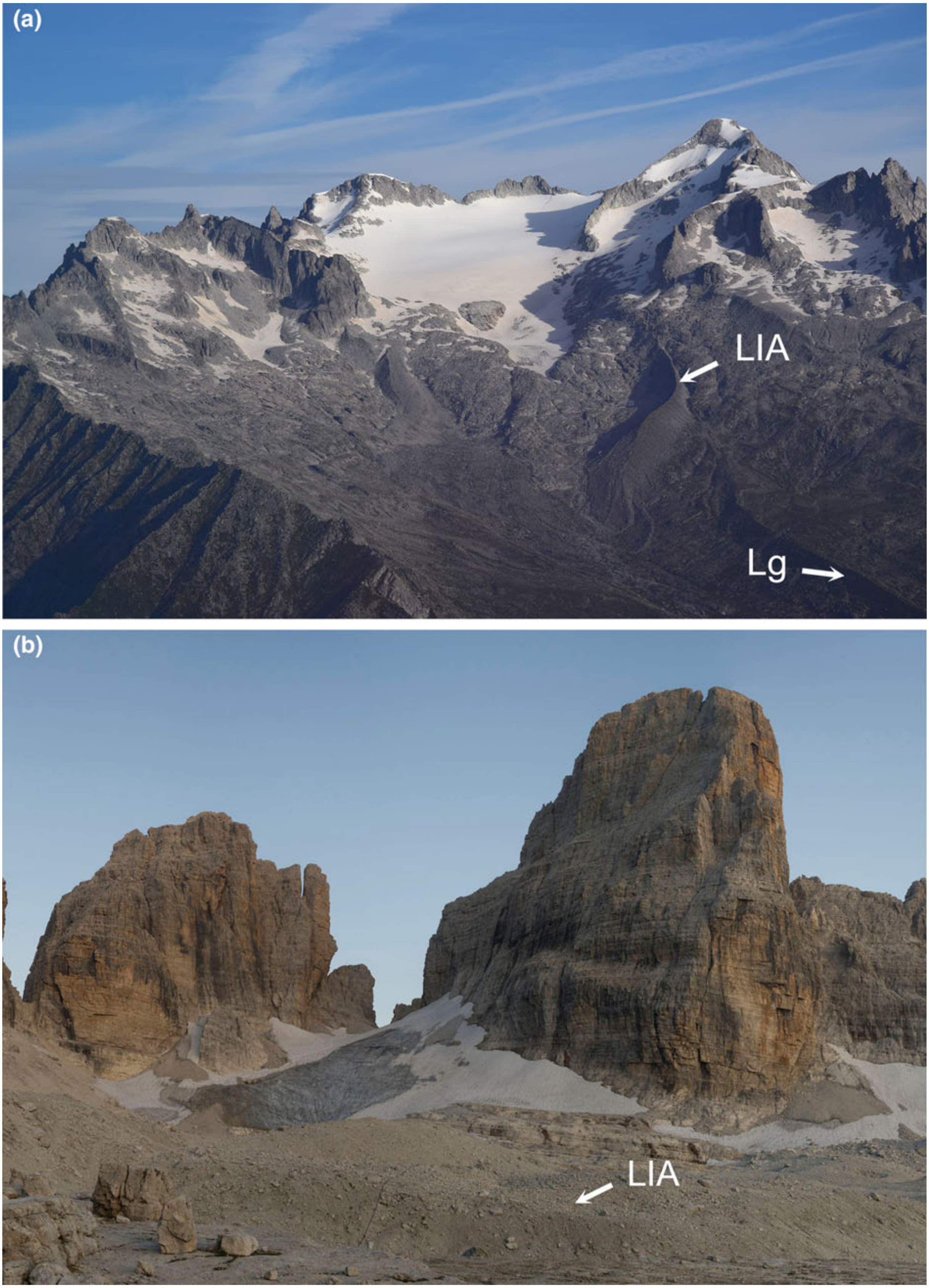

Fig. 8.8 Little Ice Age deposits (LIA) in the Adamello-Presanella massif (**a**) and in the Brenta massif (**b**). They appear as long and imposing ridges with sharp crests and steep slopes (**a**, Nardis hanging Glacier; *photo* A. Carton). In the Brenta massif the LIA moraines show modest size, as seen in correspondence of the Sfulmini northern Glacier (**b**; *photo* P. Calzà). **a** Clearly shows the top portion of the left lateral moraine of the hanging Nardis Glacier on the *lower right* of the picture, externally to the sharp LIA moraines. This moraine (Lg) is widely covered by vegetation and can be ascribed to the Late-glacial stadial phases

8.5.3 Karst Landforms

Another feature which radically differentiates the landscape of the Brenta Massif from the one of Adamello-Presanella is karst morphology (Fig. 8.9). The surface hydrographic network consists only of a few streams located at the margins of the area (Ambiez, Seghe, Tovel, Brenta valleys).

There are numerous surface karst and glacio-karst landforms, such as in the top of the Grostedi plateau and in the Lastei depression (Nicod 1976). There are also perched blocks, grikes, dolines, gikes, *bogaz*, *rohrenkarren*, staircase karts (*schichttreppenkarst*), *rinnenkarren* and *rundkarren*. These spectacular landscapes occupy vast sub-horizontal areas or glacio-karst depressions in correspondence with the outcrops of Dolomia Principale and Calcari Grigi of the Liassic. Other noticeable examples are found near Bocca della Vallazza and at Pian della Nana (Fig. 8.10). In some sectors there are also wide endorheic depressions, with diameters up to 800 m. The most typical one is Pozza Tramontana, a 130 m deep huge ellipsoidal doline-like cavity with a flat bottom. Other examples of karst landscape are found in the area, where structural surfaces subject to intense karst processes in the Dolomia Principale are cut across by slightly open sub-vertical joints, along which grikes and *rohrenkarren* were formed. The intense karst processes make this massif the largest underground hydro-structure in Trentino, with a hydrological karst difference in elevation between 3173 m at Cima Tosa and 260 m in the lower Val di Non (the highest in Italy) (Borsato 2007). In the whole Brenta Massif there are over 500 cavities made up of karst pits, many of which are up to 200 m deep. In the central-southern sector of this group several caves are also present, some of which attain a length of several kilometres.

8.6 Protection and Appraisal

Owing to their particular natural characteristics, the Adamello-Presanella and Brenta massifs are included within two regional parks: the Natural Adamello-Brenta Park (PNAB) and the Lombardy Adamello Park. The former, officially established in 1967, includes the entire Brenta Massif, the Presanella Massif and the eastern part of the Adamello Massif. The latter, established in 1993, includes the remaining part of the Adamello Massif. Initiatives to establish institutions for protection of these territories, however, date back to the 1920s. In 2011 the management boards of these two parks signed an agreement protocol establishing common initiatives and collaboration activities. As for the Adamello-Brenta Natural Park, already at the date of its foundation a modern and precursory provincial law had been enacted whose principles were later ratified by national laws. This law defined the purposes of these two natural parks as “the conservation of environmental and natural characteristics, the promotion of scientific and social use of environmental assets” and established administrative organization and general management guidelines of the protected area.

Due to extraordinary interest and geological and geomorphological values, in 2008 the Adamello-Brenta Natural Park has obtained the acknowledgement of Adamello Brenta Geopark. In this way it became part of the European and

Fig. 8.9 Thick series of *karren* at the foot of Castelletto inferiore of Vallesinella in the Brenta Massif. They are a spectacular example of high-altitude karst forms which were shaped on carbonate rocks originally smoothed by glaciers (*photo* P. Calzà)

Fig. 8.10 Pian della Nana, Brenta Massif. Wide glacio-karst trough completely devoid of surface hydrography, shaped in-between the Jurassic limestone, on the *left*, and the softer marly limestone of the Cretaceous Scaglia Rossa, on the *right* (*photo* M. Visintainer)

Global Network of Geoparks, a network of protected areas which work together in order to preserve and appraise the Earth's geological heritage under the auspices of UNESCO. In the Adamello Brenta Geopark 61 sites of high geological value (geosites) have been identified. They are now being protected by means of adequate and sustainable forms of geotourism. Nevertheless, the maximum acknowledgement achieved, dated 26 June 2009, was the insertion of the Brenta Dolomites in the UNESCO World Heritage list together with another eight Italian Dolomite areas (serial asset no. 9; Gianolla et al. 2008). This recognition pinpoints even more the geological spectacularity of these territories. The motivation for this acknowledgement is as follows: "It features some of the most beautiful mountain landscapes anywhere, with vertical walls, sheer cliffs and a high density of narrow, deep and long valleys. A serial property of nine areas that present a diversity of spectacular landscapes of international significance for geomorphology marked by steeples, pinnacles and rock walls; the site also contains glacial landforms and karst systems".

8.7 Conclusions

Peaks born from the sea and rocks formed in the depths of the Earth; glaciers which shape the mountains and waters which dissolve carbonate rocks. All this is offered by the landscapes of the Adamello-Presanella and Brenta massifs. The variety of landforms which nature has placed in a circumscribed space in the heart of the Alps is really extraordinary. Besides telling the geological history of each relief, the landscapes found in these mountain groups are educational examples, in some cases spectacular ones, which show the evolution of several geological and geomorphological processes on different type of bedrock. The determination to establish a Nature Park, which was subsequently included in the European and Global Network of Geoparks, has made the conservation, fruition and, most of all, appraisal of the geological heritage of this territory possible, thanks also to the patronage by UNESCO and the resulting dense network of scientific and cultural exchanges. Additionally, these parks provide excellent visitor centres and accompanying explanations on landform and landscape evolution.

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9

Large Ancient Landslides in Trentino, Northeastern Alps, as Evidence of Postglacial Dynamics

Alberto Carton

Abstract

The mountain landscape of Trentino (northeastern Italy) is characterized by the presence of a series of large-scale landslides locally known as *marocche*. Remarkable examples are represented by the so-called *Lavini di Marco*, *Marocche di Dro* and *Marocche di Molveno*. Various hypotheses have been suggested regarding the origin of these landslides. Some authors have proposed a glacial rather than a gravitational origin. Other authors maintained that marocche should be referred to rock avalanches which occurred in glacial conditions and whose accumulations must have been distributed by glacial processes. The latter interpretation cannot be accepted since the largest landslide is far more recent than Late-Glacial Age. Many concordant chronological data tend to ascribe them to the Holocene, between 3000 and 1000 years BP.

Keywords

Rock avalanche • Rock slide • Marocche • Holocene • Trentino • Eastern Alps

9.1 Introduction

Throughout the Holocene, valley slopes in the Alps have been in an adjustment stage after extensive reshaping by Pleistocene glaciers. The dominant response to ice decay can be observed in numerous slope instability processes, both in the bedrock and cover sediments of varying size and type, such as rock fall, rock slide and rock avalanche (Soldati et al. 2006; Prager et al. 2008; Borgatti and Soldati 2010). In Trento Province, along the southern side of the Eastern Alps, many rock slides have been documented, particularly in the lower valleys of the Adige and Sarca rivers. The most famous landslides are Lavini di Marco, Marocche di Dro, Marocche di Pietramurata, Marocche di Masi di Lasino, Marocche del Monte Palon, Marocche di Castelpietra, Marocche di Molveno and Marocche di Tovel (Fig. 9.1). In particular, the Lavini di Marco was first mentioned early in 1300 by Dante Alighieri in his Divine Comedy (Inferno, XII, 4–9).

Two large tongues of the Atesino Glacier once stretched along the Adige and Sarca valleys, reaching as far as the northern Po Plain. In several points, the two ice flows were connected by a series of transfluence saddles. Their thickness was such that the valley flanks were covered by ice nearly up to the top. The slopes now bear the marks of considerable landslides: at their foot, vast debris accumulations are scattered, often consisting of large rock blocks. These landslides are locally known with the term *marocche*. The term *marocca* is a dialect entry deriving from *mar* which means “stone”. In the Adige Valley, around Rovereto, also the term *lavini* (or *slavini*) is used. Mass movement of this type, with transport of huge amounts of rock debris for distances up to thousands of metres, are classified in the literature as debris avalanches and rock avalanches (Angeli et al. 1996).

From the end of the nineteenth century onwards, they have been described by several authors (see Venzo 2000 for a review). The use of traditional radiometric dating by means of ^{14}C (Orombelli and Sauro 1988; Bassetti and Borsato

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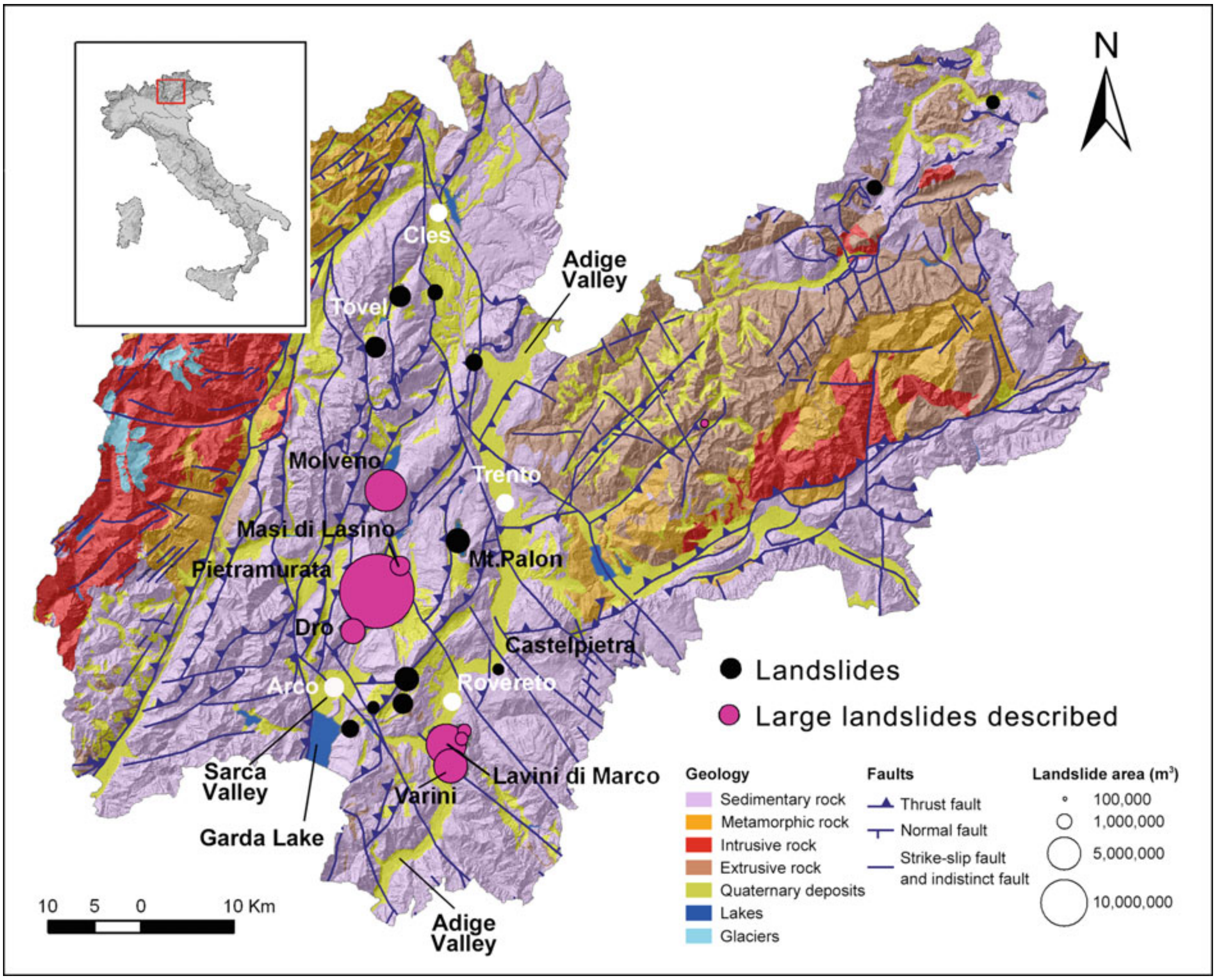

Fig. 9.1 Geological sketch map of the Trento Province with location and size of landslides (modified after Martin et al. 2014)

2007) and more recent ones based on ^{36}Cl decay rate, which allow the calculation of the exposure period (Martin et al. 2014), have opened new opportunities to date these important landslide bodies and to provide a detailed evolutional and chronological framework of the Lavini di Marco.

In the past, these large landslides were associated with the withdrawal of Pleistocene glaciers. Following the thinning up of glacial tongues, the surrounding steep slopes were no longer supported, thus leading to the detachment of large rock masses and their accumulation and limited transport on the glaciers' tongues (moraine landslides). According to this hypothesis, these landslides would be Late-glacial in age. Other researchers have interpreted them as moraines disguised as landslides. Nowadays, the hypothesis of valley deglaciation can no longer be justified since the most important landslides are definitely more recent than Late-glacial. On the basis of most chronological clues, they have been ascribed to the Late Holocene, to have occurred within an interval of 3000–1000 years BP. On the whole, the data available today testify to the activity of tectonic structures with which the landslides are associated. For some of them, a seismo-tectonic origin is assumed, since this is compatible with the seismic history of the territory.

Because of their genesis, patterns of movement and chronological plurality of the events, the complexity of these landslides still arouses great interest from both scientific and scenic point of view.

9.2 Geological Control on Landform Development

In the region north of Garda Lake and in the southern Adige Valley, geomorphological elements such as valleys and ridges are controlled by and parallel to the NNE–SSW trending tectonic lines of the Giudicarie System. The geological structures are characterized by west-dipping monocline ridges which are bordered to the east by tectonic scarps forming the right-hand side slopes of large asymmetrical valleys, sometimes split up by dip-upstream shear surfaces.

The geological structure of the southern sector of the Giudicarie System is overlain by a Triassic-Eocene carbonate succession divided into NNE–SSW elongated blocks. These blocks dip toward WNW and overlap the main lines of the Giudicarie System (Fig. 9.1). They give rise to monocline morphostructures marked by asymmetric ridges, the western slopes of which correspond to bedding surfaces, while the eastern ones are tectonic scarps. Therefore, the valleys between ridges correspond to depressions between tectonic scarps and dip slopes. This general morphological situation is very prone to vast mass movements which affect the slopes of the asymmetrical valleys, in correspondence with the monocline structures and tectonic scarps (Cavallin et al. 1997).

In this area, the Jurassic series typical of the Trento shelf crops out (Castellarin et al. 2005a, b). It is made up of limestones such as Calcari Grigi, San Vigilio Oolite, Rosso Ammonitico and Biancone. Nearly all the main scarps and slide surfaces of the large landslides originate within the Calcari Grigi.

Along the Adige River valley and other minor valleys, there are numerous landslide accumulations distributed over a relatively small area (Fig. 9.1). Exemplary case are the Lavini di Marco, the Marocche NNE of Dro and the Marocche di Molveno.

The large landslides are clearly linked to the marked asymmetry of the valleys, where western slopes are characterized by tectonic scarps as long as 20 km and there are differences in height of up to 500–1000 m, with slope gradients of 30–50°. Morphological and structural characteristics allow two main types of slope movement to be recognized: (i) rock falls from tectonic scarps which correspond to ESE facing slopes; (ii) translational slides along bedding surfaces on WNW facing slopes (Fig. 9.2).

Fig. 9.2 Lavini di Marco. Stratum surfaces, usually WNW trending, along which translational slides were generated; in the *background* the Adige Valley (*photo* R. Tomasoni)

The surface of the landslide deposits is irregular and undulated, with confined depressions and long, narrow rises. In places, arcuate, sometimes concentric structures can be recognized. They are derived from both modest bank-like rises, small, narrow valleys and alignments of large boulders or fine-textured belts, which are often revealed by vegetation. These landslide accumulation features are generally interpreted as flow structures.

Studies on neotectonics carried out in Italy in the 1980s showed that these large landslides were induced by tectonic activity. Some of the landslide scarps are, in fact, connected with presumably active structures, i.e. fault scarp-walls connected with the neotectonic evolution of the Giudicarie System (Cavallin et al. 1997).

9.3 Landforms and Landscapes

9.3.1 Lavini di Marco

Along the left side of the mid-Adige Valley, south of the town of Rovereto, on the western slope of Mt. Zugna there are at least seven large to medium-sized landslide bodies (Orombelli and Sauro 1988). From north to south they are: the Corna Calda landslide, the Dosso Gardene landslide, the 772 m elevation landslide SSE of Grotta Damiano Chiesa, the Lavini di Marco landslide, the Costa Stenda landslide, the Marco landslide and the Varini landslide (Fig. 9.3). Out of these landslide bodies, the largest is the Lavini di Marco. It is also considered as one of the largest rock avalanches on the southern flank of the Eastern Alps (Martin et al. 2014).

This landslide or *Slavini* were mentioned by Dante Alighieri, the well-known Italian poet, who interpreted the Lavini di Marco deposits as the result of missing support (*sostegno manco*), perhaps related to an earthquake (*tremoto*).

> *Qual'è quella ruina che nel fianco*
> *di qua da Trento l'Adice percosse,*
> *o per tremoto o per sostegno manco,*
> *che da cima del monte, onde si mosse,*
> *al piano è sì la roccia discoscesa,*
> *ch'alcuna via darebbe a chi sù fosse*
>
> Just like that rockslide on this side of Trent
> That struck the flank of the Adige River
> Either by an earthquake or erosion
> Where, from the mountaintop it started down
> To the plain below, the boulders shattered so,
> For anyone above they formed a path
>
> *Inferno, XII, 4–9*

Towards the end of the 1980s, the Lavini di Marco became important also from the palaeontological viewpoint since numerous tracks of dinosaur footprints were found on the bedding surfaces (Fig. 9.4). Most of the footprints,

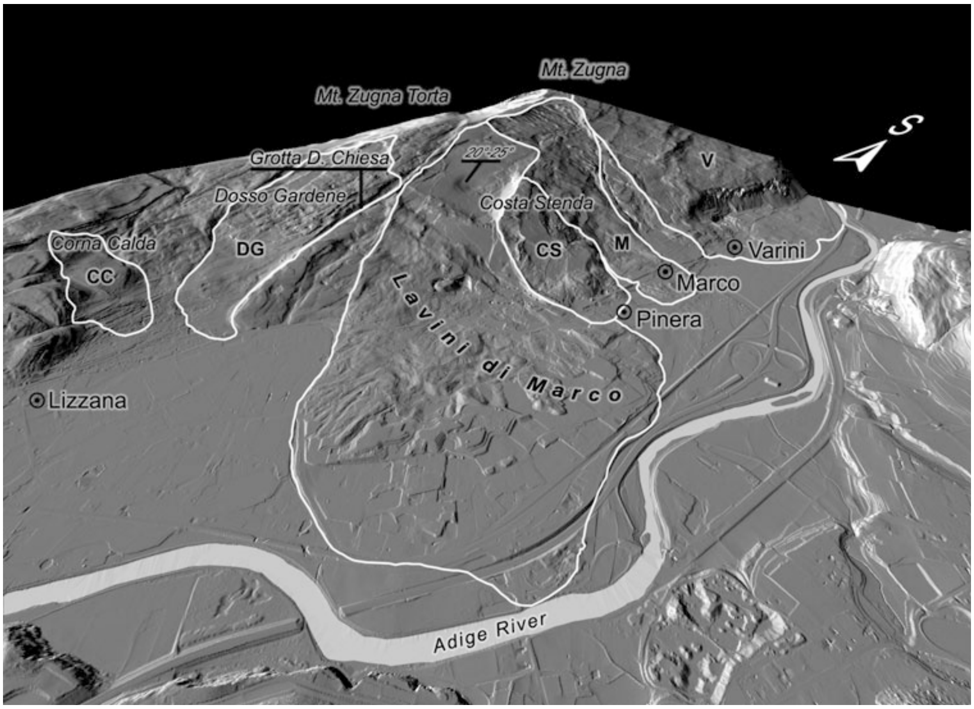

Fig. 9.3 Lidar image of the left-hand side of the Adige Valley south of Rovereto. The largest landslide deposit, known as Lavini di Marco, seems to have modified the river's course. Landslides: *CC* Corna Calda; *DG* Dosso Gardene; *CS* Costa Stenda; *M* Marco; *V* Varini (*elaboration* F. Ferrarese)

imprinted in the ancient beach mud, were left by carnivorous and herbivorous dinosaurs of very variable size. This ichnofauna is principally represented by *Grallator*, *Kayentapus*, *Anomoepus* and some *Parabrontopodus*-like ichnotaxa (Venzo 2000).

At Mt. Zugna Torta, the Calcari Grigi form a massif elongated in a N–S direction, with WNW dipping slopes, cut by several NW-trending faults belonging to the Schio-Vicenza system, one of the most active seismogenetic systems in Trento Province (Sauro and Zampieri 2001). The activity and deformation along the Schio-Vicenza fault system contributed to slope instabilities at Mt. Zugna Torta. Historical earthquakes are known in SW Trentino, in the Adige Valley, in Verona, in the adjacent Sarca Valley, Garda Lake area, and in the Venetian region (Martin et al. 2014).

Fig. 9.4 Lavini di Marco: tracks of dinosaur footprints. Ichnofauna is principally represented by *Grallator*, *Kayentapus*, *Anomoepus* and some *Parabrontopodus*-like ichnotaxa (*photo* R. Tomasoni)

The Lavini di Marco comprises Jurassic carbonate rocks of the Calcari Grigi that slid along a dip slope out onto the plain of the Adige River (Fig. 9.2). The whole complex can be subdivided into three, not everywhere well-defined parts: (i) a system of detachment scarps (ii) a series of slide planes and (iii) landslide deposits. The landslide is made up of a series of translational slides favoured by bed inclination, showing monocline 20–25° dip-downstream attitude. The detachment and slide surface correspond to wide bedding planes in several points (Fig. 9.5). They are slightly degraded, lacking soil cover, and sometimes covered by thin, discontinuous debris deposits. The extremely coherent dip of the bedding planes and the presence of numerous fractures, perpendicular to the bedding, caused sliding along clay-rich levels (Tommasi et al. 2009).

The deposit has a volume of $\sim 2 \times 10^8$ m^3 and covers an area of about 6.8 km^2. It is approximately 5 km long and 1.8 km wide, with a difference of elevation of 1030 m (Orombelli and Sauro 1988). The landslide deposits cover a wide area on the valley floor, as far as the Adige River. It has a defined contour, nearly always semicircular, with some minor lobes. At the surface it is made up of sharp coarse clasts and sometimes by large blocks up to tens or even hundreds of m^3. Flow and accumulation directions can be recognized thanks to the presence of ridges and depressions,

Fig. 9.5 Lavini di Marco landslide. The stratum surfaces along which sliding occurred are clearly visible. The landslide body is recognizable in the slope lower part (*photo* G. Carton)

ground undulations and radially, fan-arranged, discontinuous small swells, though these are not always evident.

In particular, the Lavini di Marco is composed of at least two different rock avalanche bodies; the main deposit known as Lavini di Marco (the principal) and the much smaller Costa Stenda deposit (Fig. 9.5). The latter overlies the Lavini di Marco deposits. According to Orombelli and Sauro (1988), these two lobes could have been generated at different times or be the result of a single event during which a rock spur within the landslide channel (Costa Stenda) might have divided the sliding material.

The age and origin of the Lavini di Marco deposits have been the focus of controversy for centuries, with age estimates ranging from the Last Interglacial to historic times. Over 20 years ago some buried soil levels in Lavini di Marco were dated and the different degree of development of karst corrosion forms was analyzed. Out of more than seven recognized landslide bodies, only the Dosso Gardene and Varini have radiocarbon dates. Orombelli and Sauro (1988) report a date of 5630 ± 80 ^{14}C years (6630–6290 cal years BP) from a soil buried by the Dosso Gardene rockslide, which is located just north of the Lavini di Marco deposits. Radiocarbon dates give a minimum age for the Dosso Gardene rock slide. Orombelli and Sauro (1988) report also an age of 1300 ± 100 ^{14}C years (1385–980 cal years BP) for a soil buried by the Varini slide, which is located just south of Lavini di Marco.

Recently many boulders in both the main Lavini di Marco and Costa Stenda deposits were sampled for ^{36}Cl surface exposure dating (Martin et al. 2014). Exposure ages range from 800 ± 210 to 21,310 ± 1000 years. The latter age stands as a notable outlier, suggesting that the Costa Stenda boulders were exposed for a considerable amount of time in the pre-slide bedrock.

The Lavini di Marco and Costa Stenda boulders' mean ages are 3000 ± 400 years. Although data are uncertain, the two slides seem to have been simultaneous. Significantly younger ages were obtained for the bedrock slide plane: 1600 ± 100 and 1400 ± 100 years, and for the head scarp: 800 ± 200 years (Martin et al. 2014).

9.3.2 Marocche di Dro

In the lower Sarca Valley, between Toblino Lake and Dro, there are numerous landslides of various sizes, known as the Marocche di Dro, which make up a complex rock and debris accumulation. Some make up small isolated ridges emerging from alluvial deposits. The largest one, the Marocca di Dro s.s. (also named as Marocca di Pietramurata) occupies the entire valley floor between Pietramurata and Trebi (Fig. 9.6).

Trener (1924) found a dozen diachronic landslides and mapped them as seven units in his geological map. In later studies, the various deposits identified by Trener were interpreted in different ways: as four morphological units were identified by Chinaglia (1992) and six units were recognized by Bassetti (1997). The reconstruction of the boundaries of the various landslide bodies is more evident for the more recent episodes, whereas it is more approximate for the older ones. In the valley stretch comprised between Dro and Pietramurata one of the main mass wasting events (Marocca di Dro s.s.) took place following the detachment of a huge slope portion from the Mt. Casale–Mt. Granzoline area. The deposits of this slope movement dammed most of

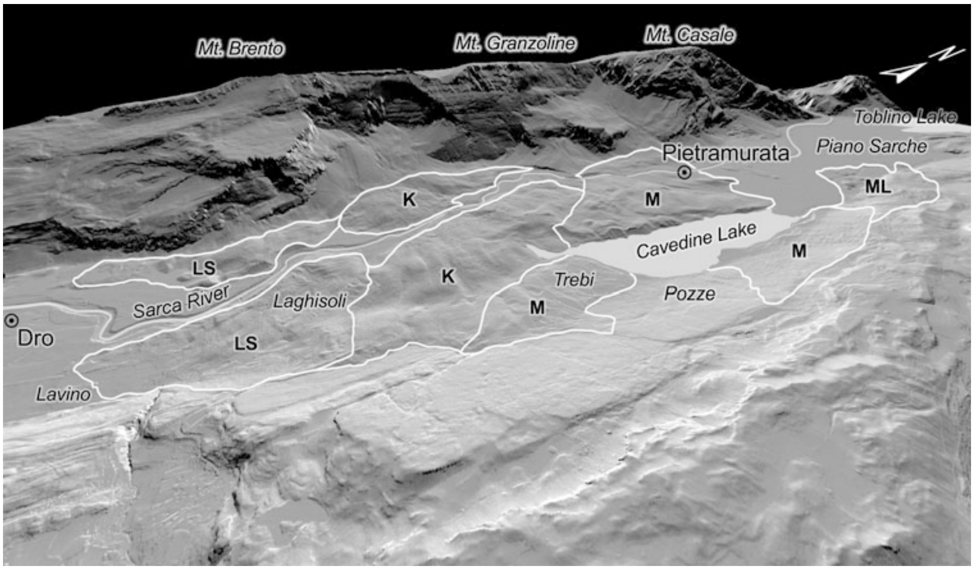

Fig. 9.6 Lidar image of the Sarca Valley, between Toblino Lake and Dro. On the right-hand side, between Mt. Brento and Mt. Casale, well-preserved large niches are present from which several landslide bodies have detached. Landslides: *M* Marocca di Dro s.s. (also named as Marocca di Pietramurata); *K* Kas; *LS* Laghisoli; *ML* Masi di Lasino (*elaboration* F. Ferrarese)

the valley floor, forced the Sarca River to shift its channel to the east, as far as the foot of the left-side slope, in correspondence with the present position of Cavedine Lake. Another mass wasting event, known as Kas landslide, occurred later on just downstream of the previous landslide body which was partially buried. A popular legend states that this landslide buried a village named Kas. The deposits coming from the area of Mt. Brento dammed the old channel of Sarca River for a long distance, among the hamlets of Laghisoli, Trebi and Pozze. Following the landslide, a large impoundment was formed which today corresponds to Cavedine Lake (Figs. 9.6 and 9.7). The Kas landslide, in turn, overlapped an older landslide body which now crops out discontinuously. Its original accumulation area is now mostly covered by the Sarca River alluvial deposits. It seems therefore plausible that this is the oldest landslide deposit concealing a valley floor at an altitude lower than the present one (Chinaglia 1992). The Marocche di Dro stretch over an area exceeding 13 km^2, with maximum length of about 5 km between the main scarp and the toe, width of 3.5 km and a difference in elevation of 1250 m (Fig. 9.8). The estimated volume is over 10^9 m^3 (Bassetti 1997). The clasts are all carbonate, large to medium in size, attaining in some cases even 500 m^3 (Kas landslide). The huge crown area from which the rock mass detached (Mt. Casale–Mt. Brento) is set along a tectonic scarp associated with a reverse fault. It appears controlled by discontinuity surfaces often corresponding to sub-vertical fault planes. On most of the landslide body there are structures which seem to point to a single provenance from the main scarp, with material deposited also on the opposite slope up to 200 m from the valley floor. Chronological information can provide this set of landslides with a temporal framework. Trener (1924) reported that during the excavation of an offtake tunnel near Laghisoli a Roman artefact was found. The datum was confirmed by a subsequent finding of Roman artefacts made up of brick fragments associated with an alluvial soil which was involved in the landslide and was rich in coal fragments (Bassetti 1997). These fragments were later subject to two radiocarbon dating analyses which produced ages of ^{14}C 2248 ± 42 years BP (2152–2344 cal years BP) and ^{14}C 2249 ± 39 years BP (2153–2344 cal years BP), respectively. The most ancient landslide accumulation material was identified in the Marocca di Dro s.s. thanks to ^{14}C dating of charcoal fragments found at the top of a buried soil level (Bassetti and Borsato 2007). It produced an age of ^{14}C 4171 ± 41 years BP (4576–4836 cal years BP). Near Pietramurata, lamellibranchiate shells were found. They produced a ^{14}C age of 3081–2998 cal years BP (Castellarin et al. 2005b).

In addition, morphological investigations were carried out concerning the effects of karst corrosion on the block surfaces and the formation of soil. The development of karst microforms is substantially homogeneous and does not appear significant for a definition of the relative age of the various landslide deposits. This seems to indicate a rather recent, maximum proto-historic age to this landslide. Similar conclusions are reached by examining the development of soils.

In the light of knowledge acquired so far, a chronological reconstruction of the most evident and most important events which took place in the lower Sarca Valley can be synthesized as follows. The Marocca di Dro s.s. seems to predate the deposition of other landslides and chronologically follows the last Ice Age since it involved late glacial deposits in its movement. The deposition of the Kas landslide—the most recent one—barred the Sarca River and formed a large lake stretching to the north over the present Toblino Lake.

Fig. 9.7 The Sarca Valley from north to south. In the *foreground* the Toblino Lake. The completely vegetated ridge at the *centre* of the photograph belongs to the landslide deposits of Marocche di Dro and generated the Cavedine barrier lake. On the *right* the long scarp between Mt. Casale and Mt. Brento, from which rock falls and slides originated, is visible (*photo* R. Tomasoni)

Fig. 9.8 The complex wide landslide body of Marocche di Dro. The landslide huge detachment zone is set along a tectonic scarp controlled by discontinuity surfaces often corresponding to sub-vertical fault planes (*photo* R. Tomasoni)

9.3.3 Marocche di Molveno

The Marocche di Molveno are located south of the lake bearing the same name, which formed due to the damming of the valley. The valley hosting the Marocche di Molveno has an asymmetrical profile, with an extremely steep western slope affected by scarp-fault-surfaces and an eastern one descending gradually along a structural slope, with slope gradient corresponding to the attitude of the stratified formations.

The landslide deposits occupy a total surface of about 6 km^2, stretching for a maximum length of about 4 km, a width of 2.7 km and a difference of altitude of about 1000 m, between 1600 and 550 m (Fuganti 1968–1969). They are made up of blocks overlying massive diamicton deposits within a finer matrix. It is possible to observe arcuate concentric features within the deposit showing different orientations. They seem to be related to different areas of provenance or could be from complex movements of the displaced materials during deposition.

The collapsed material detached from the right-hand side of the valley which corresponds to a tectonic scarp made up of the Mesozoic carbonate sequence overlying Eocene limestone. Some hundreds of metres upstream of the landslide crown, the slope is displaced by reverse slope scarp a few metres high and 1 km long. Landslide crowns are present also on the left-hand side of the valley within a monocline structure. Nevertheless, their smaller dimensions make them much less evident from the geomorphological standpoint. For this reason, it is not sure whether the landslide body is made up of a single unit of material coming from the same detachment scarp or not. In the recent Geological Map of Italy at the 1:50,000 scale (Castellarin et al. 2005a), the Marocche di Molveno are still interpreted as a single landslide body. The recognition of different landslide bodies is rather problematic owing to the homogeneity of the rock types involved, since the rock falls were developed within the same Jurassic stratigraphic units. A possible distinction of various landslide bodies must therefore be based upon morphological considerations, since no absolute dating is available.

On the basis of these remarks, Chinaglia (1992) proposed a subdivision of the Marocche di Molveno into four separate units. The Marocca di Pian delle Graone seems to have originated from a head scarp on the left-hand side of the valley, NW of Mt. Ranzo (Fig. 9.9). It seems to have been formed by a translational slide on a W-dipping bedding surface of 30°. The largest accumulation (350 million m^3) is found at Marocca delle Moline. This landslide deposit is overlapped by Marocca di Nembia, which occupies the central part of the valley (Fig. 9.9). These two latest landslide events originated within the great head scarps present on the western side of the valley and have developed in correspondence with two families of NW–SE and NE–SW oriented vertical tectonic discontinuities. Finally, the Marocca di Doss della Croce is found at the southernmost end of the area, still on the left-hand side of the valley, in correspondence with the ridge bearing the same name.

This set of landslides was investigated following the introduction of hydroelectric power generated from Molveno Lake. In the autumn of 1951, the reservoir was almost completely depleted, and its original surface reduced from 3.27 km^2 to just 0.138 km^2 (Marchesoni 1958). This intervention revealed the remains of a forest on the lake bottom. The state of preservation of the remains of the ancient forest was identical, confirming that the lake had been created by a single landslide. Nevertheless, this does not exclude that Marocche di Molveno might have been formed by several events, even subsequent to lake formation.

If we admit that Marocche di Molveno was produced by the overlapping of several landslides, then the oldest one should be Marocca del Pian delle Graone (Fig. 9.10). The presence of superficial karst forms found on the

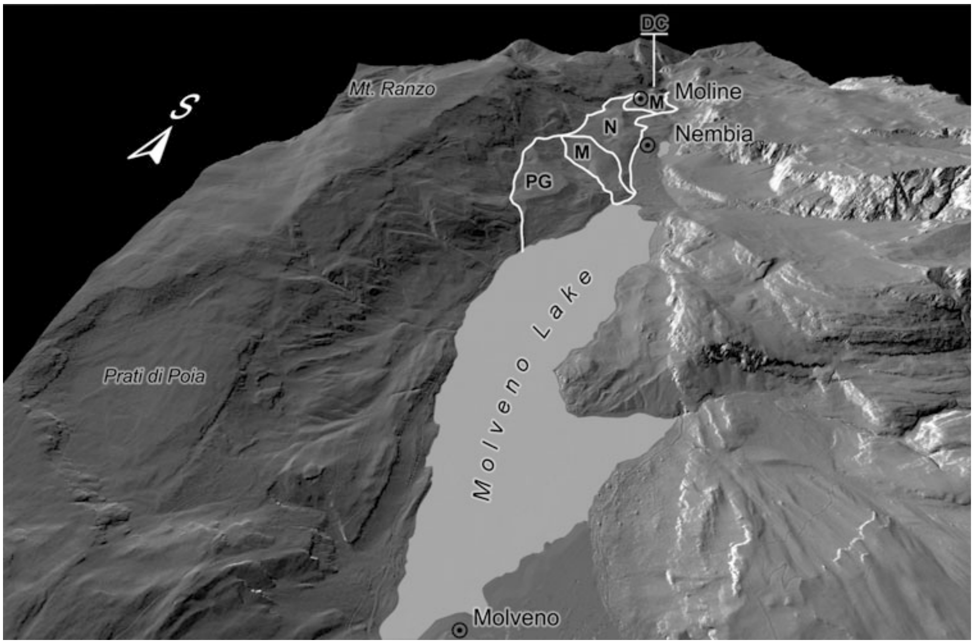

Fig. 9.9 Lidar image of the Molveno Lake area. The left-hand slope shows numerous detachment niches with their relative landslide bodies at the foot. Landslides: *PG* Pian delle Graone; *M* Moline; *N* Nembia; *DC* Dosso della Croce (*elaboration* F. Ferrarese)

Fig. 9.10 Molveno Lake and the host valley. Some frontal damming is evident in the *background*. In the *foreground*, the village of Molveno. Landslides: *PG* Pian delle Graone; *M* Moline (*photo* A. Carton)

boulders below the lake level indicates that this episode was not responsible for the formation of Molveno Lake (Chinaglia 1992) or, at least, that it was responsible only partially. Subsequently, Marocca delle Moline dammed the valley floor completely, leading to the formation of Molveno Lake. Marocca di Nembia and Marocca del Dosso della Croce seem to represent the last mass wasting episodes.

From the chronological viewpoint, the first information came as early as the 1950s from the study of a buried forest. The dominant presence of beech (*Fagus sylvatica*) in the ancient Molveno forest excluded any dating preceding the second millennium BC. In fact, the numerous peat deposits studied in Trentino showed that beech was the last tree species to colonize this area. A definitely more significant chronological datum for Marocche di Molveno is given by the ^{14}C dating carried out on a tree trunk found at a depth of 32 m in the landslide (Marocca delle Moline or Marocca di Nembia?). The ^{14}C radiometric dating obtained is 2908 ± 153 years BP. That means that the landslide which created the lake took place some 1000–800 years BC (Marchesoni 1958). According to the same author, this date would also be confirmed by findings of charcoal and artefacts compatible with the Iron Age. Therefore, these finds show the existence of a human settlement which was abandoned once the lake formed.

9.4 Conclusions

Landslide accumulation features known as Marocche are a typical morphological unit of the Alps and, in particular, of western Trentino where a large number of them can be observed. Today the old interpretations implying their origin associated with glacier decay cannot be accepted because the largest landslides are far more recent than the Late-glacial.

Studies on neotectonics showed that these large landslides were induced by tectonic activity. Some of the landslide scarps follow presumably active structures. Among the tectonic scarps found in this area, it is possible to identify "fault scarp-walls" connected to the neotectonic evolution of the Schio-Vicenza fault system and Giudicarie System.

Besides the complex geological and geomorphological vicissitudes which have generated these vast landslides, the marocche of Trentino make up typical and unique landscapes. The Marocche di Dro, for example, are one of the largest landslide deposits of the Italian Alps. The landslide features have not been obliterated by subsequent degradation processes and vegetation has colonized them only in part, so that they are still perfectly visible. Owing to their educational value as models of landslide evolution, palaeogeographical evidence, scientific and ecological importance, the three sites described here have been placed among the Trentino geomorphosites (Carton et al. 2005). As such, they are protected and listed in the inventory of unchangeable assets of the Town Planning Scheme of the Trento Province. Thanks to this conservation bill, the Province's Councillorship for Urban Planning and the Environment can preserve and enrich the distinctive features of these permanent and irreplaceable elements, which are strictly and durably linked with their own environment and territory, as well as with the community living in this area. In addition, the Lavini di Marco and Marocche di Dro are two biotopes whose value, thanks also to the presence of dinosaur footprints, has been further enhanced through the setting of nature trails, production of illustration pamphlets and guided tours.

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10

The Dolomite Landscape of the Alta Badia (Northeastern Alps): A Remarkable Record of Geological and Geomorphological History

Mauro Marchetti, Alessandro Ghinoi, and Mauro Soldati

Abstract

The Alta Badia (Eastern Dolomites) well synthetizes the remarkable geological and geomorphological features that enabled the Dolomites to be inscribed in the UNESCO World Heritage List. Spectacular dolomite mountain groups, built up during the Triassic in coral-reef and tidal-plain environments, stand out of mild slopes made up of clayey terrains deposited in deep inter-reef basins. The landscape is characterized by pale-coloured dolomite cliffs, towers and pinnacles rising above wide talus deposits and gentle grassy foothills witnessing a complex geomorphological long-term evolution. Pleistocene glaciers profoundly shaped the valleys and, at their retreat, periglacial and gravity-induced processes had a major role in slope modelling. Landslides have affected the valleys since the Lateglacial leaving a clear inprint on the landscape, as well as Man in recent times.

Keywords

Alpine landscape • Structural landforms • Glacial landforms • Landslides • Dolomites

10.1 Introduction

The Italian Dolomites are universally known for their scenic beauty and scientific interest. They are the quintessence of the 'dolomite landscape' worldwide and make up a unique geomorphological environment on Earth which was recognized by UNESCO as a World Heritage Site in 2009 (Gianolla et al. 2009; Soldati 2010).

Long-term complex geological events and Quaternary glacial advances have deeply influenced the modelling of the spectacular landscapes and landforms of this region. Majestic mountains separated by deep valleys are the remains of an ancient seabed and of reefs formed in a tropical sea due to the activity of algae, sponges and corals about 200 millions years ago. These structures were born due to long-term sedimentation associated to alternating sinking and rising of the seabed, which determined the development of very thick sequences of dolomites, finally lifted up to over 3000 m by tectonic forces.

Travellers and artists have visited the Dolomites since the eighteenth century, and described the landscape as the 'Pale Mountains' or 'Reign of Titans', which has been highly appreciated since then for its aesthetic value. The Dolomites are actually named after Déodat de Dolomieu (1750–1801), a French nobleman and scientist who discovered during his travel to Italy a 'strange calcareous stone' that did not react with acids. Thanks to the help of Nicolas de Saussure, a Swiss chemist, he realized that the rock consisted of a yet unknown mineral, which was then named 'dolomite' in honour of de Dolomieu himself.

The Alta Badia (Upper Badia Valley, Eastern Dolomites) represents an outstanding example of this dolomite landscape being characterized by high dolomite cliffs, pale-coloured rocky towers and pinnacles which rise from green gentle slopes made up of softer rocks, testifying to long-term and fascinating geomorphological evolution (Fig. 10.1).

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Fig. 10.1 Panoramic view of the Alta Badia from the Conturines group. In the background the Sella (*left*) and Gardenaccia (*right*) dolomite mountain groups are visible. In the foreground stands the Pralongià plateau at the bottom of which the villages of San Cassiano (*left*) and La Villa (*right*) are located (*photo* F. Planinschek, courtesy of Tourist Board Alta Badia)

A distinctive, spectacular geomorphological feature, common to many parts of the Dolomites, is the intersection of horizontal layers formed on the paleo-Thetys seabed and vertical fissures related to the endogenous forces which uplifted these mountains due to the collision between the Eurasian and African plates. Differential erosion has shaped the bedrock, producing a peculiar landscape, where high vertical dolomite cliffs that linked to gentle terrain underlain by clayey bedrock via ample cone and festoon-shaped debris deposits (Fig. 10.2). An added quality to the scenic value of the Dolomite cliffs is the famous phenomenon of intense colouring assumed by the rocky cliffs at sunrise and dusk ('Enrosadira' in the local Ladinian language, literally 'becoming pink').

The mountains of Alta Badia are included in two of the nine systems making up the UNESCO World Heritage Property (no. 5 Northern Dolomites, Sett Sass; no. 6 Puez-Odle). It should be emphasized that the inscription of the Dolomites on the World Heritage List is based on the recognition that the Dolomites show 'superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance' (Criterion vii) and 'outstanding examples representing major stages of Earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic feature' (Criterion viii) (Gianolla et al. 2009).

The Alta Badia is a privileged destination for winter and summer tourism. Beside the pristine areas of the mountain groups, which are part of the UNESCO property, a dense and interconnected network of ski-runs and rope ways has been developed thanks to the pioneering vision of Franz Kostner, who first opened the valley to the winter sports in 1930. He built the first sledge-track in Italy near the village of Corvara. During summer, visitors can take advantage of the numerous hiking paths and biking routes to reach any part of the valley and experience its unique landscapes.

10.2 Geographic Setting

Entirely within the Adige River basin, the Alta Badia lies in the Southeastern Alps, mainly within the Autonomous Province of Bolzano (South Tyrol) and only in a small sector in the Veneto Region (Fig. 10.3).

Fig. 10.2 The spectacular dolomite cliffs of the western side of the Conturines mountain group (*photo* C. Soldati)

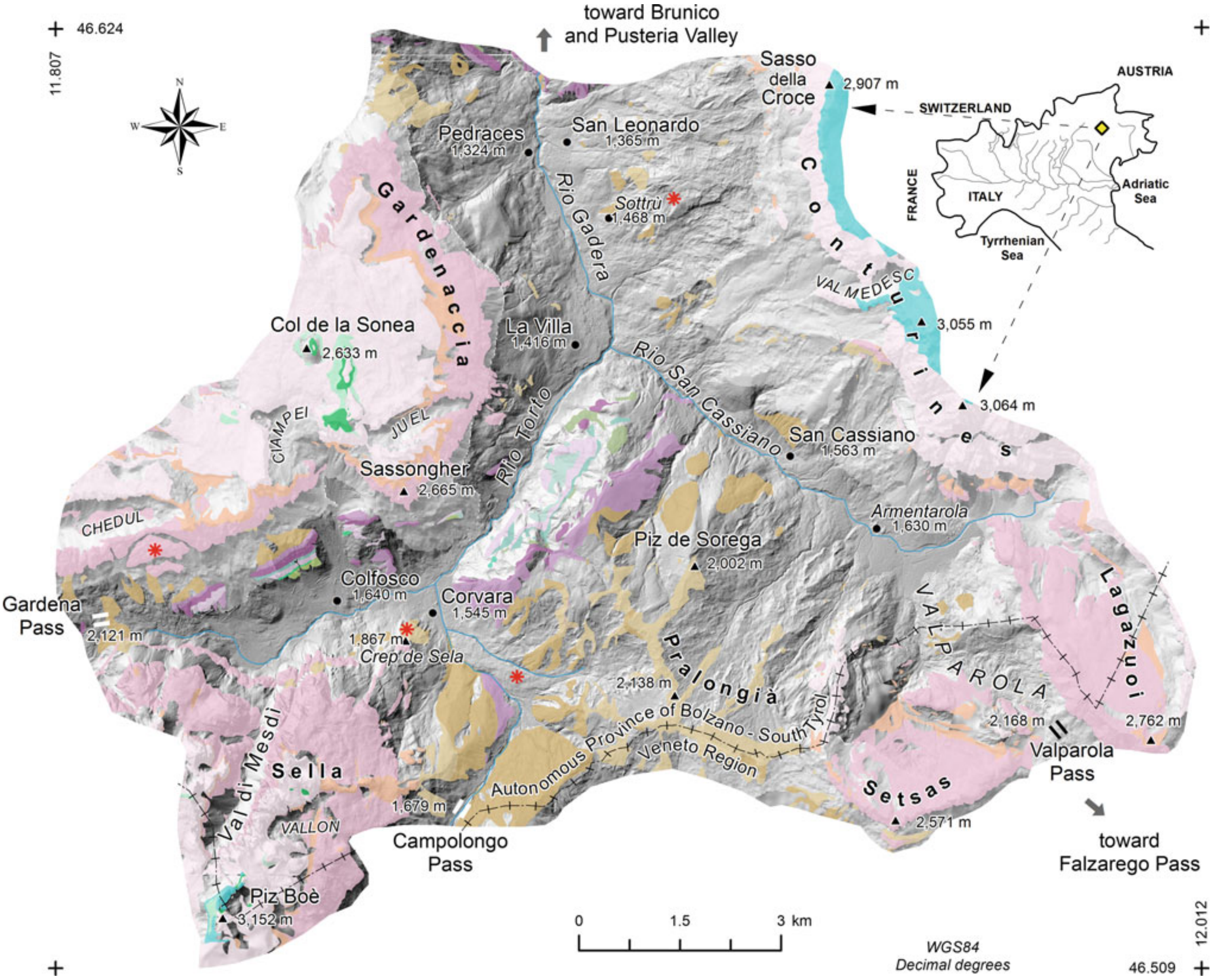

Fig. 10.3 Geographic and geological setting of the Alta Badia. Colours correspond to those used in the stratigraphic scheme of Fig. 10.4. *Red marks* refer to the landslides shown in Fig. 10.10. LiDAR data courtesy of Servizio cartografia provinciale e coordinamento geodati, Autonomous Province of Bolzano

The Badia Valley is part of the land of the Ladinians, a people that shares very old culture with roots back to almost 2000 years ago when the Rhaetians intermingled with the Roman conquerors. The latter had a strong influence on the Rhaetian language and, consequently, on the birth of the Ladinian language. After the collapse of the Roman Empire, the valley was subject to the ever growing political and cultural influence of the Germans that created a common sense of identity, even reinforced during and after the Napoleon's invasion. After the peace treaty of Vienna (1809), the Ladinian region was separated between the Napoleonic reigns of Bavaria (Gardena and Badia valleys) and Italy (Ampezzo, Fassa and Livinallongo valleys). After the Vienna Congress (1815), the Ladinian valleys and the whole South Tyrol became part of the Austrian-Hungarian Empire. At the end of the First World War (1918), the Badia Valley became part of the Italian Kingdom along with the whole South Tyrol.

Alta Badia can be reached through the Gardena Pass (2121 m a.s.l.) from the west, the Campolongo Pass (1679 m) from the southwest, the Valparola Pass (2168 m) from the southeast and from Brunico in the north, along the Rio Gadera. It is surrounded by spectacular dolomite mountain groups, such as Sella (reaching the highest elevation of the valley at Piz Boè, 3152 m), Puez (3025 m) and Conturines (3064 m). Along the three main water courses (Rio Torto, Rio San Cassiano and Rio Gadera), which trace a distinctive upside-down 'Y', the main villages are located, namely Colfosco (1640 m), Corvara (1560 m), San Cassiano (1540 m), La Villa (1420 m) and Pedraces (1325 m). These villages relied on a subsistence economy based on pasture, agriculture and handicraft until the 1950s, and only since then have undergone a continuous and well-governed urban expansion, thanks to the exploitation of the surrounding landscape especially for winter tourism.

Climate is typically alpine; it shows a mean annual precipitation of some 950 mm, with peaks in the summer months. The mean annual air temperature is around 5 °C with a mean monthly minimum in January (−4.9 °C) and a mean monthly maximum in July (15 °C).

10.3 Geological History

The Dolomites are a key area worldwide for the study of the Triassic history. In fact, the geological record from the Triassic is outstanding for the high sedimentation rates, remarkable variety of depositional environments and rich fossiliferous heritage. Subsidence and uplift events controlled the development of a series of carbonate platforms, surrounded by deep water basins, which from time to time were filled by volcanic, volcaniclastic and terrigenous sediments (Gianolla et al. 2009).

The geological record of the Alta Badia mainly includes the Triassic, though older rocks outcropping in the area testify to geological processes occurring back in the Upper Permian when the sea occupied this region for the first time after the Hercynian orogeny (Figs. 10.3 and 10.4; Bosellini et al. 2003; Brandner et al. 2007).

The Triassic sequence started with the growth of the first calcareous platforms in the area (Contrin Formation, Upper Anisian) around which basin sediments were deposited. The volcanic activity which occurred during the Upper Ladinian, when the Dolomites were part of the major volcanic district of Europe, produced pillow lavas and tuffs belonging to the so-called Fernazza Group, whose outcrops can be observed between Colfosco and La Villa. Contemporaneous with the volcanic activity, a highly subsiding area developed, creating a deep basin where thick sediment sequences made up of silty-arenaceous and claystone alternations deposited (Wengen Formation, Upper Ladinian); these mainly derived from the erosion of volcanic edifices located to the west. In the Alta Badia, these terrains crop out in the middle and lower parts of the slopes. From the end of the Ladinian to the Lower Carnian subsidence almost stopped, volcanic activity ended and a tropical shallow-sea environment allowed the growth of fringing reefs. The carbonate platforms representing this depositional environment refer to the so-called Sciliar Group (including Dolomia Cassiana, Lower Carnian) which makes up the basal portion of the Sella and Gardenaccia mountain groups and entirely composes the Setsas and Lagazuoi mounts. The surrounding basins were simultaneously filled by mainly fine sediments, giving origin to alternation of marls, marly limestones and calcareous marls (San Cassiano Formation, Upper Ladinian–Lower Carnian). These form the medium parts of most slopes and the upper part of the Pralongià plateau.

During the Carnian, the sea level dropped and the evolution of the carbonate platforms stopped, allowing for the deposition of carbonate and terrigenous sediments of the so-called Raibl Group, characterized by a typical alternation of colourful marls and argillaceous schists (Pordoi, Heiligkreuz and Travenanzes formations, Carnian) which often morphologically mark the transition between the cliffs of the Dolomia Cassiana and Dolomia Principale. The latter was formed during the Upper Carnian and Norian in a tidal flat environment; thanks to the continuous subsidence it reached remarkable thickness, up to 500 m in Alta Badia as seen in the Sella, Gardenaccia and Conturines mountain groups. At the end of the Triassic there was a remarkable change of the geological environment due to the deepening of the sea, and deposition of limestones took place during the Jurassic. The

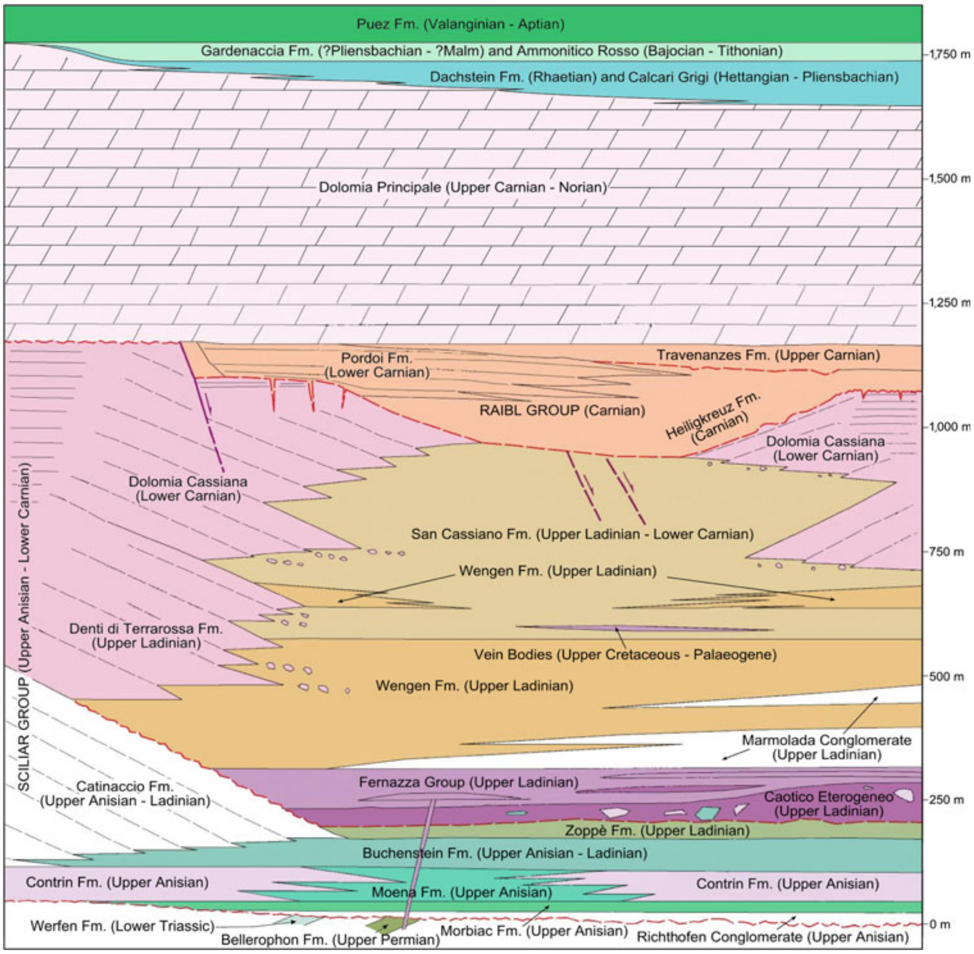

Fig. 10.4 Stratigraphic scheme of the geological sequence characterizing the Alta Badia and surrounding areas (Triassic—Lower Cretaceous). The dolomite formations are *rose*-coloured. The formations depicted in *white* are not outcropping in the Alta Badia

larger outcrops of this upper part of the sequence occur on the top of the Conturines mountain group (Dachstein Limestone and Calcari Grigi, Rhaetian-Pliensbachian), whilst more restricted outcrops can be found in the Sella and Gardenaccia mountain groups (Gardenaccia Formation, Ammonitico Rosso, Pliensbachian-Tithonian), together with the terrigenous sediments of the Lower Cretaceous (Puez Formation, Valanginian-Aptian) which close the depositional sequence of the area, preluding the onset of the Alpine orogeny.

From the tectonic viewpoint, the Dolomite region derived from the Tertiary shortening of a Mesozoic passive continental margin of the Tethys Ocean (Doglioni 1987; Doglioni and Carminati 2008). The Triassic and Jurassic periods were characterized by extensive tectonics that produced a horst-graben morphology with strong control on sedimentation. The Mesoalpine compressive phase (Eocene-Oligocene) was responsible for the origin of W- and SSW-verging thrusts which determined the overlapping of Upper Triassic to Cretaceous rocks on Cretaceous marls witnessed by isolated summits known as *Gipfelfaltungen* (summit overthrusts). Spectacular evidence of this tectonic process is the peaks of Piz Boè on the Sella group, and Col de Puez and Col de la Sonea on the Gardenaccia plateau. However, only 20 million years ago (early Miocene) the Dolomite region started emerging from the sea, during the Neoalpine compressive phase that caused a S-verging thrusting and folding of the region. During this phase a doubling of the stratigraphic sequence took place, giving origin to impressive dolomite massifs and cliffs such as those making the south-facing slopes of the Conturines group (Fig. 10.2). Since the emersion from the sea, the continuous and still ongoing uplift has raised the former coral reefs up to more than 3000 m.

10.4 Landscape and Landforms

Since the Upper Miocene, when the Dolomites emerged from the sea, terrestrial processes started shaping the uplifting rock masses which were at the same time subject to compressive tectonic forces responsible for their intense folding, thrusting and cracking. Meteoric water, weathering, gravity-induced processes and, during the Quaternary, repeated glaciations contributed to model the outstanding landscape that we can observe today. Valleys formed in weak rocks or along the major tectonic lines. In contrast, imposing mountain groups bounded by vertical cliffs correspond to the former coral reefs and massive calcareous platforms. This landscape was formed through different processes and following different rhythms, in connection with differential erosion, tectonics and climate changes. The resulting intense contrast between the light-coloured dolomite cliffs and the dark basin sediments enhances both the aesthetic appeal and scientific relevance of the Alta Badia landscape.

10.4.1 Structural Landforms

Tectonics repeatedly deformed and dismembered the original geological sequence and provided remarkable structural landforms.

Tectonic elements such as thrusts, faults and folds control the direction of valleys—as is the case of the northern Alta Badia N-S-oriented valley stretch, the San Cassiano valley and the Val di Mesdì—and have favoured the formation of saddles such as at Gardena Pass and Valparola Pass. Where tectonic elements are closely spaced, the cracking of the dolomite rocks favoured increased erosion giving rise to spectacular vertical features such as towers, pinnacles, spires and jagged crest lines which contrast with the sub-horizontal dolomite plateaus mentioned above. Inclined structural slopes can also be found, such as at Setsas mountain, where the north-facing slope shows a mild inclination with an angle equal to the slope and the south-facing slope being sub-vertical. These crossing lines provide the Alta Badia mountains with infinite shapes that are the true secret of the appeal of this region (Fig. 10.5).

Where ductile rocks are intercalated with the brittle ones, differential erosion has produced typical belts named *cengie* (ledges) that represent evident breaks in the vertical profile of dolomite cliffs and distinctive traits of mountain massifs such as the Sella group (Fig. 10.6). From a morphological viewpoint, the *cengia* is a lower inclined surface developed where the pelitic rocks of the Raibl Group are interposed between the vertical cliffs of Dolomia Cassiana and Dolomia Principale. The *cengia* is normally covered by scree deposits.

10.4.2 Glacial Landforms

During the Pleistocene, the Alta Badia was repeatedly occupied by glaciers that left a clear imprint in the area. The glacial heritage is related to the Alpine Last Glacial Maximum (LGM, 27,000–18,000 years BP; Monegato et al. 2007; Ravazzi et al. 2014) and to the subsequent Lateglacial phases. During the major glacial advances, including the LGM, ice masses reached the valley from the north, moving upstream from the Pusteria Valley. This is proved by allochtonous metamorphic and granitic clasts found within glacial deposits in the Alta Badia. Small metamorphic clasts recently found at the Gardena Pass (Fig. 10.7) lead to hypothesize also a secondary ice contribution from the west, that is from the Adige basin, through the Gardena Valley (Panizza et al. 2011).

Fig. 10.5 A close up of the Gardenaccia mountain group from the Pralongià plateau. In the *centre* the Sassongher tower which dominates the village of Corvara

Fig. 10.6 The typical 'cengia' (ledge) on the Sella group located between Dolomia Principale (*above*) and Dolomia Cassiana (*below*) in correspondence to the softer Pordoi Formation

Glaciers during the LGM were covering the whole Alta Badia up to some 2300 m a.s.l., with a maximum thickness of 900–1000 m. Therefore, only the highest peaks were jutting out of this sea of ice, though local high-altitude glaciers occurred at the top of the mountain groups (Fig. 10.8a).

The ice masses coming from the Pusteria Valley are likely to have overflowed the Valparola Pass in the eastern sector of the Alta Badia and the Campolongo Pass to the south. It should be emphasized that the whole Pralongià plateau was covered by ice during the LGM. Scattered dolomite erratic blocks can be found on its top, witnessing glacial transport since no dolomite rocks crop out there. Among LGM landforms, worth of notice are two parallel moraine ridges located at an altitude between 2000 and 2200 m on the right hand-side of the valley at the base of the dolomite cliffs overhanging the village of San Leonardo.

During the Lateglacial (18,000–11,600 years BP), once disappeared the LGM ice cap, the ice flow started its northward movement in the form of valley glaciers whose source areas were in correspondence of the Lagazuoi, Setsas and Sella groups. During this period, the Pralongià plateau was progressively left free of ice as witnessed by the dating of a charcoal sample found near Piz de Sorega, at an altitude of 1937 m. This sample was dated back to 16,610 BP (Panizza et al. 2011).

During the Lateglacial, the valley glaciers were responsible for the deposition of frontal and lateral moraines of limited height which can still be identified, especially in the southeastern sector of the Alta Badia, e.g. in the San Cassiano valley, though they were also here largely erased by subsequent erosional processes and landslides (Fig. 10.8b). Nevertheless, remnants of Lateglacial lateral moraines can be found at Pedraces and upstream La Villa, whilst quite well preserved frontal moraines can be observed in the San Cassiano valley, at Armentarola, as well as in Valparola and in the Setsas and Lagazuoi groups. These landforms testify

Fig. 10.7 The Gardena Pass seen from the Pralongià plateau. On the *left* the northern cliffs of the Sella group and on the *right* the southern cliffs of the Gardenaccia group. During the LGM, glaciers were flowing over the pass from the Gardena valley toward the Alta Badia

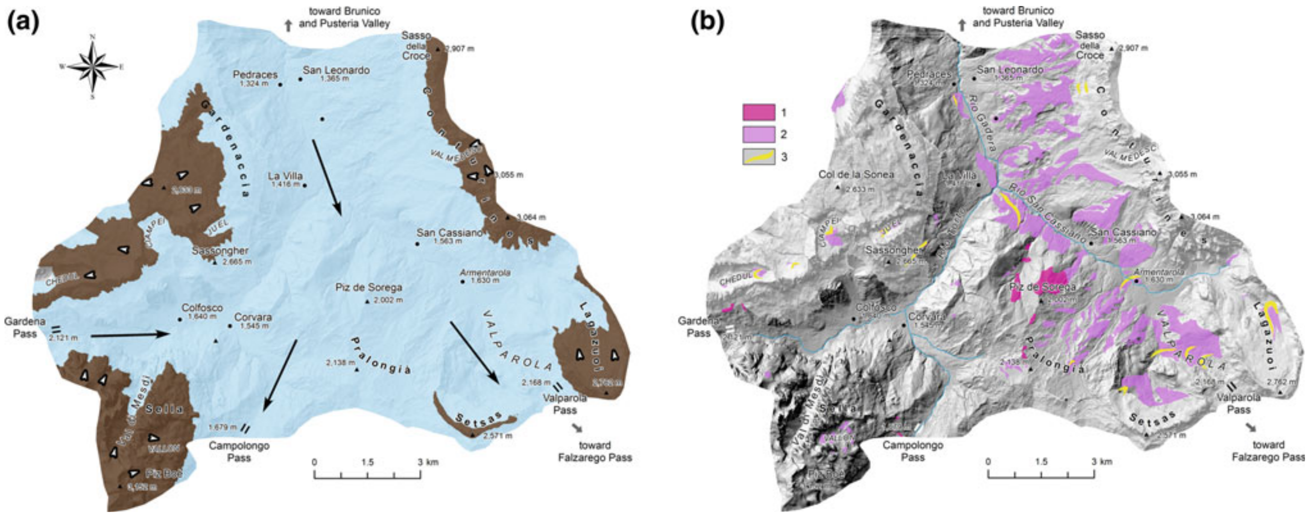

Fig. 10.8 Glacial features in the Alta Badia. **a** Ice cover during the Lastglacial Maximum; **b** moraines and glacial deposits in the area: *1* LGM deposits; *2* Lateglacial deposits; *3* Moraine ridges. LiDAR data courtesy of Servizio cartografia provinciale e coordinamento geodati, Autonomous Province of Bolzano

Fig. 10.9 The Marmolada glacier seen from Lagazuoi. In the foreground Col di Lana whose concave shape is related to a blasting occurred during the First World War. The *dark crests* consist of volcanic rocks, whilst Mt. Marmolada is made up of limestones

to glacial advances which are likely to have occurred during a general period of glacier withdrawal within the Oldest Dryas (namely, the Gschnitz and the Clavadel/Sanders stadials, *ca.* between 17,000 and 16,000 years BP), as per comparison with other Alpine valleys (cf. Ivy-Ochs et al. 2008). Moraines ascribable to younger Lateglacial stadials were not found in the Alta Badia, therefore it is possible that, after the Bølling-Allerød warmer phase, ice accumulation in the area in the Younger Dryas (12,900–11,600 years BP) was not sufficient to build new glacier tongues.

Glacial erosional landforms, in particular glacial cirques, are well preserved within the main mountain groups of the Alta Badia. They were shaped both during the LGM, when the highest parts of the main groups were emerging from the ice cap, and later on, during the Lateglacial, when they corresponded to source areas of valley or local glaciers. Spectacular examples can be found on the main mountain groups, such as on the western and southeastern margins of Gardenaccia (Chedul, Ciampei, Juel cirques), at Conturines (e.g. Val Medesc cirque), on the north facing side of Lagazuoi (e.g. Lagazuoi cirque), and on Sella (e.g. Vallon cirque).

Nowadays no glaciers are present in the Alta Badia. Nevertheless, from many parts of the area the largest glacier of the Eastern Italian Alps can be admired, that is the Marmolada Glacier (Fig. 10.9), which is located ca 12.5 km south of Corvara.

10.4.3 Periglacial Landforms

During the Lateglacial, periglacial processes became increasingly important and led to the origin of evident landforms, especially in the upper parts of the valley, at the base of the dolomite cliffs and on the top of the mountain groups.

Frost shattering processes caused detachment of debris from the dolomite cliffs, which contributed to the building-up of remarkable scree slopes and talus cones (Fig. 10.5). The size and distribution of the latter vary, depending principally on the jointing of the rock masses and secondarily on slope aspect.

At the base of the dolomite cliffs protalus ramparts can be found, mainly within the glacial cirques described above. Protalus ramparts in the Alta Badia are generally inactive, except for that of Piz Boè (2900 m). This demonstrates that at present snow and ice tend to have a lower persistence on the ground than in the past.

Two rock glaciers can be found in Alta Badia. An active one is located northwest of Piz Boè at an elevation of 2900–3000 m, showing high slope angles of frontal and lateral flanks. In turn, an inactive tongue-like shape rock glacier can be observed in the vicinity of the Valparola Pass at an elevation of 2100–2250 m; it consists of large dolomite blocks which are likely to have been detached from the south-western side of Lagazuoi and accumulated on an ancient glacier or ice field.

10.4.4 Landslides

Landslides of different type and size characterize the landscape of the Alta Badia and make up the most common and widespread Quaternary deposits in the area. Slope instability processes, developed soon after the retreat of glaciers from the valleys, are responsible also for erosion, remobilization and burying of glacial landforms and deposits (Soldati et al. 2004; Borgatti et al. 2006; Borgatti and Soldati 2010). The first phase of marked slope instability occurred in the Preboreal and Boreal (about 11,500–8500 years BP) which was characterized by large-scale translational rock slides affecting the dolomite rock masses (e.g. Passo Gardena landslide; Fig. 10.10a) and earth slides and flows affecting the underlying pelitic formations (e.g. Corvara landslide; Fig. 10.10 b). The latter are likely to have been favoured by high groundwater levels due to an increase in precipitation and/or permafrost melting. A second cluster of landslide events has been recognized during the Sub-Boreal (about 5800–2000 years BP), when mainly rotational slides and/or flows occurred. Many of the events dated can be considered as

Fig. 10.10 Landslides in the Alta Badia: **a** Passo Gardena landslide, a rock slide which affected the dolomite cliffs of the northernmost part of the Gardenaccia mountain group in the early post-glacial; **b** Corvara landslide, an active earth slide/earth flow which reaches the homonymous village determining damages to the winding road leading to Campolongo Pass; **c** Sottrù landslide, a sudden reactivation of a historical earth slide/earth flow occurred in December 2012 on the right flank of Rio Gadera at the foot of the Conturines group (*photo* January 2012); **d** Crep de Sela landslide, a rock/debris slide evolving into a muddy debris flow detached in April 2014 from the lower slopes of the Sella group in the vicinity of Corvara (*photo* June 2014)

reactivations of older movements as a consequence of increased precipitation as in other Alpine regions.

Beside the indirect effect of glacier retreat on slope stability during the Lateglacial and early Holocene, the occurrence of landslides has always been strictly linked to lithological, stratigraphic and tectonic conditions. In particular, landslides have been favoured by (i) the presence of brittle rocks, such as the dolomites, which have been affected by rock slides and rock falls, especially along the highly jointed cliffs of the main mountain groups, and (ii) the widespread outcropping of formations with a ductile behaviour, such as the San Cassiano and Wengen formations, which has favoured the development of a series of earth slides and flows on the middle and lower parts of the slopes. Often, different types of movement combine, giving origin to landslides with a complex style. This is the case of the major landslides which have affected the Alta Badia since the Lateglacial.

The oldest dated landslide in the Alta Badia is the *Passo Gardena landslide* (11,500–8500 years BP), an impressive mass movement extending over an area of about 1.4 km^2 which detached from the southern slope of the Gardenaccia mountain group near the homonymous pass (Fig. 10.10a). This is a complex landslide consisting of a rock slide affecting the dolomite rock cliff which induced a earth slide—earth flow affecting the underlying clayey rocks of the Wengen and San Cassiano formations.

Following the retreat of the ice cap which covered the entire Pralongià plateau, earth slides and flows developed on the slopes of the plateau, giving origin to multiple landslide bodies that often joined together into some of the largest landslide deposits of the valley. The most spectacular is the *Corvara landslide*, a complex landform characterized by movement from multiple source areas, where rotational earth slides have detached, joining valleyward and giving origin to an imposing accumulation which reaches the upper part of the Corvara village (Fig. 10.10b). The landslide has been active since 10,000 years BP showing an intermittent activity throughout the Holocene, with periods of increased instability related to climate changes, such as between ca 5000 and 2500 years BP (Corsini et al. 2001). The landslide is still active today, with major sliding surfaces at depth from 48 to about 10 m. The rate of movement varies in different sectors of the landslide (from centimetres to a few metres per year), with the track area being the fastest (Corsini et al. 2005; Panizza et al. 2011).

Recent reactivations of older landslides have left impressive scars within the grassy and woody slopes, visible from very long distances. This is the case of the *Sottrù landslide* that occurred in December 2012, after almost 200 years of dormancy (Fig. 10.10c) (Ghinoi et al. 2014). A huge earth slide—earth flow destroyed a few houses and almost dammed the Rio Gadera, assuming a shape strikingly similar to that of its first documented activation of 1821.

The *Crep de Sela landslide* is the most recent slope instability event occurred in the Alta Badia. It dates back to April 2014 when a rock/debris slide evolving into an earth flow was reactivated at the outer limit of the Corvara village, creating a deep cut in the slope and a two-branch mass movement which almost affected newly built houses and a base camp of the Italian Army (Fig. 10.10d).

10.5 The First World War and Related Heritage

During the First World War (1915–1918 in Italy), a part of the alpine front line between the Italian and the Austrian-Hungarian armies crossed the Alta Badia in the vicinity of the Setsas and Lagazuoi mountain groups. The fights not only caused great human losses on both sides but also changed the morphology of some mountain crests and slopes due to massive bomb attacks. One of the most impressive examples is the crest line of Col di Lana (ca 2.5 km south of the Setsas), whose shape was strongly modified after the explosion of an Italian bomb that removed ca 10,000 tons of rock creating shell craters and huge troughs that are still visible on the summit (Angetter and Hubmann 2015; Fig. 10.9). Another huge blasting was carried out by the Austrians targeting an Italian outpost on the 'Cengia Martini' ledge on the Lagazuoi, close to the Falzarego Pass, removing ca 200,000 m^3 of dolomite rocks. Both armies dug tunnels within the Lagazuoi, which have been recently opened to the public, representing an open-air museum of the First World War (Fig. 10.11).

Though outside the Alta Badia, it is worth mentioning the 'Ice city' of the Marmolada glacier as a valuable heritage of

Fig. 10.11 Entrance to a First World War tunnel on the top of the Laguzuoi mountain group, at an elevation of ca 2600 m

the First World War. It was a 12 km-long network of tunnels and caves dug by hand into the glacier ice (up to 50 m-thick) by the soldiers of the Austrian-Hungarian army to protect themselves from the Italian bombing attacks. The ice retreat of 3.4 km^2 in the last 100 years has brought to light interesting remains of that life beneath the ice, including bodies of soldiers.

10.6 Conclusions

Besides its outstanding aesthetic value which has been appreciated since a long time ago, the Alta Badia is a site of exceptional scientific and educational value. The dolomite plateaus and cliffs—defined by the Swiss architect Le Corbusier 'the most impressive buildings in the world'—as well as the slopes beneath them, are a remarkable record of geological and geomorphological history, making them an open-air laboratory for Earth scientists and destination not to be missed by visitors interested in natural and environmental sciences. Research activity carried out within this 'laboratory' dates back to 1841 when Wissmann and Münster described in detail the famous fossil fauna of the San Cassiano Formation, named after the village of the Alta Badia, soon followed by the first geological map of the valley performed by Fuchs (1844). Since then, the valley has attracted natural scientists, at first, and later on specialized geologists and geomorphologists, who provided extensive literature on the area.

The dense network of rope ways and hiking paths developed in recent years favours the reachability of a series of geoheritage sites and observation points, even at the highest elevations, which enables visitors to take full advantage of different landscape components. It should be emphasized that an exemplary range of diverse landforms—resulting from the complex geological structure of these mountains and from climatic changes through time—provides the background of high geomorphodiversity both at a global and regional scale (Panizza 2009).

The conservation and protection of geological and natural heritage of the Alta Badia is guaranteed not only by UNESCO rules, but also by the long-standing existence of two Natural Parks in the area, Puez-Odle and Fanes-Senes-Braies established by the Autonomous Province of Bolzano, respectively in 1978 and 1980. Furthermore, it should be noted that the inhabitants of the Badia Valley have always been deeply tied to their land which has enabled harmonious development of villages and tourist infrastructures, and profoundly respectful of natural assets, even in recent times when tourist activities have largely become the main source of income.

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The Vajont Valley (Eastern Alps): A Complex Landscape Deeply Marked by Landsliding

11

Alessandro Pasuto

Abstract

On 9th October 1963 the Vajont Valley was strongly modified due to a world known landslide, which claimed the lives of almost 2000 people. At that time a huge amount of material collapsed into an artificial reservoir generating a water wave, which overtopped the dam destroying seven villages in the Piave River Valley. The landslide accumulation filled the valley blocking its drainage that is now guaranteed by a by-pass built soon after a previous smaller landslide occurred on 4th November 1960. However, the whole valley has been affected by a series of landslides, which buried ancient glacial and fluvial landforms sealing and preserving them. The chapter is therefore not only focusing on the Vajont Landslide, but also on other gravitational, glacial and fluvial landforms, which are crucial for the reconstruction of the post-glacial geomorphological evolution.

Keywords

Landslides • Glacial morphology • Vajont • Eastern Alps

11.1 Introduction

On 22:39 9th October 1963, some 270 × 10^6 cubic metres of rock slid down from the northern slope of Mt. Toc into the Vajont reservoir generating a huge wave propagating both upstream and downstream. The wave overtopped the dam and plunged into the Piave River Valley. It swept away seven villages killing 1917 persons. It was the largest catastrophe occurred in Italy since the end of World War II.

The Vajont Valley has always been prone to landslides due to its geological, geomorphological and tectonic setting upstream the deep gorge cut into Jurassic limestones which was considered as a suitable place to build a double-curvature concrete arch dam 261.60 m high (the highest dam in the world at that time).

The lower part of Mt. Toc north slope consisted of an ancient landslide deposit and not of bedrock, as initially inferred. After the Vajont slide, many scientists (e.g. Carloni and Mazzanti 1964; Chowdhury 1978; Müller 1964, 1987; Nonveiller 1987; Kilburn and Petley 2003) dealt with many different aspects of the landslide (e.g. rheology of material, kinematics, wave propagation), but a specific study worth to be mentioned is that of Hendron and Patton (1985). This is a very comprehensive study that takes into account different issues related to the landslide event: tectonics, geotechnics, rheology, etc. analysing the wide literature produced until then. Moreover, various review papers summarizing the events preceding the catastrophe and highlighting the valuable contributions to the comprehension of the triggering factors were published by scientists directly involved in researching the landslide event (Müller 1964; Selli and Trevisan 1964; Semenza 1965; Müller 1987; Semenza 2010) and by some of their collaborators (Semenza and Ghirotti 2000; Genevois and Ghirotti 2005; Ghirotti 2012; Genevois and Prestininzi 2013). Somehow paradoxically, due to such a wide scientific interest in the Vajont Landslide (cf. Genevois and Tecca 2013) and to the great emphasis given to this event by national and international media, the striking geomorphological features of the valley related to its

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Quaternary evolution were almost neglected and underestimated. Consequently, there has been an evident paucity of geomorphological investigations and landscape evaluations, contrasting with clear evidence of glacial, gravitational and fluvial processes co-existing in a unique environment strongly affected by human action, but still preserving ancestral characteristics.

11.2 Geographical and Geological Setting

The Vajont Valley is located in the Eastern Italian Alps—in the buffer zone of the Dolomites UNESCO World Heritage Site—some 100 km north of Venice (Fig. 11.1). It can be considered a typical Alpine valley with a superimposition of forms and deposits of different origins. The valley has been dammed several times after the Last Glacial Maximum (LGM) by landslides and the Vajont Torrent was diverted probably cutting an epigenetic gorge more than once. The Vajont Valley is a left-hand tributary of Piave Valley, one of the main access routes to Dolomites. Despite its wild landscape, it is easily reachable by motorway from the Veneto plain area.

The Vajont Torrent has two main tributaries: the Mesazzo Torrent on the left and the Zemola Torrent on the right, originating from Col Nudo Group on the south and Mt. Duranno on the north, respectively. They are more or less aligned along a N-S oriented structural discontinuity and this has an impact on the great amount of available debris on the valley bottom.

The higher peaks bordering the drainage basin generally exceed 2000 m a.s.l. (Mt. Borgà, 2228 m; Mt. Duranno, 2652 m; Col Nudo, 2439 m; Mt. Toc, 1921 m), and the confluence with the Piave River is located at an elevation of

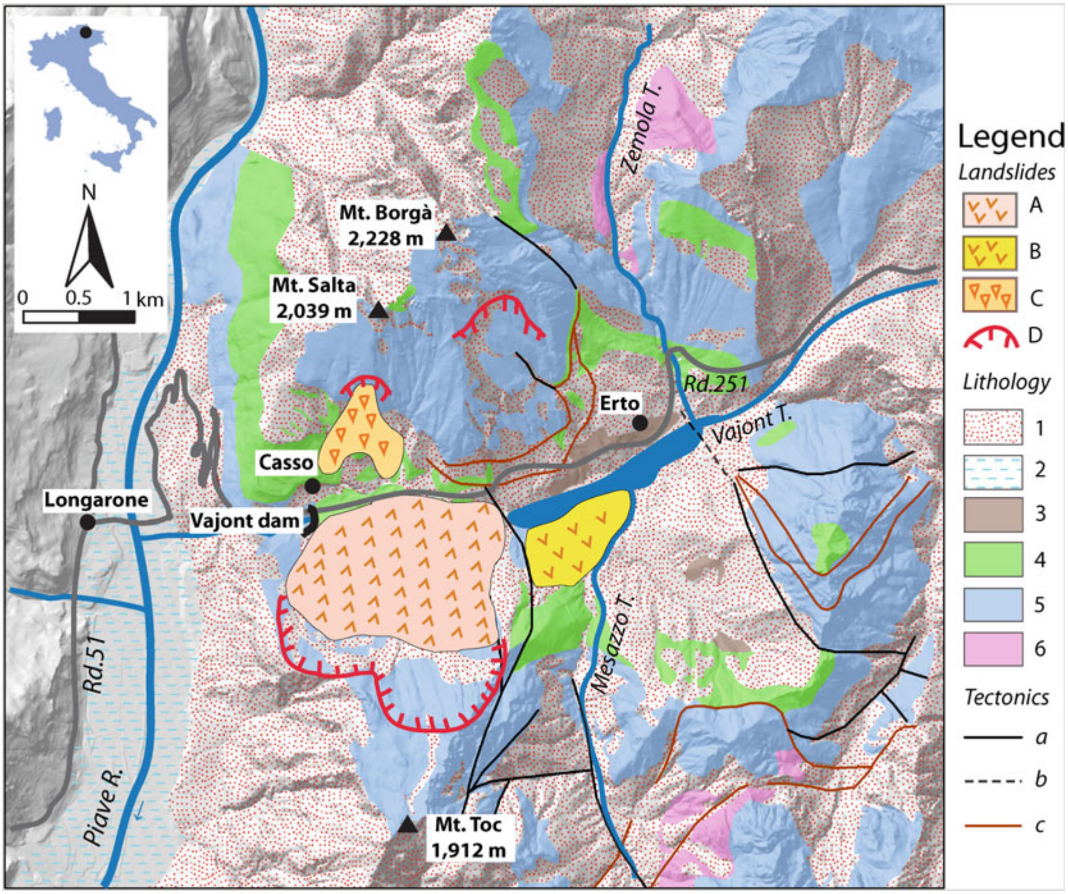


Fig. 11.1 Geomorphological sketch map of the Vajont Valley. Legend: *A* Vajont Landslide; *B* La Pineda Landslide; *C* Salta rock fall; *D* landslide scarp; *1* slope deposits; *2* fluvial deposits; *3* marls, marly limestones and flysch (Marne di Erto and Flysch Formation, Palaeocene p.p.—Eocene); *4* reddish and nodular limestones, white micritic limestones (Ammonitico Rosso, Biancone, Scaglia Rossa, Lower Cretaceous–Lower Palaeocene p.p.); *5* white oolithic and bioclastic calcarenites, grey dolomitized micrites and limestones with alternanace of thin clayey layers (Soverzene Formation, Igne Formation, Vajont Limestones and Fonzaso Formation, Jurassic); *6* white or grey massive dolomite (Dolomia Principale, Upper Triassic); *a* fault; *b* uncertain fault; *c* overthrust

430 m. It follows that the area is characterized by considerable differences in elevation and a deeply incised fluvial network. This results in a significant landslide susceptibility, enhanced by poor geomechanical characteristics of some of the outcropping geological formations.

In the Vajont Valley and adjacent mountain groups, geological formations range in age from the Upper Triassic (Dolomia Principale) to the Middle Eocene (Flysch). They are mainly represented by limestones and dolomites occasionally interbedded by thin layers of clays and marls that represented a predisposing factor for the sliding process of the Vajont landslide (Hendron and Patton 1985).

The E-W trend of the valley is related to the presence of the south-verging asymmetric Erto Syncline, which is part of a greater regional tectonic structure, namely the Belluno Line. N-S minor folds and faults that further complicated the geological setting of the area affect the Erto syncline.

Climate of the valley is characterized by heavy rainfall generally concentrated in late spring and autumn. The average annual cumulative precipitation is about 1800 mm; the maximum daily rainfall at the Cimolais Station (some 5 km eastward) in the period 1944–2000 has been recorded on 25 November 1987 (175.9 mm), whereas the highest cumulative values for 3, 5, 10 and 15 days have been recorded in September 1965 with 342.4, 369.0, 377.8 and 379.4 mm, respectively. Permanent snow cover remains on the ground normally from December until March, and locally (e.g. north slope of Mt. Toc) until May.

11.3 Landscape and Landforms

Generally speaking, the Vajont Valley shows rugged morphology with deep gorges and steep slopes. The landscape retained an ancestral character and only two small villages with few hundreds of inhabitants are now present. Before 1963, the people living in the valley were many more, but most of them emigrated soon after the catastrophe.

The main geomorphological feature of the valley is the presence of several huge landslide accumulations of different age and size. The most impressive one is certainly that related to the October 1963 catastrophic landslide and consequent wave. However, besides landslides, the valley is rich in glacial and fluvial landforms and deposits, somewhere buried and sealed by gravitational ones that allowed them to be preserved. Actually, during the LGM the Vajont Valley was occupied by a local glacier merging into the Piave Valley which hosted the main glacial tongue in the surrounding area with a thickness of more than a thousand metres.

11.3.1 Glacial Landforms

Due to the above-mentioned Quaternary setting, a wide range of glacial landforms and deposits are still present in the valley. The special character and the high value of these traces are mainly related to their clearness and degree of preservation as well as to the broad variety of forms and sediments representing a comprehensive picture of the valley glacial evolution.

One of the clearest evidence of glacial erosion processes in the valley is the sidewall recently exhumed some tens of metres above the village of Casso (Fig. 11.2). Thanks to the protective action of a thick scree slope that covered the wall since thousands of years ago, it is well preserved and exhibits a textbook example of glacial grooves and striations.

Exhumation of this erosional landform was due to the excavation of a deep trench to protect the houses of the village from rock falls that have periodically affected the above hanging cliff. The erosive surface involving the limestones belonging to the Scaglia Rossa formation (Upper Cretaceous–Lower Paleocene) is smooth, undulated and deeply striated due to the abrasion action of the clasts incorporated in the ice mass. Considering the elevation and orientation of the sidewall as well as the micromorphology of the striations, we can infer that this landform is related to the erosional action of the Piave glacier which probably branched out into the Vajont Valley during the LGM.

Noteworthy are also the glaciolacustrine deposits outcropping along the Vajont riverbed represented by a thick rhythmic sequence of silt and clay interbedded by sandy layers somewhere affected by glaciotectonic deformation and including exceptional examples of dropstones (Fig. 11.3).

Deep boreholes drilled in the area of La Pineda showed the existence of a well-preserved layer of glacial deposit, namely bottom moraines, beneath a 90 m thick layer of gravitational deposits related to the La Pineda Landslide (cf. Sect. 11.3.2). A sequence of such glacial deposits can be also observed within an erosional scarp located along the Mesazzo Valley (Fig. 11.4). This outcrop clearly illustrates the role of post-glacial gravitational deposits, namely La Pineda Landslide, in protecting and preserving the glacial ones. In particular, it shows a typical delta sedimentary sequence, probably related to the presence of a proglacial lake, represented by bottom-sets, foresets and topsets covered by moraine and landslide deposits. The uniqueness of this stratigraphic sequence is evident and certainly rare in the Eastern Alps.

Fig. 11.2 Glacial sidewall located on the right side of the Vajont Valley above of the village of Casso characterized by evident grooves and deep striations (*photo* A. Pasuto)

Fig. 11.3 Remarkable example of dropstone in a rhythmic sequence of fine glaciolacustrine deposits (*photo* Dolomiti Project)

11.3.2 Gravitational Landforms

As stated above, the landscape is dominated by gravitational landforms and deposits, and the landslide of 1963 is only the last of a series of events that shaped the morphology of the valley. This is mainly due to the complex tectonic setting of the area that makes it prone to gravity-induced processes. The effects of tectonic activity, which is still active (Mantovani and Vita-Finzi 2003), consist of steep slopes, deep valleys and intense jointing and fracturing of the outcropping rocks. This has favoured the presence of thick and widespread layers of loose debris that can be mobilized not only by gravity, but also by water and snow avalanches. It should be also emphasized that the Vajont Valley is located very close to one of the most active seismic zone of Italy (namely Friuli Venezia Giulia), which experienced a strong earthquake (M 6.4) in 1976 causing almost 1000 victims some 60 km eastward.

Among the widespread active and dormant slope instability phenomena, the most relevant in terms of geomorphological risk, long-lasting evidence in the landscape and damage caused are Salta rock fall, La Pineda Landslide and Vajont Landslide, respectively. The main geomorphological features of these landslides are described below.

The *Salta rock fall* area is located on the northern slope of the Vajont Valley and severely threats the small village of Casso in which some tens of people live (Fig. 11.5). Rock falls can be considered the most hazardous process still active in the valley. Falling debris originates from the uppermost part of the southern slope of Mt. Salta, at an elevation of about 1500 m. The footslope deposit is the result of multiple events; the first known rock fall event in the area occurred in 1674. In the 1960s, large boulders reached the secondary road connecting the village of Casso to Regional Road no. 251. Since 1990, minor rock falls have been repeatedly reported on the same slope in the vicinity of the village. The rock fall deposit covers an area of about

Fig. 11.4 Stratigraphic sequence outcropping on the eastern side of La Pineda Landslide along the Mesazzo Valley. The *top layer* is composed by landslide deposits; just below there is a layer of glacial till overlying glaciodeltaic cemented deposits characterized by well recognisable topset and foreset beds (*photo* Dolomiti Project)

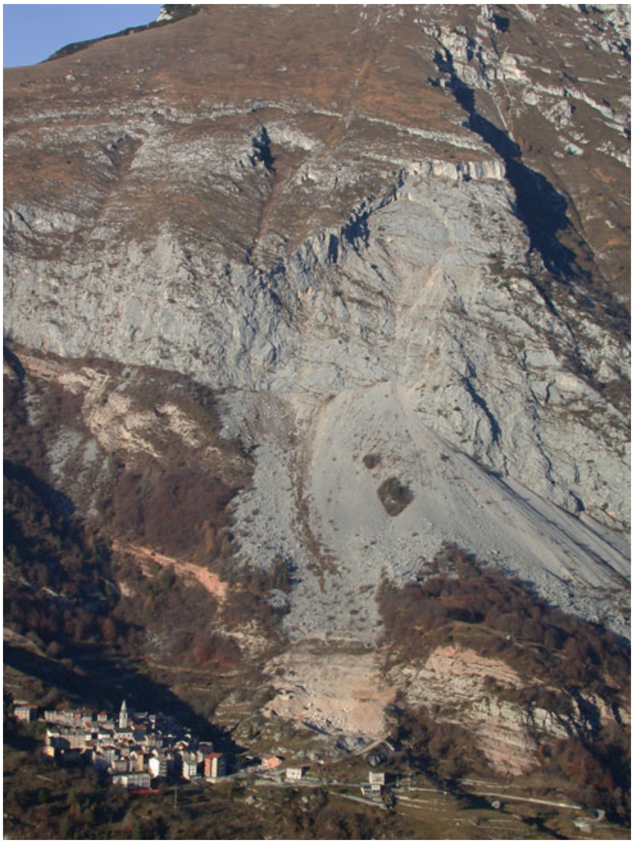


Fig. 11.5 The Village of Casso at the base of Mt. Salta. On the *right* large rock fall deposit is visible (*photo* Dolomiti Project)

5×10^5 m^2 between 1250 and 850 m a.s.l. and has an estimated total volume of 2.5×10^6 m^3. A quarry was opened east of Casso to exploit the rock fall materials for construction purposes and to obtain a retaining zone to protect the village and trap the falling boulders. The geomorphological evolution of the slopes is mostly conditioned by the tectonic setting. In particular, the Mt. Borgà thrust is certainly the main conditioning structural element that led to the weakening of the rock mass and the subsequent slope failures. Emplacement of the thrust sheared the rock and produced intensive and pervasive fracturing processes. Above the thrust zone, folded and faulted bedding planes dip steeply toward the slope free face, producing instability conditions predisposing to rock falls. The source area is characterized by the presence of different scarps, distributed along tectonic discontinuities. Field surveys revealed unstable rock blocks with individual volumes exceeding 1×10^3 m^3. These blocks are separated by fractures up to 2 m wide and 15 m deep. The scarp and the accumulation zone of the 1674 event are still evident. The main scarp has a semicircular shape, delimited by steep walls, several metres high, carved in the Vajont Limestone formation. The deposit is arranged at an inclination up to 50° because of the presence of abundant huge blocks, which can reach a volume of some hundreds of cubic metres. Some of them got close to the houses in the past forcing the people to move away.

La Pineda Landslide, similarly to the Vajont landslide, permanently changed the morphology of the valley due to its huge volume and fast dynamics. Since no organic matter has been collected in the accumulation area it has not been possible to establish the timing of this event, but it can be approximately dated back to the post-LGM period. The event can be defined as a translational landslide which turned into a rock avalanche, as suggested by the stratigraphic sequence of Fig. 11.4. The main landslide features are represented by the sliding surface visible on the right side of the valley along a footpath that connect the villages of Casso and Erto, and the large accumulation located at the base of the opposite slope (Fig. 11.6). This means that the landslide dammed both the Mesazzo and Vajont valleys. The source area is currently characterized by great amount of loose debris often involved in debris flow phenomena, and slabs of displaced rock clearly showing the bedding planes and other structural features; these rock portions have been considered remnants of the unstable mass still in place or slightly shifted and potentially prone to sliding. This is why a tunnel protecting the Regional Road no. 251 running at the base of the slope had to be built. The landslide accumulation zone has been deeply reworked by human activities since it represented a favourable location for agriculture and settlements. The geometry of the body clearly reflects past, buried valley morphology and a deep borehole drilled in the area revealed a 94 m thick layer of landslide material overlying a 4 m layer of alluvial deposits of the Mesazzo Torrent and at least 20 m of glacial deposits. Edges of the landslide accumulation zone have been found on the right side of Mesazzo Valley, confirming the damming of this valley. A part of landslide deposit rested at the base of the easternmost slope of Mt. Toc and therefore this could have favoured the stability of this sector, acting as a supporting wedge.

The *Vajont Landslide* is a worldwide known mass movement due to both its catastrophic effects and peculiar dynamics. Many scientists visited the site and studied the phenomenon and a huge literature has been produced about this event and its implications. Nevertheless some aspects, mainly related to the high speed reached by the landslide during its collapse, still remain unsolved. However, the Vajont event represents a clear example of man-induced disaster, which marked an indelible scar both in the landscape and in the consciousness of the population.

Despite different interpretations on the dynamics of the initial stages of movement and of the final collapse, it seems evident that the most important triggering factor would have been groundwater level variations related to the reservoir filling operations. Therefore, the dam construction—aimed at the exploitation of the Vajont Torrent and the creation of a

Fig. 11.6 A panoramic view of the Vajont Valley from east to west. In the foreground La Pineda Landslide and the large debris plain caused by the depositional activity of Mesazzo Torrent. In the background the 1963 landslide and its scar on the left side of the valley (*photo* Virtualgeo)

Fig. 11.7 Mt. Toc and Vajont Landslide and dam. The central part of the accumulation zone is characterized by the abandoned valley of Massalezza Stream backtilted toward the sliding surfaces. On the *right* the Piave River Valley is visible (*photo* Virtualgeo)

reservoir with huge water storage capacity—can be considered as the starting point of a predictable disaster.

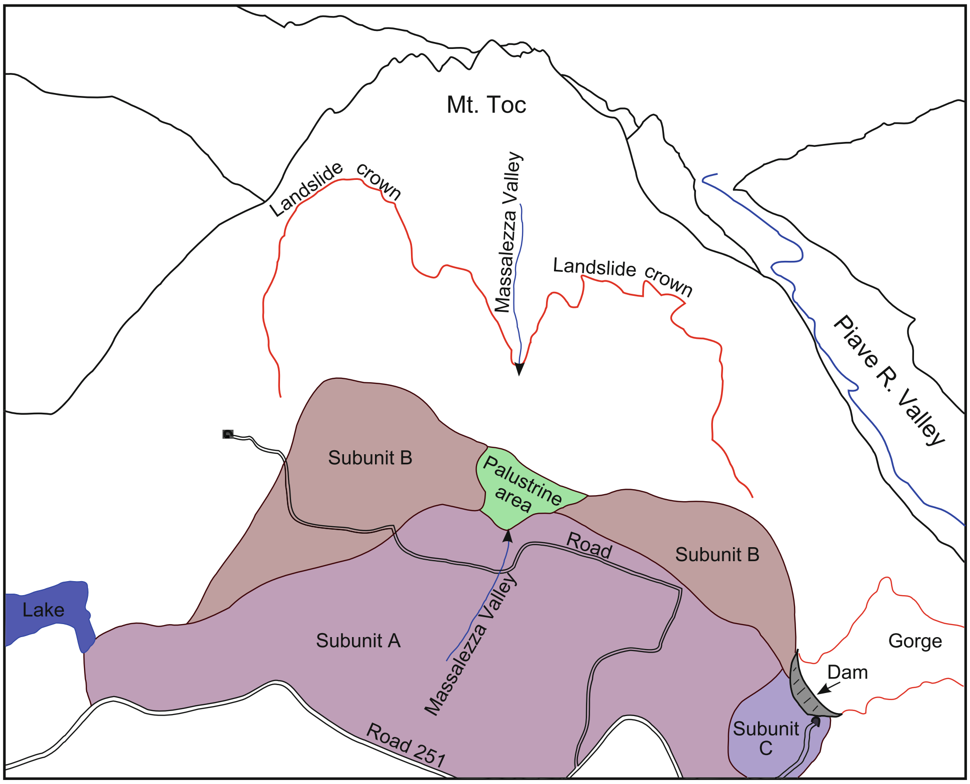
The reservoir was created artificially in 1960 after the Vajont Torrent was dammed as part of regional expansion in hydroelectric-power generation. The dam is 261.60 m high and 190 m wide across the top and, at the time of construction, was the highest and one of the most advanced double-arched dams in the world. Nowadays it is part of the landscape of the valley and, in recent years, has become a tourist attraction.

After the reservoir level had been raised and lowered several times, the southern margin of Mt. Toc became eventually destabilised and, after nearly three years of intermittent creeping, it catastrophically collapsed at 22:39 on 9th October 1963. Within 30–40 s, some 270 million m^3 of rock crashed into the reservoir, causing a water wave, which overtopped the dam. The vast slope movement, ascribable to a rock slide, started to move along a surface corresponding to one or more downstream-dipping clayey interbeds having the same angle as the slope surface. The slide displaced a 250–300 m thick mass of rock for 300–400 m horizontally. The mass reached a velocity of over 20 m/s before running up and stopping against the opposite slope of the valley (Fig. 11.7). The slide filled the valley and the reservoir in a few tens of seconds and the water wave propagated both upstream and downstream. This wave reached a maximum elevation of 935 m a.s.l. (235 m above the reservoir level) (Ghirotti 2012). It swept across the dam and the Vajont gorge and eventually fell onto the Piave Valley floor, where it destroyed the town of Longarone and neighbouring villages, claiming 1917 lives.

The topographic features of the valley changed enormously following this event, especially with the infilling of the gorge with landslide material consisting of fractured rocks, moraine deposits, ancient alluvial deposits (fluvial and torrential), sometimes cemented, and slope debris, all Quaternary in age. Nevertheless, the impressive limestone layers representing the sliding surface of the 1963 landslide mostly characterize the landscape. They are somewhere quite clean and smooth but, since the scarp is still active, thick scree deposits are present at the toe of the slope.

Along the sliding surfaces peculiar landforms are present which could be interpreted at a first view as badlands affecting scree slopes. However, a closer analysis highlights

Fig. 11.8 Schematic interpretation of geomorphological features and landslide subunits (compare with Fig. 11.7)



that they are slabs of rock deeply fragmented and partially metamorphosed due to friction, mainly formed by clasts regularly shaped and arranged in a sort of brick walls and representing source areas for debris feeding the scree cones at the base of the sliding surfaces.

The landslide accumulation zone can be roughly divided into three subunits, which can be interpreted as the result of different and partially successive sliding phases (Fig. 11.8).

Subunit A includes the northernmost part of the landslide which now fills the valley. Before the collapse, this portion was located at the toe of the unstable slope of Mt. Toc and represents the sliding front, which pushed out the water of the Vajont reservoir causing the huge wave. It consists of a single mass in which the original layering, even if strongly deformed during collapse, is still clearly visible. All pre-failure vegetation was removed by the return water wave after the event. Some morphological features of the north slope of Mt. Toc are still preserved in different locations and with different settings. This is the case of Massalezza Valley which drained the unstable slope before 1963 and is now shifted of about 400 m northward in a sub-horizontal position. It can be observed driving over the landslide accumulation on the road to La Pineda and splits the unit in two main parts (Figs. 11.7 and 11.8). This incision is now draining the landslide accumulation zone to the south, into a large closed depression at the base of the outcropping sliding surface. Soon after the event, this depression was occupied by a lake, which is now completely filled by debris and only during snow melting period or heavy rainfall still contains a small pound. Close to the dam, on the western margin of this unit, some small depressions are also visible, probably related to a subsidence phenomenon caused by the settling and reworking of the moving materials.

Subunit B consists of two different parts located in the easternmost and westernmost sectors of the accumulation zone respectively, in an intermediate position between the sliding surface (at a higher elevation) and Subunit A. An analysis of the vegetation age demonstrated that most trees are older than 50 years thus confirming that this unit was not affected by the water waves produced by the collapse and this seems to be consistent with the hypothesis of a second-stage collapse, shortly after the displacement of Subunit A.

Finally, *Subunit C* is represented by the small portion of the landslide deposit located directly against the dam, south of Regional Road no. 251. It is topographically in a lower position with respect to Subunit A and is mainly composed by sand, gravel and other loose material derived from fragments washed back onto the landslide by the return wave immediately after the collapse and covering the originally displaced slope. Similarly to what happened at the base of the sliding surface, after the 1963 landslide this depression was occupied by a small lake, which rapidly disappeared probably due to sufficient permeability of the highly fractured and deformed rock.

Fig. 11.9 The deep narrow gorge of the Vajont Valley seen from the top of the dam. On the *right* hand side a water cascade flowing from the by-pass which allows the drainage of the Vajont Valley toward the Piave River (*photo* A. Pasuto)

11.3.3 Fluvial Landforms

The action of fluvial erosion is clearly visible in the valley and the most remarkable landform is the deep gorge carved in the limestone outcropping close to the outlet to the Piave River Valley west of the dam (Fig. 11.9). It is more than 200 m deep and some tens of metres wide and is easily observable along the road running on the left side of the Piave River bed. However, both the tributaries of the Vajont Torrent are characterized by deeply incised V-shaped valleys and narrow gorges; noteworthy is the view of the Zemola gorge from the bridge along the Regional Road no. 251 immediately eastward of the village of Erto. It is quite impressive and significant examples of potholes can be observed along the sidewalls. During the Holocene, the Vajont Valley has been repeatedly dammed by landslides, causing base-level changes and a succession of incision and aggradation phases. This evolutionary behaviour is evident upstream of the 1963 landslide accumulation zone which is now representing the new base level for the upper catchment. Soon after the landslide, a residual lake draining the upper catchment was present eastward. This lake was connected to the valley outlet by means of a by-pass built after the 800,000 m^3 landslide which detached from the Mt. Toc slope at the beginning of November 1960 and fell into the reservoir. Now the residual lake is being progressively filled by sediment discharged by the tributaries and a large flat area characterizes this sector (see Fig. 11.6), thus determining an increase in the elevation of the local base level.

Therefore the past dynamics of the river network, and in particular base-level changes of the main stream through time, have strongly conditioned the development of the fluvial landforms allowing some of them to be preserved and even rejuvenated. This situation is also typical of the Zemola and Mesazzo valleys where several remarkable erosional forms (Fig. 11.10) can be observed at different elevation on the slopes, confirming water level changes during the Holocene.

11.4 Conclusions

The Vajont Valley represents an almost unique case in the Eastern Alps in which glacial landscape (including landforms and deposits) has been protected and preserved by an intense landsliding activity which occurred after the retreat of the LGM glaciers. The largest mass movement, whose evidence is still clear and easily recognisable, took place in 1963. The Vajont Landslide has completely twisted the valley and now the landscape is composed by natural and anthropic elements, such as the impressive dam, which represent an admonition for future generations to avoid waste of natural resources and improper land use, and to consider the land as an asset to be protected and preserved.

Fig. 11.10 Pothole cut into the conglomerate in the Zemola Valley (*photo* Dolomiti Project)

In recent years, many initiatives have been carried out in order to preserve the memory and transfer the lesson learnt as well as to solve some of the problems not yet tackled since 1963. In-depth investigations were promoted by the regional government for assessing the residual geological risk in the landslide area and removing the heavy restrictions regarding land use. This activity was also targeted towards favouring the homecoming of the population moved away soon after the catastrophe.

Besides that many other events have been sponsored and organized especially on the occasion of anniversaries (in 2013, the year of the 50th anniversary, important scientific conferences were held to discuss unsolved questions) and other celebrations. A couple of museums collecting historical images, films, finds and other materials may be visited in Longarone and Erto-Casso. Moreover, many projects, both scientific and social, such as student workshops, conferences, guided tours, etc., involving national and international universities and research centres as well as local associations and institutions have been established and promoted, thus favouring the influx of many visitors to this site.

Even if the area is easy to reach by motorway, it nevertheless still does not offer adequate tourist infrastructures. However, since 2009, when the Dolomites became a UNESCO World Heritage Site, things have been changing and improving. This is certainly a right step towards more sustainable and environmentally aware tourist approach and an effective landscape conservation.

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Karst Landforms in Friuli Venezia Giulia: From Alpine to Coastal Karst

12

Franco Cucchi and Furio Finocchiaro

Abstract

Around 20–25% of the Friuli Venezia Giulia region consists of karstified rocks. The geological, geographical and climatic conditions have given rise to a whole series of karst landscapes which have developed in different ways on limestone of different ages, located at different altitudes. One encounters splendid examples of alpine karst (Mt. Canin and Cansiglio–Cavallo Massif), mountain-hill karst (Mt. Ciaurlec, Julian Prealps) and marine-coastal karst. In the Classical Karst near Trieste, the worldwide symbol of karst phenomena, over 3000 caves are known while half a dozen are over 1000 m in length. There are about 80 solution and collapse dolines with a diameter greater than 100 m.

Keywords

Karst landscapes • Alpine karst • Classical Karst • Friuli Venezia Giulia

12.1 Introduction

Carbonate rocks make up about a quarter of the Friuli Venezia Giulia area and almost 40% of the mountainous and hilly territories. It is not therefore surprising that there is a high presence of strongly karstified areas, among which the Classical Karst (hereinafter: Karst) and Mt. Canin are famous for their surface and subsurface karst landforms (Cucchi et al. 2009). The intensity of karst processes is illustrated by the more than 7000 caves explored to date, with densities of up to 70 caves/km^2 in the Karst and 264 caves/km^2 on the plateau of Mt. Canin. Surface karst forms are just as many: there are dolines, karren and limestone pavements, often of remarkable dimensions and types (Cucchi et al. 2010).

Carbonate rocks of different ages and in different structural settings outcrop at variable altitudes, between 2500 and 1200 m above sea level in the Alps, and between 900 and 700 m in large part of the plateau in the Prealps, and from 300 m in the classic karst region that overlooks the Adriatic Sea (Fig. 12.1). The Mts. Creta di Timau and Canin are the most representative areas of the alpine karst. In the prealpine zone karst features are most extensive in terms of area. Cansiglio–Cavallo Massif, Mt. Ciaurlec and Julian Prealps between Torre River and Cornappo Torrent present characteristic karst landscapes (Cucchi and Zini 2009).

Karst processes have been acting over several millions of years and therefore in this area karst landscapes best represent various stages of the development of karst, not only due to different altitudes and hydrological gradient, but also to the changing climatic conditions during the late Cenozoic.

12.2 Geological and Geomorphological Setting

Friuli Venezia Giulia's mountainous terrain can be divided into orographic units with geographic characteristics strongly influenced by geological features. In structural terms, three geological chains meet in this area: the Paleocarnic and Sudalpine Chains and the Dinaric Alps. The stratigraphic sequence (Fig. 12.2), which is entirely sedimentary, has a thickness of 30,000 m and represents 450 million years of geological history (Carulli 2006).

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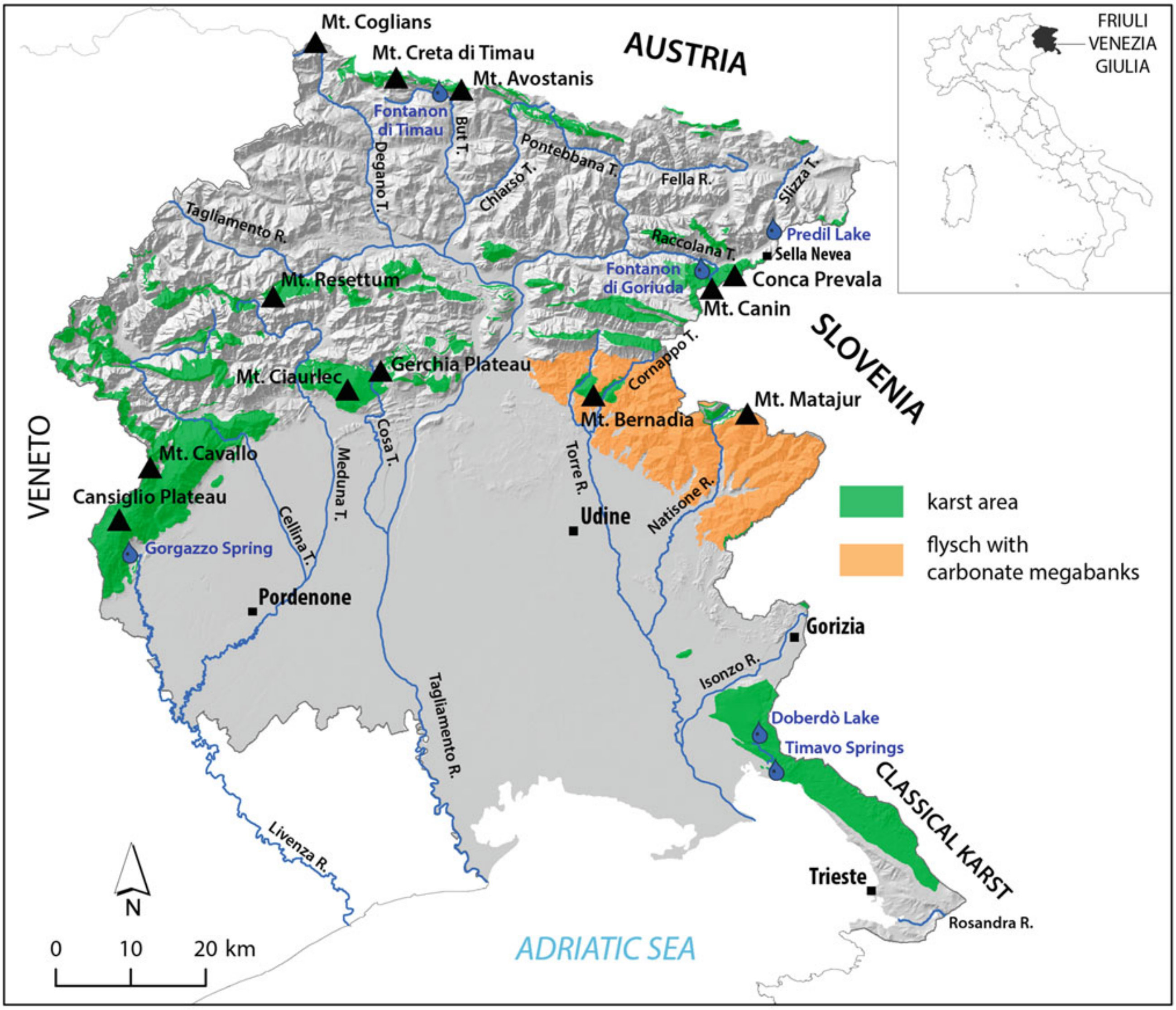

Fig. 12.1 Karst areas in the Friuli Venezia Giulia region

To the north, the Paleocarnic Chain, between 10 and 20 km wide, consists almost exclusively of Paleozoic rocks spreading from the Gail fault, in Austria, in the north to the Fella-Sava line to the south. Both the Hercynian and Carboniferous–Permian sequences outcrop here, whilst they are hidden below the Mesozoic successions to the south. In the Hercynian sequence, the stratified limestone at Orthoceras of the Mt. Lodin Formation, Silurian in age, and the massive reef limestone of the Devonian lie on siltstones and marls of the Val Visdende and Uqua formations. The Devonian limestone, between 200 and 300 m thick, is often intensely karstified. In the successive Carboniferous–Permian sequences, it is possible to distinguish many formations that consist of alternating continental, deltaic and shelf deposits in terrigenous or carbonate facies with a total thickness of up to 3000 m, but without significant karst landscapes.

In the Carnic Alps and the Julian Alps, the Mesozoic shelf sequence, which contains many limestone formations, including thick ones, is today intensely karstified. However, it is pointed out that on the Monticello Formation (dark marly limestone with siliceous rocks) there is the Dolomia Principale Formation (Norian) composed by massive dolomite and stratified dolomitic limestone with a maximum thickness of 2000 m, which in some cases present limited karst phenomena. On the other hand, in the highly stratified grey limestone of the Dachstein Limestone Formation (Rhaetian), that reaches a thickness of 800 m, and in the overlying grey oolitic limestone, of the Calcari Grigi Formation (Lias), about 200 m thick, intense and widespread karstification occurs. Karst landforms can be found also in siliceous limestone with oolites and crinoids (Vajont and Cellina formations) and in the highly stratified limestone

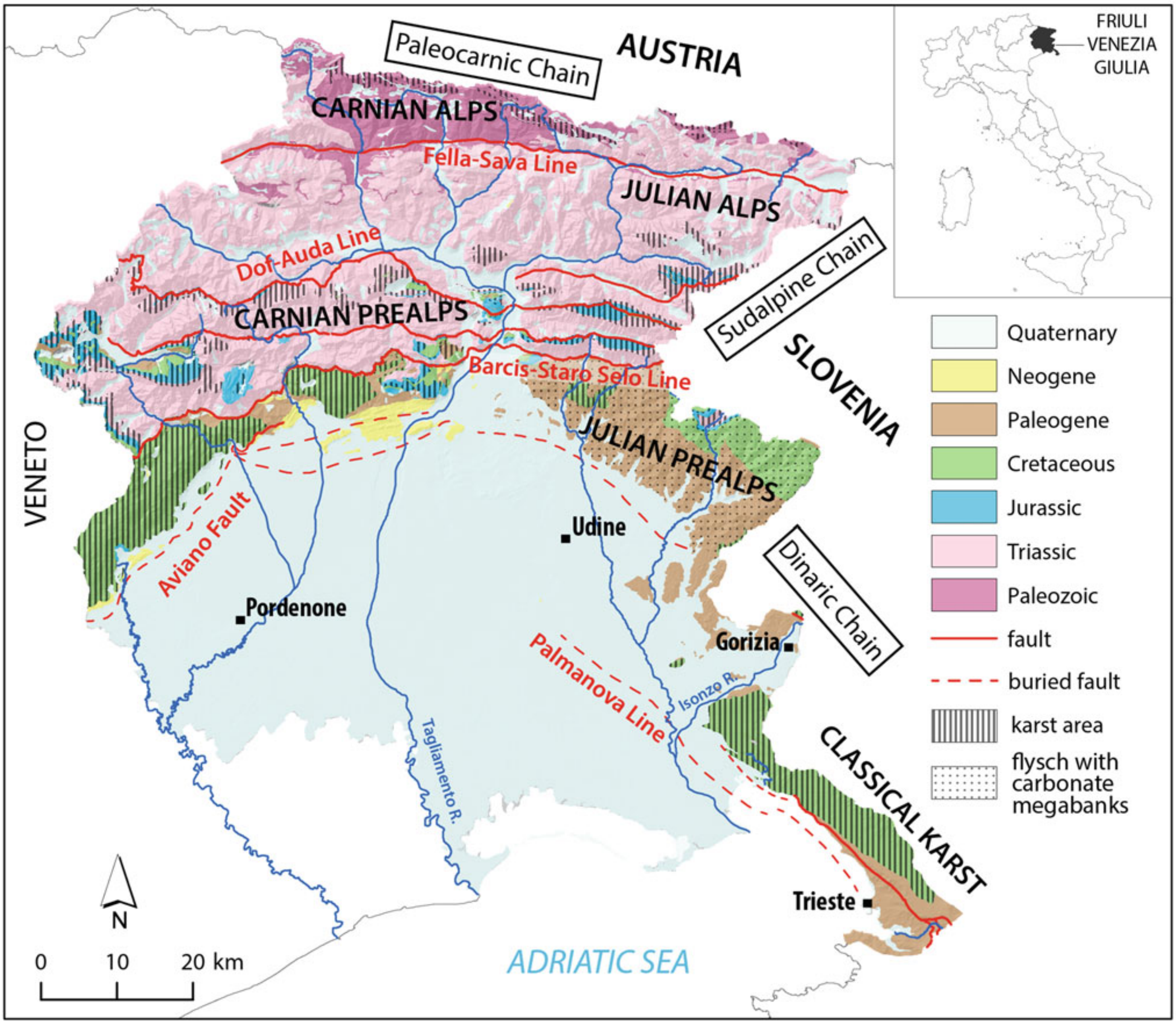

Fig. 12.2 Geological sketch map of Friuli Venezia Giulia region (modified after Carulli 2006)

with a thickness of about 360 m of the Soccher Formation (Dogger-Malm).

Further south, the high ground of the Carnian Prealps rises above the Friuli Plain forming an arch, where Mesozoic and Cenozoic rocks prevail. Further east, the Julian Prealps have developed an interesting active cave network, even where facies of Cenozoic flysch outcrop.

The Classical Karst, the northern tip of the Dinaric Chain, is the most typical karstified area, where heavy karstification of limestone outcrops has created all possible surface and subsurface features in such numbers, dimensions and types to render the area the universal symbol of karst phenomenon. This is why the Timavo springs, already mentioned by ancient Latin authors, universally represent the impetuous outflow of waters from the underground caves of the Karst. The plateau is underlain by a thick succession of mostly carbonate rocks, from the Triassic to the Eocene, covered by flysch. In the Trieste Karst, in particular, carbonate lithotypes (limestones and, subordinately, dolomites) from the upper Cretaceous to lower Eocene crop out.

12.3 Alpine Karst Landscapes

The karst epigean forms are not very common on the Paleocarnic Chain, with the exception of some areas along the southern slope of the range across the border with Austria, from Mt. Coglians (2780 m) to Mt. Avostanis (2207 m). The most characteristic form is limestone pavement, furrowed by grikes a few decimetres wide, up to a metre deep, and also more than ten metres long (Fig. 12.3). Through this mountain range, about 12 km long, a well developed and

Fig. 12.3 Large grikes and grooves in the Carnian Alps (*photo* G.D. Cella)

deep karst drainage is active mainly from west to east. During 2012, the link between a shaft on the Mt. Coglians and the Fontanon di Timau, an important spring that feeds the But Torrent and is located ten kilometres apart, has been established by chemical tracing test.

Mt. Canin (2587 m) straddles the Italian–Slovenian border, in the heart of the western Julian Alps. It can be easily seen from the Friuli Plain, as well as from many parts of the coast and from the Karst, due to its size and the vast plateau on its southern side. The entire massif is the most spectacular example of alpine karst in Italy, due to the richness and variety of its surface forms, its morphological features and the size of deep caves which occur within it. Covering 180 km^2 and split between Italy and Slovenia, it contains thousands of caves (2031 in Italy alone): these are significant numbers, especially when compared with other karst regions in the world. What makes it unique is its network of approximately 130 km of caves explored to date, a number of which reach depths of over 1000 m. The distinctive appearance of the landscape is due to the vast exposure of limestone outcrops on the plateaus, a continuous display of alternating micro- and macro-karst forms. In this moonscape, with its sparse vegetation, it is possible to find caves, shafts and dolines of various dimensions, as well as countless karren grooves and grikes.

Mt. Canin is principally composed by Triassic carbonate rocks, such as Dolomia Principale and Dachstein Limestone, where karst features occur. The massif is divided into two distinct structural subunits which form two monocline folds with opposite attitudes: the northern one (lower Italian slope) dips northwards, while the southern (higher Italian slope and the Slovenian slope) dips southwards. The occurrence of minor faults, fractures and stratification have favoured the development of karst networks within the individual blocks which, from a hydrogeological point of view, constitute semi-independent units. There are no passageways connecting the voids in the different blocks, which are also characterised by the presence of levels of phreatic galleries at different altitudes. In most cases, the blocks are hydrogeologically limited at their base by the Dolomia Principale, which contributes to the formation of an undefined permeability threshold of the karst aquifer.

The regional landscape is characterised by surfaces shaped by glacial erosion and exposed to intense karstification. We can find glaciokarst forms, such as glaciokarst depressions, the largest of which is represented by the Conca del Prevala, roches moutonnées and narrow ridges elongated in shape in the direction of the steepest slope of the surfaces with smoothed sides, called "skedenj" in Slovenian language. The latter are products of lateral movement of ancient glaciers, which only partially covered the original structural peaks.

Among epigean macro-karst forms, the snow shafts and dolines give the local landscape a characteristic appearance. Their density makes travelling over the plateaus difficult, especially off the paths. Snow shafts have the peculiar characteristic of being circular, a few metres in diameter and about a dozen of metres deep. The dolines often have very steep or subvertical slopes, generated at the intersection of major tectonic discontinuities. Snow deposits often remain all summer in the larger, deeper dolines.

The high degree of karstification of the Dachstein Limestone and of the Jurassic carbonate series, combined with the favourable structural setting, has produced a multitude of twisting micro-forms. Solution grooves and holes (pits and grikes and kamenitzas) characterise the whole plateau. Meandering karren, rarely found in other karst areas, are common. Solution grooves dominate along the steepest slope of the bedding planes, where the strata are thicker and slightly fractured. Deep grikes occur where fracturing has favoured water penetration (Fig. 12.4).

Hypogean karst is characterised by shafts forming some of the deepest abysses in the world. Mt. Canin caves have typical high mountain abyss morphologies, characterised mainly by the presence of vadose forms (waterfalls and structural shafts) which intercept active and inactive sub-horizontal systems (syngenetic phreatic galleries, with circular or elliptical sections). Underground drainage is directed (as in the past) towards four distinct valley systems, with different base levels, spring areas and evolution.

All around the massif there are nine permanent springs and other temporary springs that have an overflow function. Some have been identified in specific caves while others are not so clearly definable as they constitute true springs only during the heavy rain season, with water pouring from karstified fractures or interstrata. On the Italian side the most important is the Fontanon di Goriuda, a spectacular mouth suspended over the bottom of the valley from which the waters flow in a series of cascades with a drop of approximately 100 m,

Fig. 12.4 Glaciokarstic alpine landscape of northern slope of Mt. Canin, Julian Alps

reaching Raccolana Torrent, an affluent of Fella River. Other important springs of the Italian slopes are situated to the east of the small village of Sella Nevea and are used for drinking water. These waters feed the Predil Lake and the Slizza Torrent, flowing towards the Danubian basin.

12.4 Cansiglio–Cavallo Plateau

The Cansiglio–Cavallo is a plateau area bounded by higher ground and rising above the plain which extends along the western zone of the Carnian Prealps. Its western side is partially shared with the nearby Veneto Region. It rises steeply from the Friuli Plain and includes two large basins of karstic origin, the Pian del Cansiglio and the Piancavallo. These two depressions entrap cold air, thus the plateau is characterised by a continental climate with higher than normal humidity and average annual temperatures 2 °C below normal values based on the altitude alone.

The mountain range is a relatively homogeneous tectonic unit enclosed within major regional tectonic lines (Aviano fault and Barcis-Staro Selo line). It consists of limestone formed in the interval from the Triassic to the Cretaceous, topped by Eocene and Miocene siliciclastic rocks. It has huge limestone outcrops which are karstified to variable degree with large, diverse and diffuse surface forms, the predominant ones being dolines which bound the plateau to the east: symmetrical, closely spaced, deep, with sides sometimes marked by splendid karren.

In strictly morphological terms, the massif can be divided into three altitudinal zones, consisting of ridges at higher altitudes (>1800–2000 m), plateaus at intermediate altitudes and escarpments at the foot of the plateaus. Obviously the three zones are characterised by distinct landscapes. The intermediate altitudinal zone is made up of a system of more or less rectangular plateaus, with surface areas of approximately 450 km^2, and altitudes between 1000 and 1500 m. It has a more gentle relief towards the western region and steeper slope towards the plain. Piancavallo is a structural polje and is carved entirely within the limestones; Pian del Cansiglio is a border polje which has also evolved as a result of marginal corrosion (Fig. 12.5).

The surface of the Cansiglio–Cavallo sometimes features limestone pavements, while sometimes it is interrupted by fields of large- and medium-sized dolines separated by conical residual hills. Elsewhere the karst is characterised by rounded ridges and wide valleys with well-formed dolines. The occurrence of massive, resistant rock leads to a landscape dominated by blocks, often aligned along preferential directions, with rounded surface, interrupted by holes and narrow grikes. As a result of the outcropping of marly limestone of the Scaglia Formation in the western part of the Pian del Cansiglio subsidence dolines with sub-circular perimeters and flat bottoms predominate.

Over 250 caves are known today in the Cansiglio–Cavallo area. The deep karst is primarily vertical in structure, including a lot of small shafts. The most famous caves are the Bus de la Lum and the Abisso del Col della Rizza in the Friuli Venezia Giulia region, and the Bus de la Genziana located in the Veneto region. The latter opens out into the Scaglia, but extends for over 580 m deep into the underlying limestone of the Monte Cavallo Formation. Almost devoid

Fig. 12.5 Pian del Cansiglio plateau from Mt. Cavallo, Carnian Prealps. In the foreground an outcrop of Cretaceous limestone with a little kamenitza (*photo* B. Grillo)

of speleothems, it is characterised by alternating shafts and galleries and rises for almost 5 km of total length. It is one of Italy's two subterranean nature reserves.

The escarpment varies in width according to lithology and is crossed by torrential grooves and landslide scars. A polje opens out at the base of the southeast escarpment in which several springs emerge, their waters supplying a marsh from which a number of river branches originate, flowing into the Livenza River.

The largest spring is the Gorgazzo that owes its origin to the barrier caused by a system of thrust faults of a regional nature. The Gorgazzo is a vauclusian spring which feeds a pond, the outflow from which occurs only during high-water episodes (altitude 52 m a.s.l.). Still a destination for extreme cave diving explorations, the Gorgazzo is the deepest karst spring in Italy, as it has been explored down to a depth of 212 m below ground level (it goes down to at least 160 m below sea level!). The spring is characterised by a highly irregular regime, with high peak flow rates which return to normal within a few hours. The other perennial springs (at altitudes approximately 30 m a.s.l.) have average discharge rates of over 16 m^3/s and are characterised by a low degree of flow variation and extremely long depletion times. All these springs are source for Livenza River.

12.5 Carnian Prealps

The Carnian Prealps extend from Mt. Resettum (2067 m) to the Tagliamento River, thus covering an area of approximately 1000 km^2, with several karst areas. Geologically speaking, the area is composed primarily of karstified limestones of Jurassic and Cretaceous age. Structurally, the area forms part of an imbricated structure as a result of the presence of several overthrusts of regional significance.

The most highly karstified zones are Mt. Ciaurlec (1148 m) and the nearby Gerchia Plateau. The structure of the area is characterised by folds, the most important of which is Mt. Ciaurlec anticline. Surface karst features are represented in particular on Mt. Ciaurlec by small but numerous dolines and infrequent karren. Of particular note is the deep doline of Valmaggiore on its southwest slope. There is a high degree of karstification on the Gerchia Plateau (500–700 m), mainly in the southern part, where numerous dolines are found, usually elongated and non-symmetrical in form, some with coalescent edges. Large areas with frequent, intensely karstified outcrops like hums, pillars, karren and large grikes give rise to a ruiniform karst (Fig. 12.6), similar to a "città di roccia" (rock town) landscape (Perna and Sauro 1978). There are over a hundred caves in this area of approximately 3 km^2, many of which are characterised by a complex pattern with speleogenetically different voids, although they extend mainly horizontally. They are often hydrogeologically active springs or sinkholes at the end of small blind valleys. The plateau is dissected by a deep gorge about 1 km long, delimited by walls 250–300 m high. This active fluviokarstic canyon is rich in waterfalls, rapids, potholes and incised meanders and has intercepted a system of tunnels and caves. One of the caves—the Grotte Verdi di Pradis—and the entire gorge are easily accessible.

Fig. 12.6 Ruinform karstic hum emerges in the wood near Gerchia Plateau, Carnian Prealps

12.6 Julian Prealps

In the Julian Prealps, where the Eocene Flysch Formation outcrops, the landscape is predominantly fluvial but between marls and siliciclastic sandstones one finds several megabanks of calcarenites and carbonatic conglomerates and two tectonic wedges of Cretaceous (Mt. Bernadia, 878 m) and Jurassic (Mt. Matajur, 1641 m) limestones.

Some of the carbonatic banks outcrop as a result of differential erosion. Sinkholes or cave springs open out, creating the classical landscape of a marginal karst. Sometimes, limited thickness of the siliciclastic cover has allowed small suffosion dolines to originate, created by the collapse of caves in the underlying carbonatic conglomerate megabeds.

As a result of coarse texture, which does not allow for the formation of karren or kamenitzas, there are limited grikes or hums (toothed karren), surrounded by high vegetation. Carbonatic intercalations have led to the genesis of several active cave systems composed of blind valleys, sinkholes, cave networks and resurgence (Fig. 12.7). Close to the northern side of Mt. Bernadia there is a show cave (Villanova Cave) where erosion morphologies in the Flysch Formation and corrosion morphologies in calcarenitic banks occur side by side. A few kilometres away, at the end of a blind valley in the Flysch Formation, the impressive Viganti sinkhole opens up. This abyss is linked by a 40 m long siphon to the Pre Oreak cave, a horizontal gallery 400 m long, that opens near the Cornappo riverbed, 270 m below. The contrast between the characteristic fluvial landscape and karst features is striking.

12.7 Classical Karst

Classical Karst is a vast morphological unit that ranges from the southeast of the Isonzo River to Postojna (Slovenia). It forms a rectangular plateau with an area of 600 km^2, extending along a SE–NW axis for about 50 km and about 15 km wide, from sea level to about 600 m in altitude. The plateau is created by a thick succession of mostly carbonate rocks, from the Triassic to the Eocene, covered by flysch.

The large-scale landscape of the plateau is closely related to the petrographic characteristics of carbonate rocks. Along the Italian–Slovenian border we find a broad band of Lower Cretaceous limestone in which dolomitic levels are frequent, reducing the extent of karstification. At the centre of the plateau, where the most extensive karren and deepest dolines are located, very pure, highly stratified limestone of Upper Cretaceous age outcrop. On the edge of the plateau, sloping downwards towards the sea, slightly marly limestones dating to the Paleocene, often impure, outcrop. The various degrees of karstification naturally imply variable rates of corrosion. It is for this reason that the karst surfaces over time have evolved in such a way as to lead to a greater depression of the central part of the Trieste Karst, where limestone rocks dated to the Upper Cretaceous crop out. The effect on the landscape is a wide valley bounded to the northeast by elevations which follow the line of the border and to the southwest by smaller elevations which separate the plateau from the sea. This specific landform led a number of authors during the last century to suppose the action of a paleoriver during the Miocene in the initial stages of emergence of the

Fig. 12.7 A passage in Villanova Cave, Julian Prealps. The gorge is carved in marls and sandstones of Eocene Flysch Formation, on the ceiling a bank of calcarenite occurs (*photo* A. D'Andrea)

plateau when the subterranean hydrological network was still undeveloped.

The Karst plateau is the product of relatively advanced karst processes that have acted for almost 10 million years. Although the rate of surface dissolution is extremely low (0.02 mm/year, Furlani et al. 2009), time has rendered the original landforms almost unrecognisable. In the limited Trieste Karst sector (a surface area of less than 300 km^2) over 3000 caves are known; approximately 150 reach a depth of over 100 m, while half a dozen are over 1000 m in length. Several surface karst forms are worthy of note, giving the landscape its highly distinctive appearance (Cucchi 2009). There are about 80 solution and collapse dolines with a diameter greater than 100 m, and limestone pavements and karren cover a total area of some tens of km^2. The most representative surface forms are undoubtedly the polje hosting the Doberdò Lake, the Duino cliff, the Riselce doline, Borgo Grotta Gigante and San Pelagio karren fields (Figs. 12.8 and 12.9).

The hydrogeological model roughly distinguishes between three significant sectors: one in which waters flow from above ground (as they are flowing down non-karst valleys) to below ground (when they disappear into the depths) and flow into the karst-level waters (Cucchi and Zini 2002). The Timavo River (Reka River in Slovenian) disappears into the extraordinary sinkhole of the Skocjanske Jame (Slovenia), and then, after 40 km of a subterranean passage of which only a few parts are known, it re-emerges at full strength in San Giovanni di Duino (Italy). Another sector is the Karst Plateau in which waters flow at depth within a complex network of underground drainage systems and are also increased by surface infiltration of rainwater. The third sector, where karst waters emerge and flow into the sea, hosts a couple of temporary lakes covering the bottom of base-level poljes and a large number of springs, such as the Timavo springs. The spring system has an area of about 20 km^2. It consists of a series of modest, blunt elevations, including the Doberdò and Pietrarossa lakes, the Timavo springs, the minor springs that feed the Lisert and Moschenizze canals and the marine-coastal springs spread along the almost 7 km of high coastline—the Gulf of Trieste cliffs.

It is difficult to recommend the most interesting caves in the area, given their large number. The Grotta Gigante has been a show cave since 1908 and was included in the Guinness World Records in 1995 as the largest natural show cave in the world, whilst the Abisso di Trebiciano is the most famous vertical shaft, in which a branch of the Timavo River flows at the bottom. The caves conserve rare primary morphology, modified by filling deposits, collapses and all types of speleothems. The present morphology is related to polycyclic climate and base level changes. In this regard, two other caves are of great interest: the Skilan cave, near Rosandra Valley, which extends for over 6 km to a depth of 380 m (approximately the sea level!), and Savi cave, with its 4 km of galleries and beautiful rooms to the right of the Rosandra River. Only the Abisso di Trebiciano and the nearby of Lazzaro Jerko cave reach the branches of the underground Timavo River, and only a few others are reached by groundwaters during the biggest floods.

In the southeast area of the Karst, Val Rosandra stands alone: a valley deeply excavated or engraved in Tertiary limestones, marls and sandstones, with a morphology controlled by lithology and tectonics.

The Rosandra River is the morphological type representing a typical fluviokarstic valley, having carved out white limestone canyons, ingrown meanders, escarpments and created waterfalls, potholes and rapids.

Along the slopes marls and sandstones tectonically interbedded with limestones outcrop. The different erodibility has created a stepped slope. There are many caves inside the limestone of the side valleys: wide galleries and tight passages, large rooms highly covered by speleothems

Fig. 12.8 Karstified vertical strata of Cretaceous limestone in the cliff near Duino Castle, few kilometres from Timavo Springs, Classical Karst

Fig. 12.9 Limestone pavement of Cretaceous limestone with large kamenitzas near Borgo Grotta Gigante, Classical Karst

or by ceiling breakdowns and tiny spaces in smoothed rock. Speleothems of every type and thick filling fluvial and pre-historical deposits with traces of recent history, are a testimony to majestic flows and geological changes.

The interaction between physical features, vegetation and geographical location all go towards making Val Rosandra a geosite of global significance. The Karst is situated in a geographically strategic position and is marked by traces of human presence dating back to prehistoric times and intensified over recent centuries which have contributed to landscape modifications. Yet it was over the course of the past century, in particular during the First World War, that the landscape has been intensively and dramatically modified by human activities and needs, although these have had to adapt to the peculiarities of karst features. For example, people had to respect dolines in the planning of road and transport systems, and were guided in selecting the location for crops where the soil was more fertile and productive.

They avoided karren and grikes in grazing activities and sealed the bottom of a number of dolines, thus creating small artificial watering troughs.

The area characterised by Classical Karst landscape, which is extremely homogeneous in geological terms, has been and continues to be administered by two different States. This has led, since the end of the Second World War, to different kinds of anthropogenic modifications in terms of both type and intensity. We need only consider the presence of a large city such as Trieste, the suburbs of which have encroached over karst areas, and the constantly expanding population of small towns and villages built on the karst terrain. The Province of Trieste has a population density of over 1000 people per km^2 because of its provincial capital and also because the population of some of the municipalities located exclusively on the plateau has increased by 25% over the last 50 years, reaching densities of around 70 people per km^2. For comparison purposes, Slovenia's coastal region, which takes in the city of Koper, has a population density of 106 people per km^2, falling to just 36 people per km^2 in the inland karst regions.

All of this, in Italy, has resulted in an extremely dense road and transport system and fairly extensive and widespread civil and industrial urbanisation, which have fragmented the natural karst landscape. Slovenia, in contrast, despite undergoing considerable economic development over the last twenty years, has seen much less invasive modifications to the landscape.

12.8 Conclusions

Around 25% of the Friuli Venezia Giulia region consists of more or less karstified carbonate rocks. Moreover, in Friuli Venezia Giulia the specific geological, geographical and climatic conditions have given rise to a whole series of karst landscapes which have developed in different ways on limestone rocks of variable ages, located at different altitudes and exposed to karst processes for periods of time which vary but which nonetheless can be measured in millions of years.

Thus, from north to south one encounters splendid examples of alpine karst, mountain-hill karst and coastal karst. Alpine karst has developed on Palaeozoic and Triassic-Jurassic rocks; the mountain-hill karst is supported by Triassic, Jurassic, Cretaceous and Eocene rocks, and coastal karst is associated with Cretaceous and Paleocene rocks. Dolines, poljes, fluvio-glacial-karst valleys, blind valleys, karren, hums, caverns, shafts and caves, sinkholes and springs occur in a range of morphological variants.

The result is an extremely wide, complex variety of karst landforms, which take on different appearance and form according to altitude, exposure times, rock type and structure and overburden. Their exploration, both for scientific and excursion/tourism purposes, enables a comprehensive interpretation of the power of karstification.

The importance of Classical Karst as a model of karst landscape is highlighted in Slovenia by the inclusion of Skocjianske Jame in the list of UNESCO World Heritage Sites. Environmental protection and the management of protected areas in Slovenia value karst landscape greatly. Unfortunately, not the same is the case in Italy, but we hope that in the future the whole Classical Karst will be managed according to common protection rules and joint initiatives for promoting and enhancing geomorphological features of karst landscape will be implemented.

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The Tagliamento River: The Fluvial Landscape and Long-Term Evolution of a Large Alpine Braided River

13

Nicola Surian and Alessandro Fontana

Abstract

The Tagliamento River represents a reference system to observe natural, or semi-natural, forms and processes in the Alpine environment. In this chapter, the morphology of the Tagliamento in its lower sector (i.e. in the Friulian Plain) and the medium-long-term evolution of the river are described. The river is very wide and has a spectacular braided pattern. Its morphology undergoes rapid and abrupt changes, such as channel avulsion and bar formation or destruction. Islands are a distinct feature in this river and they are characterized by a rapid turnover. Besides recent channel adjustments due to some human interventions, the Tagliamento has undergone a complex evolution in the last 30,000 years and formed an alluvial megafan. Since the Last Glacial Maximum the downstream limit of gravel transport and channel typology have changed dramatically in response to climate change and sea-level variations.

Keywords

Braided river morphology • Channel adjustments • Last Glacial Maximum • Holocene • Friulian Plain

13.1 Introduction

Most Italian rivers have been subject to remarkable human impact over time, leading to significant alteration of river forms and processes (Surian and Rinaldi 2003). The Tagliamento River is one of the few large rivers draining the Alps where human impact has been relatively low, representing a reference system to observe and understand natural, or semi-natural, forms and processes. For this reason several geomorphologists and ecologists have widely studied this river over the last 15 years (e.g. Ward et al. 1999; Gurnell et al. 2000; Tockner et al. 2003; Gurnell and Petts 2006; Surian et al. 2009; Bertoldi et al. 2011; Ziliani and Surian 2012). Nowadays, the Tagliamento is well known within the scientific community but there is also a greater awareness among local population and different stakeholders (from water agencies to environmental organizations) of the major value of this river (Bianco et al. 2006).

Besides being a reference fluvial system, the Tagliamento displays a spectacular braided morphology along most of its course. The river channel is very wide, up to 1 km, and dynamic. Channels, bars and islands shift in position and change their form frequently. This implies that the overall morphology of the river is renewed year after year. In this chapter the morphology of the Tagliamento in its lower sector (i.e. in the Friulian Plain) and the medium-long-term evolution of the river are described. Over the last 30,000 years the Tagliamento formed an alluvial megafan and terraces, paleochannels and abandoned fluvial ridges are generally well preserved in the alluvial landscape. These landforms have a fairly higher visibility than in the other large Alpine alluvial systems of northeastern Italy (e.g. Piave, Brenta and Adige rivers) and their study has allowed to reconstruct the different phases of deposition and erosion that occurred in this fluvial system since the Last Glacial Maximum (LGM).

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13.2 Geographical Setting

The Tagliamento River is located in northeastern Italy, in the Friuli Venezia Giulia Region. It drains a 2580 km^2 basin and has a length of 178 km. The river flows from the eastern Alps and pre-Alps and has its source at 1195 m a.s.l. in the Dolomites and its mouth in the Adriatic Sea.

Mean annual precipitation is about 2000 mm/year, but there is significant variation within the basin, ranging from 1500 mm/year in some small portions of the upper and lower parts of the drainage basin up to 3100 mm/year in some central parts of the basin. Seasonal maxima and minima occur, respectively, in the autumn and spring and in the winter. Daily precipitation can exceed 400 mm. The Tagliamento River is characterized by a flashy pluvio-nival flow regime, which results from both alpine and Mediterranean, snowmelt and precipitation regimes. At the Venzone gauging station (located 22 km upstream of Pinzano gorge, Fig. 13.1) the maximum and the mean discharges in the period 1932–1973, were 4050 and 81 m^3/s, respectively (Surian et al. 2009). We refer to that period because there are some gaps in recent discharge measurements and significant changes of flow regime have not occurred over the last decades, except for low flows.

The Tagliamento catchment belongs to the eastern South-Alpine Chain, which is a SE-verging thrust-fold belt dominated by limestones and dolostones of Paleozoic and Mesozoic age. Several tectonic structures are still active and an earthquake with Magnitude 6.4 occurred in 1976 (the earthquake epicentre was in the pre-Alps, near Venzone). Besides the structural constraints, Quaternary glaciations played a key role in the morphological evolution of this region. During the LGM, which took place between 29,000 and 19,000 years ago, a large end-moraine system was built at the outlet of the Tagliamento catchment (Monegato et al. 2007) and fluvioglacial systems developed and shaped the Friulian Plain (Fontana et al. 2014b).

The Friuli Venezia Giulia Region is less populated than other regions in northern Italy (e.g. in comparison to Veneto and Lombardia). This fact explains why the Tagliamento River has undergone relatively lower human impact than other Italian rivers, and why recent and ancient fluvial features are often well preserved in the Friulian landscape.

13.3 Present Landforms and Recent Evolution

13.3.1 Channel Morphology in the Friulian Plain

The morphology of the Tagliamento River in the Friulian Plain (i.e. downstream of Pinzano gorge) varies in relation to bed material, channel slope, and human structures for flood control (Fig. 13.1). The river displays braided morphology from Pinzano (130 m a.s.l.) to Belgrado (15 m a.s.l.), where the channel bed and banks are mainly made of gravels, the channel slope is relatively high (i.e. 0.2–0.5%), and levees for flood control are far apart, having little influence on lateral channel mobility. Because the slope decreases notably downstream of Belgrado, the river becomes single thread. The river retains essentially natural features and dynamics up to Latisana (1 m a.s.l.), while in the lower course, the river has few natural characteristics because artificial levees constrict it in a relatively narrow channel. From Ronchis to the mouth, the river displays a sinuous or meandering pattern and flows along a fluvial ridge that is about 1000–2000 m wide and elevated up to 2–4 m over the adjacent floodplain (Fig. 13.1). The influence of the Adriatic Sea is felt up to Latisana, where the tide amplitude is 60 cm. Gravels are found almost up to that town, while downstream the bed is made of fine and medium sands. In the single-thread reach the depth of the channel is 2–3 m, but it can be up to 8 m in the outer side of the bends. Tagliamento mouth is a typical wave-dominated delta, characterized by a cuspate morphology with two wings occupied by the touristic beaches of Lignano Sabbiadoro and Bibione (Fig. 13.2).

13.3.2 Braided Morphology and Processes

The following part will focus on the braided reach because this is the dominant morphology of the Tagliamento. Braiding is a distinctive alluvial river morphology characterized by multiple intersecting channels (“anabranches”) separated by exposed bars, commonly unvegetated (Ashmore 2009) (Fig. 13.3). Braiding occurs in noncohesive sand and gravel and is common in mountain and piedmont environments, alluvial plains and glaciated regions with high rates of sediment supply. The channel morphology is extremely unstable and characterized by rapid and abrupt changes, such as channel avulsion and bar formation or destruction. Such changes take place only during periods of high flow, therefore dynamics is intermittent in these rivers. This means that channel morphology may remain stable for some months and then change notably in response to a single flood.

Between Pinzano and Belgrado, the Tagliamento displays a spectacular braided configuration. The channel is very wide, being 1850, 760 and 140 m at maximum, average and minimum width in this reach, respectively. As shown in Fig. 13.3, the flow is divided in two or more anabranches: commonly, there are 3 or 4 anabranches in this reach of the Tagliamento. Anabranches are separated by bars or, in some cases, by islands. The bars are completely unvegetated if their formation has recently occurred, while they can be covered by some herbaceous vegetation if sufficient time is

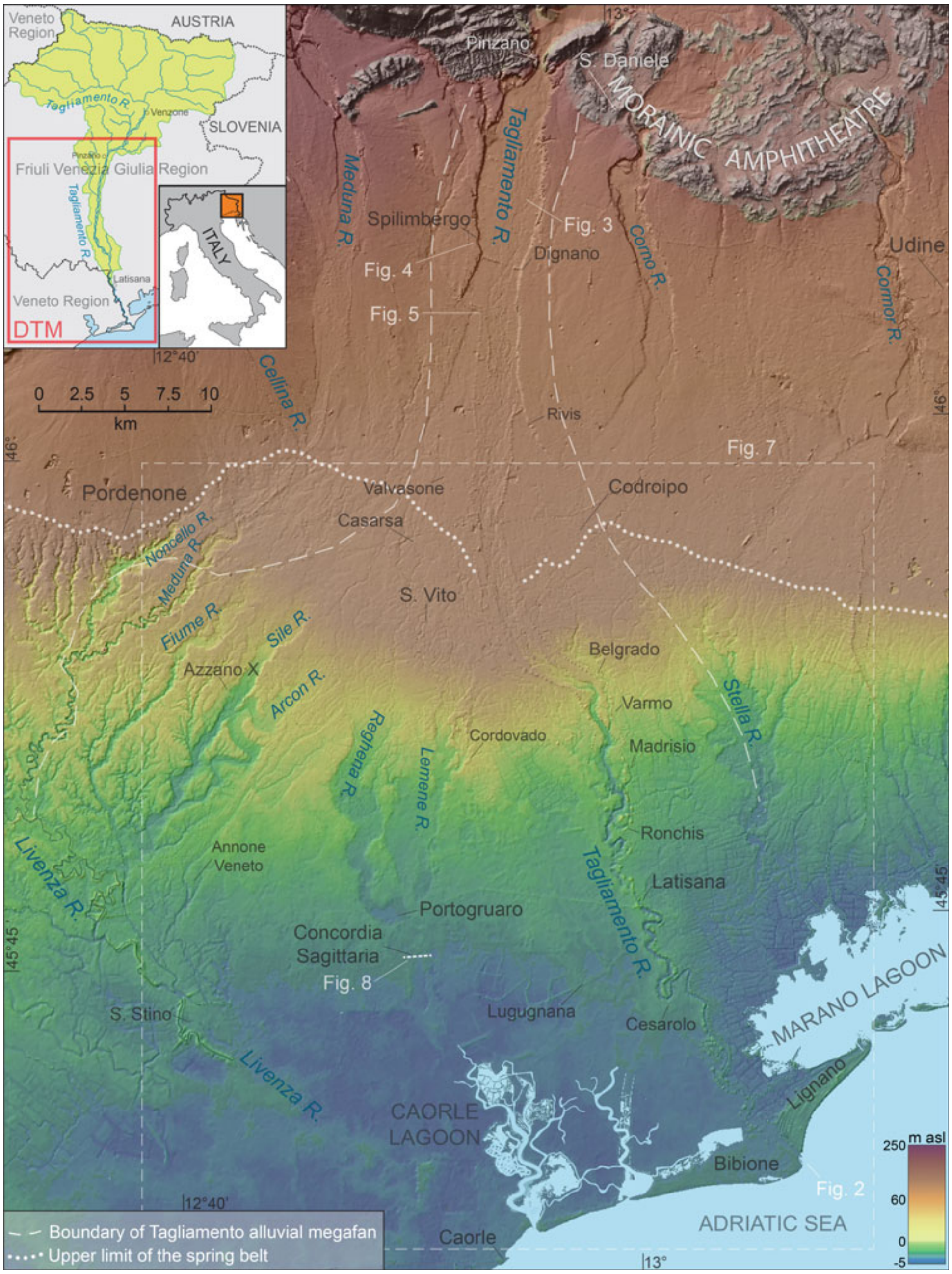

Fig. 13.1 Digital Elevation Model of the Friulian Plain showing the present course of the Tagliamento River and main landforms (e.g. paleochannels, scarps, fluvial ridges) related to its late Quaternary evolution (DEM obtained from reprocessing topographic data after Tarquini et al. 2007)

given to vegetation to develop. In some cases, a bar can be colonized and stabilized by more mature vegetation (i.e. high shrubs and trees), becoming an island. This implies that the overall braided morphology of this river is determined by the interplay between water, sediments, and vegetation. The Tagliamento is one of the most famous "natural laboratories" in the world, where the role of vegetation on channel morphology and processes has been investigated (e.g. Gurnell et al. 2000; Gurnell and Petts 2006; Bertoldi et al. 2011).

A large portion of the channel (i.e. bars and islands) is dry for most of the years when the flow is low and occupies only the anabranches. During summer, or other periods with very low flow, the channel can be completely dry in some sections, in particular near Casarsa. This is due to the efficient infiltration that takes places between Pinzano and Casarsa. Commonly, the river becomes "active" only some days in a year, when high flows or floods occur. When the flow exceeds a given threshold, gravels start to move in the channel bed and, then, on bars (Mao and Surian 2010). Besides gravel transport, bank erosion is another important process that contributes to the dynamics of this river. Banks can retreat several tens of metres up to more than 100 m during a single flood event (Surian et al. 2009). It is worth noting that not only very large floods but also frequent

Fig. 13.2 The mouth of Tagliamento separates the tourist beaches of Lignano Sabbiadoro and Bibione. In the foreground the wave crests evidence the present-day mouth bar, while in the *left* part of the *photo* (*middle*), the remnants of past sand ridges covered by woods can be seen. Between the river mouth and the lighthouse (white building on the *left*), jetties and other protective structures have been built in the last decades to reduce coastal erosion (*photo* A. De Rovere)

floods (e.g. with recurrence interval of 1.5–2 years) are able to produce remarkable changes of channel morphology (i.e. shifting of anabranches, bar migration, bank erosion).

As mentioned above, islands are distinctive features of the Tagliamento River. Islands are not homogeneously distributed between Pinzano and Belgrado because conditions for their formation (e.g. stream power, driftwood supply, moisture availability) vary along the reach. Vegetative regeneration from uprooted trees (i.e. large wood) deposited on gravel bars during floods is an important process in the development of islands (Gurnell and Petts 2006). Occasionally, islands are entirely generated by growth of riparian tree seedlings, but this is unusual on the Tagliamento because of the frequent flow disturbances. Vegetation turnover (i.e. the time that vegetation persists within the channel) is remarkably rapid in the Tagliamento. Comparing aerial photos of different dates, it was observed that about 50% of vegetation persists for less than 5–6 years and only 10% for more than 18-19 years. Besides, significant erosion of vegetation does occur with relatively frequent floods, i.e. floods with a recurrence interval of 1–2 years.

A fluvial landscape such that found along the Tagliamento in the Friulian Plain is rare in Italy, as well as in Europe. Besides the channel features and processes described above, it is worth noting that the whole fluvial corridor still remains in good environmental conditions (Fig. 13.3). First, the presence of artificial levees and bank protection structures (e.g. groynes) has limited effects on channel dynamics. In particular, such structures do not prevent lateral mobility, except in specific sections (e.g. bridge crossings). This is very important because lateral mobility is a key process in a braided river. Second, riparian forests are still widely present within the fluvial corridor. Besides their ecological values, riparian forests are important for the morphology of this river because large wood has a role in channel processes.

13.3.3 Channel Adjustment Over the Last 200 Years

Historical analyses have shown that the Tagliamento has notably changed its morphology over the last 200 years, and particularly over the last 40–50 years (Ziliani and Surian 2012). The river was wider in the past: channel width at the beginning of the nineteenth century was about twice the present width (Figs. 13.4 and 13.5). The river channel underwent three main phases of adjustment over the last 200 years. The first two phases, from the end of the nineteenth century to the early 1990s, were characterized by narrowing (very intense during the 1970s and the 1980s) and incision (i.e. bed level lowering of about 1 m). Widening

Fig. 13.3 Aerial photo of the Tagliamento River near Dignano, with Pinzano gorge in the background (*photo* R. Pizzutti). *Yellow arrows* mark the scarps limiting the post-LGM terrace

and slight aggradation have taken place in the third phase, from the 1990s to present-day. This evolution of the Tagliamento was driven primarily by human intervention at reach scale (i.e. sediment mining and channelization) (Ziliani and Surian 2012). The very recent channel changes (i.e. channel widening and aggradation), connected to a remarkable decrease of mining activity, were interpreted as part of a new phase of adjustment that is likely to continue for several decades.

In addition to channel width and bed-elevation, other morphological changes are worth to be described. In the reach from Pinzano to Belgrado, the river has maintained a braided configuration over the last 200 years, but braiding intensity has changed notably. The braiding index (BI), which gives a measurement of the number of anabranches in a river reach, decreased moderately from the nineteenth century (BI = 5.9 in 1833) to 1954 (BI = 4.9) and then more intensely in the following decades (BI = 2.8 in 2007). On the other hand, changes in channel configuration took place downstream of Belgrado (Fig. 13.1). First, it worth noting that there used to be a braided morphology also 4–5 km downstream of Belgrado. For instance, this was the river condition at the end of the nineteenth century. Second, starting from the 1970s, there has been a reduction in the number of reaches with transitional (i.e. wandering) and meandering morphology and an increase of those with sinuous or straight configuration.

13.4 Long-Term Evolution

The recent morphological changes documented along the Tagliamento River have been mainly controlled by the variations in sediment flux and flow regime. From a general viewpoint, these factors are the same that have driven the long-term evolution of the Tagliamento megafan. But, considering the Quaternary evolution, the magnitude of the variations in sediment flux and flows were higher because of the dramatic climate changes and sea-level fluctuations that have occurred since the Late Pleistocene.

13.4.1 River and Floodplain Dynamics During Last Glacial Maximum

At the peak of the last glaciation, when the Adriatic shoreline was south of Ancona and the Tagliamento glacier reached the Friulian Plain, the Tagliamento River was one of its main outwash rivers together with Corno, Cormor and Torre rivers. It formed an alluvial megafan of 1200 km^2, with a typical divergent shape, extending from Pinzano to the present Adriatic shelf (Fontana et al. 2014a). The glacial front supported the fluvial system with an enormous quantity of sediment and allowed a widespread aggradation of the whole plain, with deposition of 20–30 m of sediments between 29,000–19,000 cal. years BP (A in Fig. 13.6). Channel shifting was very frequent, especially during summer meltwater, and avulsions at the apex of the fan was the main process leading to alluvial deposition over the entire megafan surface. The river channels were unconfined and transport capacity was lost within the proximal portion of the plain. Thus, gravels travelled only up to 10–20 km from the apex of the megafan (see dotted line in Fig. 13.1 and #3a in Fig. 13.7), while medium and fine sands were the only coarse material reaching the distal plain. This strong grain-size sorting led to the differentiation between the proximal gravelly plain and the distal fine-dominated sector: the so-called *alta* (high) and *bassa pianura* (low plain) in Italian, that are divided by the spring belt, where groundwater crops out and feeds a dense network of minor streams. During LGM peak, before 22,000 years BP, even in the distal plain the channel belts of the Tagliamento were braided, but sandy, while meandering pattern was present only in the very terminal sector of the megafan, now submerged by the Adriatic Sea. Geophysical soundings carried out in the Adriatic platform allowed to recognize the Tagliamento megafan up to 15 km from the present coast, while downstream a floodplain environment was present.

The retreat of the Tagliamento glacier started around 22,000 years BP, but ice mass occupied part of the moraine amphitheatre until 18,600 years BP, when it definitively abandoned the plain (Fontana et al. 2014b). During the onset of glacial withdrawal (B in Fig. 13.6), in the apical sector of its megafan, the Tagliamento River entrenched for about 15–20 m from the top of the surface of LGM peak (Fig. 13.4). But, at the same time, deposition still occurred in the distal plain, where narrow and low fluvial ridges formed downstream of the spring belt (#4 in Fig. 13.6). These are characterized by single channels with low sinuosity, consisting of gravelly sands as far downstream as the present lagoon area, with a maximum grain size of 1 cm. Channel deposits have a mean depth of 2–4 m and a width of 40–250 m. Because of the entrenchment in the apical sector, the sedimentary flux became confined and the funnelling effect led to transport of gravels even in the distal sector. It is likely that a large part of the gravels forming the channel infill was cannibalized from the tract upstream of Codroipo, where the Tagliamento was eroding the deposits of LGM peak.

Fig. 13.4 The castle of Spilimbergo is built on the LGM terrace and faces the western scarp limiting fluvial incision of the Tagliamento. The river was flowing below the castle until the beginning of twentieth century and moved toward the eastern scarp due to the progressive narrowing related to construction of groynes and gravel mining activity. In the background, the *light stripe* of gravels coincides with the active channel (*photo* S. De Toni)

13.4.2 Lateglacial and Early Holocene Fluvial Incisions

Since about 18,500 years BP, when the glacier finally contracted in the inner mountain valley, the Tagliamento River persisted as the only stream fed by the mountainous drainage basin. On the contrary, the other former glacial outwashes (i.e. Cormor, Corno) became minor streams with small catchments. Because of the concentration of water discharge along a single river and vanishing of the important sedimentary input represented by the glacial front, the Tagliamento megafan experienced a phase of severe erosion (C in Fig. 13.6). During Lateglacial the river strongly incised into the LGM gravelly deposits of the piedmont sector along a valley and the resultant incision has a width between 1 and 3 km and it still confines the present-day river channel up to Rivis (Figs. 13.1 and 13.4). The scarps have a maximum height of 70 m near Pinzano and they progressively diminish downstream, until they disappear near Casarsa. On the contrary, in the distal sector of the plain, the Tagliamento formed several different valleys, but they have been filled and reworked by the deposition of the post-LGM lobe of the megafan (D in Fig. 13.6). The different channel belts forming this lobe (Fig. 13.7) show a divergent pattern from an avulsive node situated at the limit of the spring belt, where the gradient abruptly changes from 3 to 1‰. The oldest channel belts, dated between the Lateglacial and early Holocene, are deeply incised into the LGM deposits, while the late Holocene channel belts aggraded on the LGM surface and formed fluvial ridges.

Some valleys are still partly visible in the present landscape or through the analysis of topographic microrelief (Fig. 13.1). In particular, the Lemene, Reghena, Arcon, Sile and Fiume rivers, which are fed by groundwater, flow along depressions previously formed by the Tagliamento during Lateglacial (#14 and 15 in Fig. 13.7). Other fluvial incisions or parts of them have been buried by younger depositional units of the Tagliamento that re-used its older valleys; this fact is documented for the directions of Portogruaro—Concordia Sagittaria, Cordovado−Lugugnana and Latisana (#5, 6, and 7 in Fig. 13.7) (Fontana 2006). The valleys formed by the Tagliamento in the distal sector of its megafan had widths spanning between 500 and 2000 m; their depths reached 2–4 m near the spring belt, but it increased downstream to 15–20 m over a distance of 20 km. This area corresponds to the present coastal sector, where these fluvial incisions have been later completely filled by Holocene lagoon and alluvial deposits. Thus, now these valleys can be detected in this sector only through examination of stratigraphic record from boreholes, as in the case of Concordia Sagittaria (Fig. 13.8). The continuation of some of these fluvial incisions has also been documented in the Adriatic seafloor by cores and geophysical soundings.

Some metres of gravels are documented at the base of the valleys up to the present lagoon and, thus, they arrived some tens of kilometres downstream than during the LGM peak. These coarse sediments reached the distal sector of the megafan because of the funnelling effect related to the concentration of the sediment flux along the incised channels. Large part of the gravels found in the distal part of the megafan had been cannibalized by the Tagliamento River from the deep incision of the apical portion.

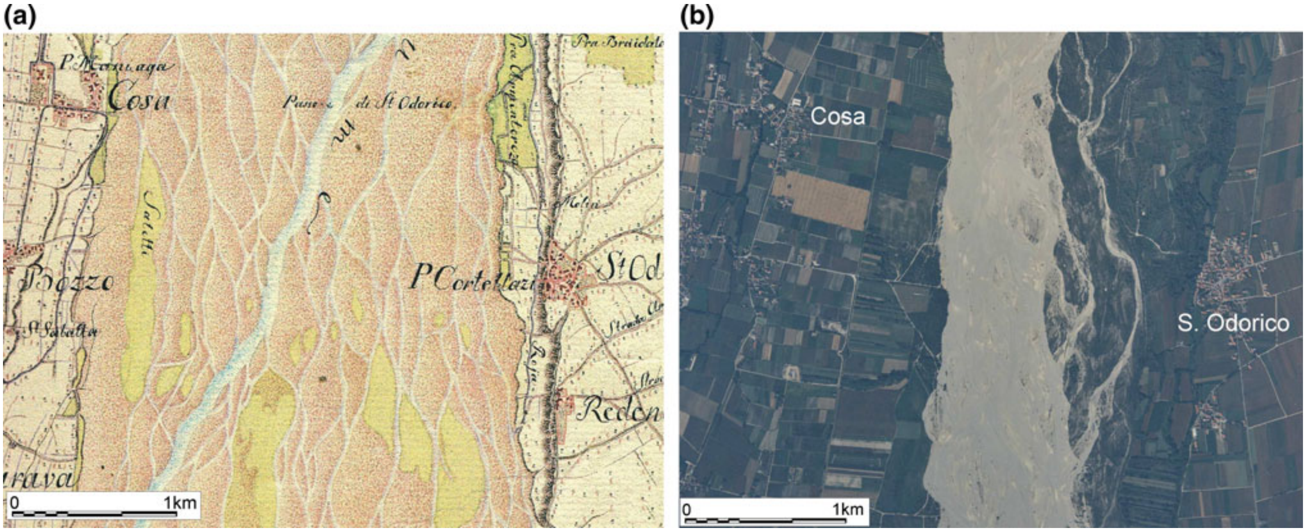

Fig. 13.5 Comparison of channel morphology in 1805 **(a)** and 1999 **(b)** in a reach few kilometres downstream of Spilimbergo

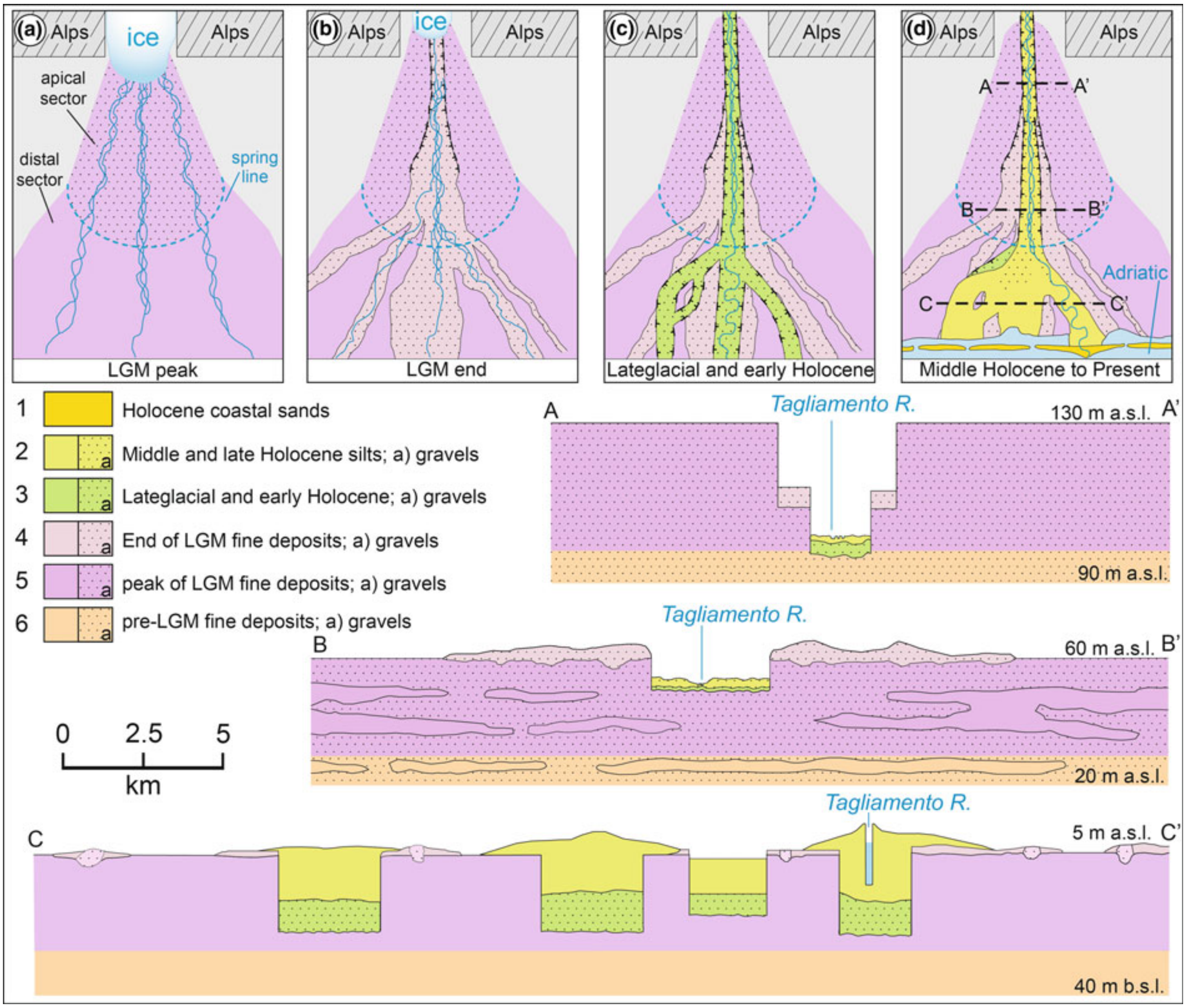

Fig. 13.6 Scheme of the geomorphological evolution of the Tagliamento alluvial megafan since Last Glacial Maximum (modified after Fontana 2006, 2014a)

13.4.3 Interaction with Marine Transgression and Late Holocene Evolution

As documented in the section of Concordia Sagittaria, the valley was already partly filled by gravels at 14,000 years BP and was subsequently abandoned by the Tagliamento at 8500 years BP; a comparable chronology was recognized in the valley now occupied by the Reghena River and in the fluvial incision underlying the channel belt of Roman time (Fontana 2006). The fluvial system incised during Lateglacial and early Holocene, thus concurrently with sea-level rise due to postglacial climate warming. But gravel transport in the distal plain lasted until about 8500 years BP, when the sea reached a relative level of about 10 m below the present one. Since that period the coastline achieved a setting that was already fairly comparable to the present one and the base of Caorle and Marano lagoons is dated at 7500 years BP.

Sea-level highstand strongly lowered the channel slope in the distal plain and, therefore, the stream power of the Tagliamento. In the last millennia, the limit of gravel transport has progressively migrated upstream, following the relative sea-level rise. Along the present-day Tagliamento channel the gravels come to rest slightly north of Latisana, that is 10 km upstream than the most distant position reached during Lateglacial. Since 8000 years BP, in the distal plain, the valleys started to be mainly filled by fine alluvial deposits.

During post-LGM the Tagliamento followed different directions that diverged from the avulsion area located between Valvasone and S. Vito. In response to flood periods or severe events, the river shifted position quite frequently in the last 17,000 years. Because of the topographic depression represented by the Lateglacial fluvial incisions, these valleys were re-used several times by the river. In the time elapsed between one phase of activity and another, the valleys were

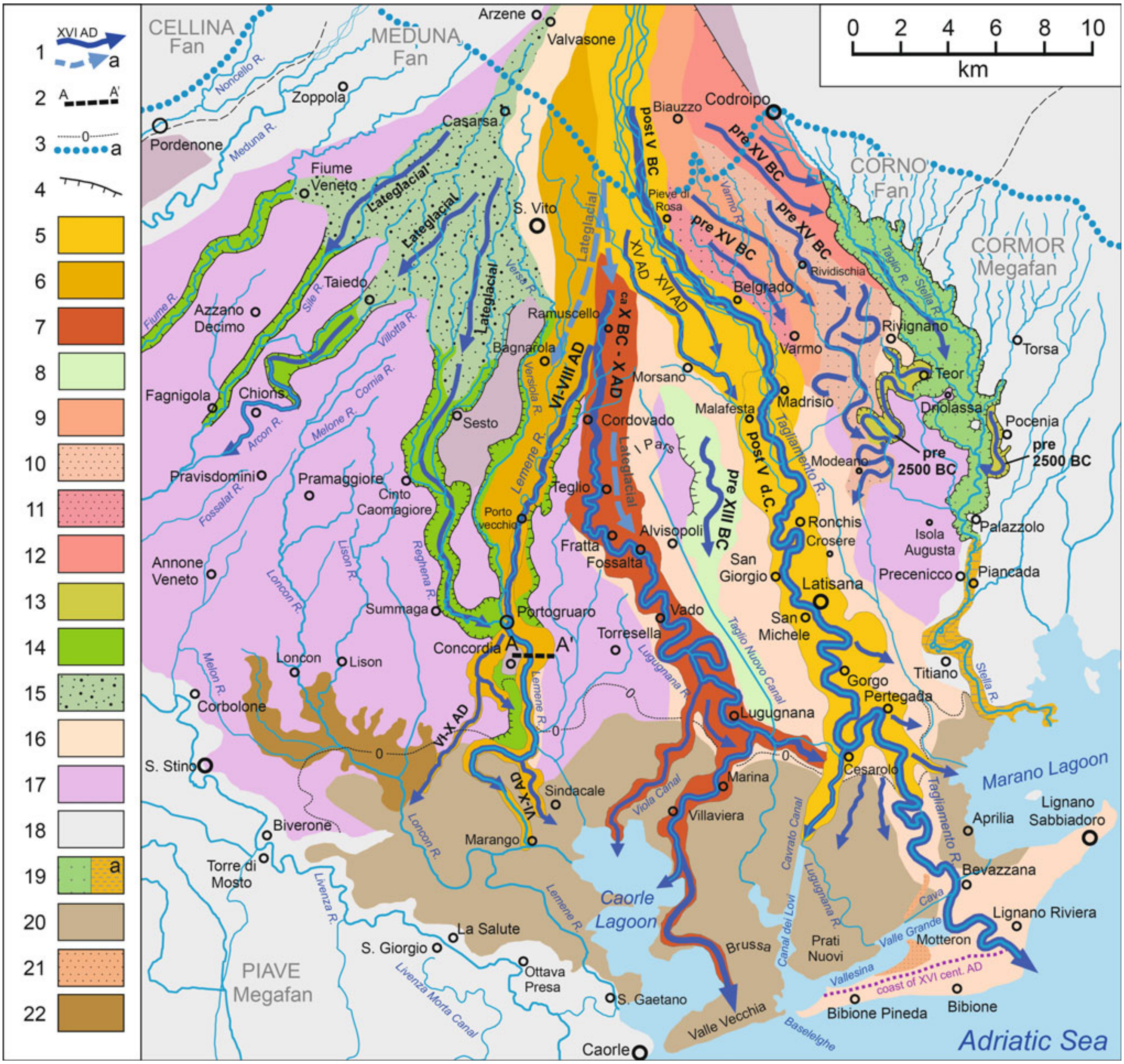

Fig. 13.7 Simplified scheme of the Tagliamento River evolution during post-LGM (last 17,000 years) (modified after Fontana 2006). Legend *1* channel belt, with indication of the period of activity, *1a* buried channel belt, *2* trace of stratigraphic section in Fig. 13.8, *3* isoline 0 m a.s.l., *3a* upper limit of the spring belt, *4* fluvial scarp, *5* present Tagliamento unit <sixth century AD, *6* Concordia Sagittaria unit sixth-eight century AD, *7* unit of *Tiliaventum Maius* active in Roman period 1st millennium BC—eight century AD, *8* Alvisopoli unit, >3300 BP, *9* Glaunicco-Varmo unit, >3500 BP, *10* Rividischia unit, >3500 BP, *11* San Vidotto unit, >3500 BP, *12* Iutizzo unit, >3500 BP, *13* Campomolle and Pocenia units, >4500 BP, *14* Lateglacial units, *15* Lateglacial valleys now reoccupied by groundwater-fed streams, *16* undifferentiated post-LGM deposits, *17* LGM deposits, *18* deposits of other fluvial systems, *19* incision of Stella River, remodeled by Tagliamento in 4500–2800 BP, *19a* deposits of Stella River with input from Tagliamento River, <4500 BP, *20* Holocene lagoon deposits, *21* pre-Roman coastal sand ridges, *22* swamp of Loncon

temporarily occupied by the groundwater-fed rivers that created a swampy environment and favoured accumulation of peaty and organic layers (#5 in Fig. 13.8). Due to the post-LGM marine transgression, around 7000 years BP the relative sea level was at about −10 m. Since that time the coastline reached a position comparable to the present one, but brackish waters expanded further inland along the pre-existing depressions connected to the sea. This dramatic environmental change occurred also along the fluvial incision of Concordia Sagittaria that had been already abandoned by the Tagliamento at that time, and led to the sedimentation of lagoon deposits until the city of Portogruaro (#4 in Fig. 13.8). This setting lasted for several millennia, but the Tagliamento temporarily re-used the valley of

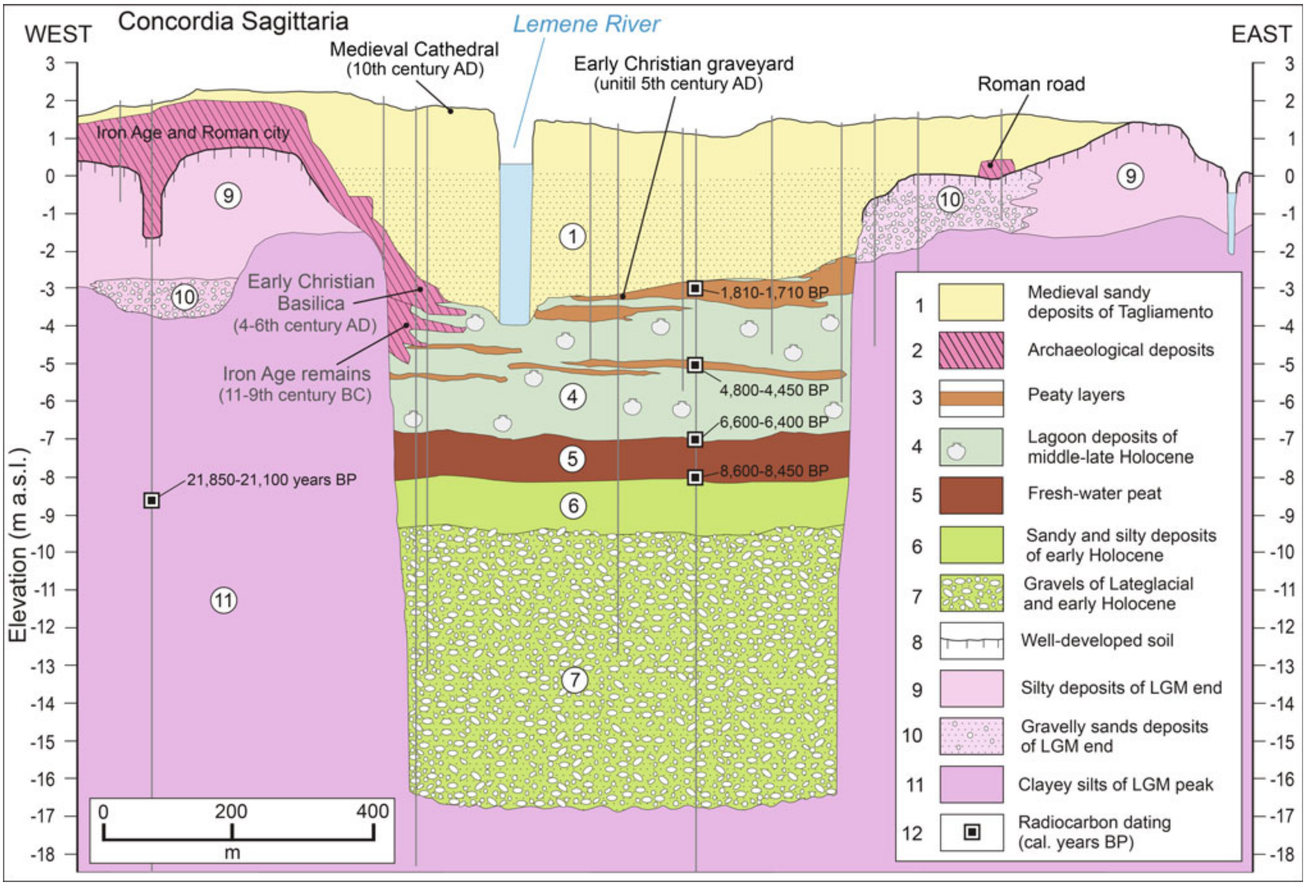

Fig. 13.8 Concordia Sagittaria, stratigraphic section of the fluvial incision formed by the Tagliamento River during Lateglacial and filled in the middle-late Holocene (modified after Fontana 2006)

Concordia Sagittaria around 4,500 years BP and completely filled it with silty sands between the sixth and eight centuries, sealing large sectors of the Roman city of Concordia (Fontana 2006). The alluvial cover preserved the archaeological remains that, after the stratigraphic excavation of the nineteenth–twentieth centuries, are widely exposed and available for tourist visits, in particular, the mosaics of the early Christian Basilica.

Except the deltaic area, alluvial deposition was confined within the fluvial incisions until about 3500–3000 years BP. At that moment, probably in response to sea-level position and sediment supply, the active channel belt of the Tagliamento started to flood over the LGM surface and a new phase of widespread deposition has begun. Wide and high fluvial ridges have developed along the meandering channels and the related floodplain extends for 1–2 km far from the river. This situation characterizes the channel belts numbered as #5, 6, and 7 in Fig. 13.7. The first corresponds to the so-called *Tiliaventum Maius*, cited by Plinius the Elder, and was active from the 1st millennium BC to early Middle Age. Between the sixth and ninth centuries AD several floods led the Tagliamento to flow along the directions of Concordia Sagittaria and Latisana and to progressively abandon the *Tiliaventum Maius*. Since the tenth century AD the present course has been the only active channel belt and minor variations occurred to this path.

The present cuspate delta started to form in the sixth century AD and experienced an almost continuous progradation between the Middle Ages and the beginning of the twentieth century, but a clear erosional trend has been noted since 1960s. In the last 50 years, the area of the mouth retreated by about 400 m and sediment loss occurred in many tracts of the beaches of Lignano and Bibione, leading to management problems of touristic activity (Fig. 13.2). This process is probably related to the sediment mining activity that took place upstream from Latisana, which could have had effects on the quantity of sand reaching the mouth.

13.5 Final Remarks on River Management

This chapter illustrates the fluvial landscape of the Tagliamento River, pointing out that both its present river corridor and the whole alluvial plain are peculiar in comparison to those of other large Alpine rivers. The fact that the Friuli Venezia Giulia Region has undergone a lower human impact compared to other alpine regions helps to explain why the river can be still considered semi-natural and why ancient fluvial features are often well preserved in the Tagliamento riverine landscape. That said, river management—which has to take into account several issues (e.g. different water needs, flood risk, ecological aspect)—is very challenging in the Tagliamento. For instance, a strong debate has been going on about how to reduce flood risk at Latisana (the town was heavily affected by the 1966 flood), without affecting the great ecological value of the river. It may be concluded that this river represents a good opportunity to reconcile the aims of the two European Directives that are driving river management at present, the Water Framework Directive (2000/60/CE) and the Flood Directive (2007/60/CE) whose goals are to improve the ecological quality of rivers and to reduce flood risk, respectively.

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Lake Garda: An Outstanding Archive of Quaternary Geomorphological Evolution

14

Carlo Baroni

Abstract

Pleistocene glaciers repeatedly filled the elongated crypto-depression presently hosting Lake Garda, building a complex suite of end moraines at the Alpine foothills and looping out onto the Po Plain. The moraine amphitheatre impounded Lake Garda, the widest Italian lake, and offers a well famous example of glacially originated landscape. The mountain sector of the lake depression deeply enters the alpine border and the complex geological structure strongly conditioned the geomorphological setting of the area. A suite of well-preserved lacustrine relict landforms document the articulated history of the paleo-Lake Garda that developed after the withdrawal of Pleistocene glaciers. Relevant is the connection of landscape features and Quaternary sediments with the archaeological heritage of human frequentation of the area, furnishing a very helpful tool for investigating the paleoclimatic evolution of this region as well as for investigating neotectonic activity.

Keywords

Glacial geomorphology • Relict shorelines • Pleistocene • Holocene • Lake Garda

14.1 Introduction

Pleistocene glaciers repeatedly filled the valley depression hosting the Lake Garda in Northern Italy, similarly to most of the Alpine valleys reaching the Po Plain. The spectacular relict glacial landforms and the impressive moraine amphitheatre abandoned at the alpine foothills preserve an outstanding geological and geomorphological archive of the Pleistocene paleoclimatic and paleoenvironmental evolution of the entire Alpine Chain. The Garda region is representative of an archetypal landscape that characterizes the southern margin of the Alps. The lake is nestled between the dominating mountain ridge of Mt. Baldo to the east and the articulated relief of Lombardian Prealps to the west (Fig. 14.1). These mountains surround the lake today but they also hung over the glacier filling the lake depression during the repeated Pleistocene glacial advances. Even during glacial periods these mountain terrains offered an ice-free environment, suitable for human settling in the surrounding of the glaciated world since the Early Paleolithic.

Following the complete deglaciation of the region, the lacustrine landscape features and their surroundings attracted human occupation since at least 15 ka BP, essentially without interruption. In particular, as it concerns the near-shore belt, modern humans first settled during the Neolithic at the margin of the paleo-Lake Garda and since then interacted more and more intensely with the evolution of the landscape of this region. As a result, the present-day landscape is deeply anthropized and very rich in human settlements and other remains of considerable archaeological interest.

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World Geomorphological Landscapes, DOI 10.1007/978-3-319-26194-2_14

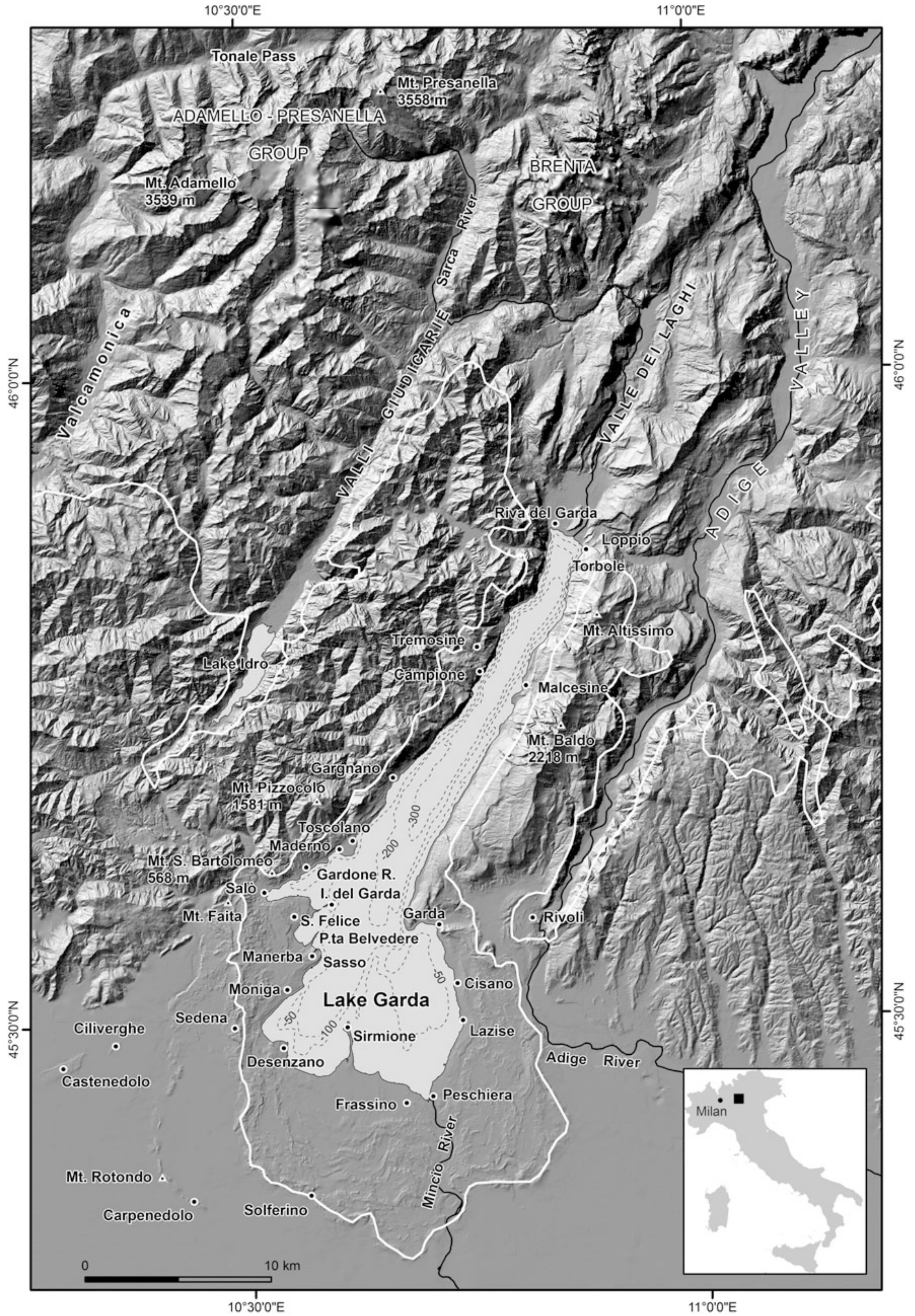

Fig. 14.1 Lake Garda and location of sites geomorphological interest. The *white line* indicates the limit of the Garda Glacier during the LGM

The marine appearance of the southern portion of the lake expanding on the high Po Plain is a significant feature of the landscape, unique in all the Po Plain; this characteristic of the lake contributed to the fame of Lake Garda (also known as Benàco) since the Roman Period. At that time, Virgilio (Georgiche, II, 158–160) underlined the marine nature of the lacustrine waves under storm condition (…*fluctibus et fremitu adsurgens Benace marino)* and Catullo celebrated the beauty of the peninsula of Sirmione. For thousands of years, the mild sub-Mediterranean climate regulated by the lake water and the 'Mediterranean' landscape of the Benàco have assumed an enduring, strong, cultural and aesthetic attraction, inspiring many poetries and artists (e.g. J.W. Goethe and G. D'Annunzio).

14.2 Geographic Setting

Lake Garda is the largest Italian lake, covering a surface of 368 km^2 (Fig. 14.1). Its maximum length and width are 51.9 km and 16.7 km respectively, while the perimeter extends for 155 km. Lake Garda occupies a depression transversally oriented with respect to the Alpine chain. Actually, the Garda basin develops in a deep crypto-depression (−346 m below the present lake level and −281 m below the mean sea level) roughly oriented NNE–SSW, stretching from the margin of the Po Plain into the Southern Alps. The characteristic shape of the lake defines, along the major axis, two main portions: (i) an inner valley segment entering the Southern Alps (about 35 km long and from 3 to 6 km wide); and (ii) a larger portion of the lake expanding in the foothills up to the maximum width of 16.7 km, bordered by a complex moraine amphitheatre. The peninsula of Sirmione and the line joining Sirmione—Garda separate the foothill portion of the lake in two main portions: the western portion consists of large bays, from Salò to Desenzano, with depths between 100 m and 200 arranged in continuity with the maximum depths that characterize the intermountain valley. The most eastern portion of the piedmont basin, instead, is characterized by relatively low depth, largely lower than 50 m, anyway not greater than 80 m.

The catchment area covers 2260 km^2 and deeply enters in the Southern Alps, reaching the maximum elevation of 3558 m a.s.l. at Mt. Presanella (Fig. 14.1). The ratio between the area of the lake and the area of the basin (1:6) is much greater than that of all other pre-alpine lakes (always less than 1:30). The total volume of water stored in the lake is about 50 km^3, with an average residence-time of about 28 years. The average lake level is about 0.9 m over hydrometric zero set at 64.027 m a.s.l. at Peschiera del Garda. The seasonal fluctuation is around 1 m and maximum values do not exceed 2 m. Since the nineteenth century, a dam across the River Mincio at Peschiera has regulated the Garda basin. The maximum springtime limit is at present 140 cm in April, while the autumn limit is around 80 cm; the minimum absolute limit is set at 15 cm over hydrometric zero (Baroni 2010).

14.3 The Origin of Lake Garda Depression: The Morphostructural Setting

The Garda depression divides two different geological domains of the Southern Alps, the Lombardy basin to the west and the Venetian Platform and Trento high ridge to the east (Fig. 14.2). This depression is located to the south of the Adamello-Presanella composite batholith, the largest Cainozoic plutonic body in the Alps (Late Eocene to Late

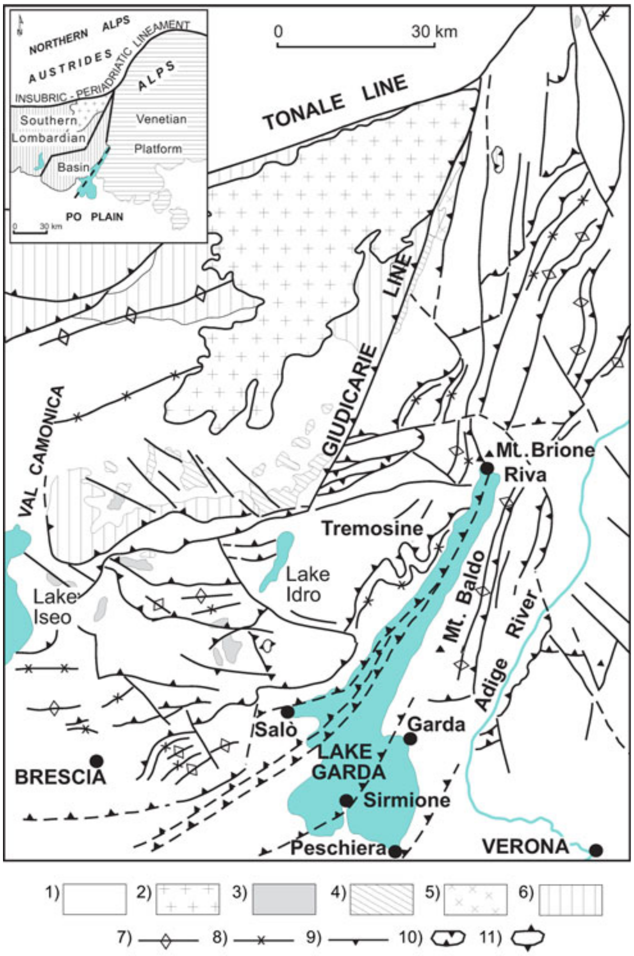

Fig. 14.2 Geological sketch map of the Adamello-Presanella Group area. Legend: *1* Sedimentary cover (upper Permian-Neogene); *2* Paleogene Adamello-Presanella granitoids; *3* Middle Triassic effusive and intrusive rocks; *4* lower Permian volcanic plateau (mainly rhyolitic rocks); *5* post-Hercynian granitoids; *6* metamorphic basement rocks; *7* anticline (selected); *8* syncline (selected); *9* main thrust; *10* klippe and summit overthrust; *11* tectonic window. Redrawn and modified after Castellarin et al. (1992, 2005) and Baroni (2010)

Oligocene in age), intruded in a structural wedge bordered by the Periadriatic fault system (Insubric Line) and by the Giudicarie Line (Castellarin et al. 1992; Callegari and Brack 2002; Castellarin et al. 2005). The Garda depression, developed during the Mesozoic, was successively reactivated on several occasions during the alpine compression, and still separates structural sectors with different kinematic behaviour and is still considered as seismogenic.

The complex geological structure of the region strongly conditioned the geomorphological setting of the area. The mountain sector of the lake depression deeply enters the alpine border (Fig. 14.3) and, to the north of Riva del Garda, is connected with the Sarca River valley (the main tributary of the Benàco). Further north, the elongated Garda Lake—Sarca Valley depression extends to a segment of a dead valley, known as Valle dei Laghi, whose head is suspended above the Adige Valley and which drained a significant transfluence of the Adige Glacier toward the Garda Lake depression during Pleistocene glaciations. In this area, the geological structure is characterized by a complex sequence of asymmetric folds conditioned by the activity of the Giudicarie System. In extreme synthesis, the Triassic-Eocene carbonate succession is divided in NNE–SSW elongated blocks dipping toward WNW and separated by several tectonic lineaments. The folded-faulted complex system gives rise to a sequence of monocline morphostructures defining asymmetric ridges with western structural slopes and eastern tectonic scarps with dip slopes. Therefore, the resulting valleys correspond to depressions between tectonic scarps and dip slopes (Cavallin et al. 1997). This morphostructural setting is very prone to the development of deep-seated gravitational slope deformations (DGSDs) along the asymmetrical valleys, particularly in correspondence with the tectonic scarps (Carton 2017). Landslides which originate in this environment are both rock falls detaching from tectonic scarps and translational landslides along bedding surfaces on the opposite side of the valleys. Such landslides are locally known as '*marocche*' and have been recently recognized as rock avalanches, able to move for kilometres, to cross the valley bottom and go up on the opposite slopes (Cavallin et al. 1997; Castellarin et al. 2005).

The complex geological structure of the area gives rise to several morphostructures, well identifiable as distinct landscape features, worthy of being considered as geomorphosites. Relevant is the asymmetric syncline hosting the northern portion of the lake, that gives rise at Mt. Brione, in the Riva del Garda area, to a cuesta-like structure with *Calcarenite* of Middle–Late Oligocene to Early Miocene age dipping toward WNW (Fig. 14.4).

A sequence of impressive flatirons occurs on the western slope of the Mt. Baldo ridge. They have developed on the western side of a faulted anticline structure bordering the eastern side of the syncline described above (Fig. 14.5). These morphostructures are elements that give identity to the landscape of the northern sector of the Lake Garda, being visible from any observation point.

On the opposite side of the lake, on the western coastal margin, cliffs due to differential erosion roughly oriented NNE–SSW represent outstanding landscape features. They underline the overthrusts developing along the western coast of the Lake Garda and verging towards ESE and SE (Tremosine-Tignale thrust and associated folds; Fig. 14.2).

According to Bini et al. (1978) and Finckh (1978), the Lake Garda crypto-depression (like the crypto-depressions

Fig. 14.3 Panoramic view from N (Mt. Altissimo) of Mt. Baldo ridge on the *left*, the Lake Garda and on the *right* the articulated relief of the western coast (*photo* G. Carton)

Fig. 14.4 The northern margin of the Lake Garda with Mt. Brione cuesta-like structure near Riva del Garda (*photo* G. Carton)

Fig. 14.5 The western slope of Mt. Baldo with the well developed flatirons (*photo* G. Zordan)

presently hosting the other Pre-Alpine southern lakes) originated from canyons deeply eroded by rivers during the Messinian evaporitic drawdown (Late Miocene), when the Mediterranean basin was isolated from the Atlantic Ocean. At the beginning of Pliocene, with the opening of Gibraltar Strait and the filling of the Mediterranean, the sea transgressed onto the lower part of the Southern Alps foothills, entering the Messinian canyons (Corselli et al. 1985). The continuous uplift of the region caused a definitive regression of the sea from the Lombardian plain, which was then successively filled by continental fluvial and fluvioglacial deposits. In fact, deltaic to continental sediments, late Miocene to late Pliocene (?) in age, uplifted to elevation exceeding 500 m at Mt. S. Bartolomeo (Salò), document the continuous uplift of the western coast of the lake. Neotectonic activity occurred also during the middle and late Pleistocene, as evidenced by the anticlockwise rotation (toward east) of the moraines of the different phases, and during the Holocene, as documented by the displacement of Holocene lake levels (Baroni 1985, 2010).

Neotectonic activity is well documented also in the southern sector of Mt. Baldo (Forcella and Sauro 1988) where evident scarps cut and displace dolines and other karstic features. Furthermore, in the same area a ribbon-like scarplet documents a recent (Holocene) episode of seismogenic surface faulting, probably originated due to a destructive earthquake.

14.4 Pleistocene Glaciations and the Moraine Amphitheatre

The Pleistocene glaciations profoundly re-shaped the main alpine valleys that reach the Po Plain and repeatedly determined also glacial re-modelling of the Lake Garda depression. Alpine glaciers infilled the Prealps margin along the Garda trough several times since at least the late Early Pleistocene. There is a lively discussion concerning the evidence of Pliocene glaciations in the southern alpine margin. Stoppani in the nineteenth century hypothesized that glaciers entered into fjords at the alpine foothills, whilst Corselli et al. (1985) documented a sequence of glaciomarine sediments with striated pebbles, Pliocene in age, in western Lombardy (Varese). In the Garda area, evidence of Pliocene glaciation of the southern alpine margin has not yet found. Quaternary glaciers were responsible for the deposition of several arcuate ridges that constitute the moraine amphitheatre of the Lake Garda, edging the Southern Alps foothills, and advancing on the Po Plain for tens of kilometres. At least five glacial stages can be recognized in the moraine amphitheatre, as evidenced by moraine ridges and related outwash plains, and loess deposits (Penck and Brückner 1909; Cremaschi 1987). Glacial tills, fluvioglacial deposits and loess deposits of different age retain several well-developed paleosoils, which allowed to recognize and differentiate glacial stages on the basis of their thickness, rubefaction, clay content and other pedologic characteristics. These deposits, together with the intercalated paleosoils provide a valuable archive of information for reconstructing and characterizing paleoclimatic conditions of the entire region. Aeolian sedimentation typically accompanied glacial periods and loesses have accumulated since the beginning of the Middle Pleistocene. On the other hand, three main articulated phases of large-scale loess sedimentation have been recognized, the oldest pertaining to the late Middle Pleistocene, the second and the third being attributed to the Late Pleistocene. These loess deposits are widely distributed along the alpine margin and on isolated hills of the Po Plain. It is worthy to note that several archaeological findings allow attributing these two main phases of aeolian sedimentation to the Mousterian and to the Upper Paleolithic (Cremaschi 1987).

The oldest glacial deposits of the moraine amphitheatre are exposed on the western margin of the Ciliverghe hill, a minor relief feature 1.5 km long and 0.5 km wide, emerging a dozen of metres above the surrounding fluvioglacial deposits (sandur). The Ciliverge Hill defines the western limit of the moraine amphitheatre and lies in between the continental Garda system and the Pleistocene marine sediments outcropping on the nearby Castenedolo Hill (Cremaschi 1987). Glacial till and related fluvioglacial deposits are to be found at the base of continental deposits (late Early Pleistocene in age, Günz *Auct.*; dated to late Matuyama paleomagnetic Epoch, presumably postdating the Jaramillo event; possibly MIS 22).

According to Cremaschi (1987), three glacial phases recognizable in the Garda amphitheatric system date to the Middle Pleistocene (Mt. Faita, Carpenedolo and Sedena Stages. The oldest one, linked to the early Middle Pleistocene (possibly MIS 16), is well recognizable at Mt. Faita, near Gavardo, at the western margin of the Garda region. On the other hand, this stage is not really well evidenced further to the south in the amphitheatre.

Among the other two glacial phases dated to the Middle Pleistocene, the oldest one (Carpenedolo) is well documented by a series of isolated hills depicting an arcuated and well identifiable moraine ridge. On the basis of the well rubified paleosol developed on glacial deposits of this stage in the Carpenedolo area, covered by loess deposits containing Early Paleolithic artifacts (that supply a minimum age for the moraine), this stage is possibly linked with MIS 12 (Mindel *Auct*., or perhaps to MIS 10).

The Sedena stage represents the last glacial phase dated to Middle Pleistocene and most probably is ascribable to MIS 6 (Riss *Auct*.). This stage is testified by deeply eroded hills that represent the remains of a moraine ridge covered by the Late Pleistocene moraine complex (well evident at the western margin of the amphitheatre). The Val Sorda section (to the ESE of Garda, at the LGM border of the moraine amphitheatre), where two loesses bracket fluvioglacial deposits, gives the date of this stage. Late Pleistocene glacial till covers the youngest loess that, in turn, supports a chernosem-type soil and is most probably datable to a glacial phase pre-dating the Last Glacial Maximum (LGM) (Cremaschi 1987). Loess deposits of this stage in the vicinity of the section described in Val Sorda supplied Mousterian artifacts (Middle Paleolithic).

The last recognized stage of the moraine amphitheatre (Solferino Stage) is dated to the Late Pleistocene and it can be subdivided in two sub-stages, presumably linkable to

MIS 4 and MIS 2, respectively. Moraines from this glacial stage are widespread and associated with evident outwash plains that characterize a very wide portion of the Garda moraine amphitheatre and its surroundings.

The progressive eastward rotation of the glacial tongues since the Early Pleistocene caused by more pronounced uplift of the western coast of Lake Garda with respect to the eastern one explains why the oldest moraines of the amphitheatre are preserved to the west of the lake and lack in the eastern side.

14.5 Last Glacial Maximum and Glacial Retreat

During the last great glacial expansion (LGM, MIS 2) bracketed between 26–25 and 19 ka, the Alps were almost completely mantled by a glacial cover, which was characterized by ice caps and ice fields feeding an interconnected system of valley glaciers (Ehlers and Gibbard 2004; Vai and Cantelli 2004; Bini et al. 2009). The ice cover reached in the main valley troughs maximum thickness that in places exceeded 2000 m. Only the most elevated alpine sharp crests (arêtes) and pyramidal peaks emerged above the ice.

Powerful ice tongues descending from the Adamello, Presanella, Ortles-Cevedale and Brenta groups filled the main and secondary valleys descending to the Po Plain. These huge valley glaciers reached the Alpine forelands infilling the depressions in the foothills, which presently host lakes at the border of the Southern Alps.

The huge glacier filling the Lake Garda reached the thickness of about 1000 m near Tremosine and expanded on the Po Plain to form a flat piedmont glacier (*ca*. 50 km wide). The tongue was fed by transfluences from the Adige Valley (i.e. from the Valle dei Laghi and from the Loppio saddle). The ablation tongue also insinuated into confluent valleys locally damming glacio-lacustrine basins. Relict moraines, together with the ridges of the piedmont moraine amphitheatre depict the elevation reached by the glacier along the lake trough (Fig. 14.6). Elevation of relict moraines decreases from the internal portion of the valley toward the southern border of the former glacier. In the upper lake area elevation of moraine crests exceeds 1000 m a.s.l., while descending to the lower lake area elevation is about 650 m at Tremosine, 400 m at Gardone Riviera, 300 m at Manerba del Garda, and less than 200 m at Solferino, where the minimum elevation is reached at the southernmost boundary of the amphitheatre.

During the LGM, valley glaciers descending to the Po Plain also isolated intervening mountain blocks and wide ridges with secondary valleys, which remained completely ice free. In fact, the Equilibrium Line Altitude (ELA) reconstructed on the basis of LGM drop in temperature is estimated to have been located at 1300–1500 m at the southern margin of the Alps (Kuhlemann et al. 2008). This means that wide portions of the Prealps located on mountain blocks delimited by valley tongues were lacking ice cover. In the Garda region, the glacierization level of the intervening blocks was located at 1600–1700 m, a couple of hundred metres above the reconstructed ELA for alpine glaciers. Therefore, wide portion of the Prealps to the west of

Fig. 14.6 Late Pleistocene moraine of the Garda system in the vicinity of Salò (*photo* C. Baroni)

the Lake Garda were completely deglaciated and only the highest portions of mountain groups and ridges exceeding about 1600 m hosted local glaciers.

Very peculiar is the case of the Mt. Baldo, embraced by the huge Garda valley and piedmont glacier to the west and by the glacier tongue of the Adige Valley, feeding the small Rivoli Amphitheatre, to the east. The summit backbone of the Mt. Baldo (2218 m) was still above the snowline and, therefore, allowed the development of local cirques glaciers. On the other hand, a wide deglaciated belt surrounded the mountain ridge, bounded at the bottom by the Garda glacier and on top by local cirque glaciers. Only a narrow passage located in between the Garda and Rivoli amphitheatres margins allowed the connection of the Mt. Baldo with the Po Plain.

Elongated valley troughs with very peculiar parabolic profiles and a number of confluent valleys hanging above the main valleys emerged as a consequence of the glacial retreat that followed the LGM. In the paraglacial environment left by glacial retreat, numerous small and shallow lakes formed in the intermoraine plains. Sediments from these lakes represent natural archives to investigate paleoenvironmental evolution of the region, particularly because small lakes are extremely sensitive to change in precipitation and local temperature. At Lake Frassino (Peschiera), for example, lithological, malacological and stable isotope composition of freshwater shells allowed to recognize lateglacial conditions as drier than during the Holocene, although a wetter period was inferred before about 14 ka (Baroni et al. 2006). Data from the Frassino and other localities suggest that the glacial retreat after the LGM was underway in the Garda Lake area by 18–19 ka cal BP. Glacier collapse likely started at *ca.* 16 ka BP and most probably at 15 ka the Garda region was completely deglaciated. In particular, during Late Glacial stadiums (since the Gschnitz and later on) glaciers were confined to the interior of the Adamello-Presanella and Ortles-Cevedale massifs. At that time, the main troughs and several confluent valleys were completely deglaciated (Cavallin et al. 1997; Baroni et al. 2014).

14.6 The Paleo-Lake Garda and the Holocene

Following the collapse of Late Pleistocene glaciers, the moraine amphitheatre impounded the elongated valley crypto-depression and paleo-Lake Garda was established at elevations higher than those reached at present (65 m a.s.l.; Baroni 1985, 2010; Cavallin et al. 1997; Castellarin et al. 2005). In fact, LGM moraines produced a damming effect for the huge amount of water released by melting glaciers. The not-yet effective erosion of the threshold by the Mincio River, dammed the paleo-lake at elevation exceeding 30 m above the present level. The main streams feeding the newly formed lake started to build deltaic deposits made of sandy gravels. The apices of lacustrine deltas in correspondence of the main watercourses witness the existence of very high lake levels during the Late Glacial. To the north of Salò, on

Fig. 14.7 The Holocene delta of Toscolano Maderno (view is from ENE, *photo* G. Zordan)

the western coast, streams cut into deep and spectacular gorges of suspended valleys and fed these deltas (Fig. 14.7). On the other hand, along the lake's lower sector the dismantling of the innermost deposits of the moraine amphitheatre generated several small deltas. The oldest and highest deltas were terraced as a consequence of the progressive lowering of the lake level during the Late Glacial and the Early Holocene. The resulting converging scarps underline the relict suspended deltas, as also clearly evidenced by foreset and topset beds, recognizable up to their apices, at elevation as high as 100–120 m a.s.l.

Along the rocky shores, large stretches of relict cliffs retain traces of ancient lake levels such as relict wave-cut notches, suspended abrasion platform (rocky lacustrine terraces), paleo-beaches, and calcareous rims. The best-preserved evidences are wave-cut notches and abrasion platforms, these latter being mainly preserved in the lake's southwestern sector, swept by dominant winds. The contemporary abrasion platform emerges at present on the occasion of seasonal low-standing level of the lake. The most outstanding features develop at the border of main islands and peninsulas (Sirmione, S. Fermo, Punta Belvedere, Manerba Sasso, Isola S. Biagio and Isola del Garda).

The highest evidence of paleo-lake levels is preserved in the Manerba area where wave-cut notches are visible up to several dozens of metres above the present lake level (Figs. 14.8 and 14.9). Consistent records of paleo-lake levels are identifiable at various elevations between 80 m a.s.l. and the present lake level (65 m a.s.l.). Raised abrasion platforms in the SW portion of the lake represent the best-preserved landscape features that testify to high-standing lake levels, the most spectacular being eroded at about 3.5 m above the present lake level.

Relict beaches made up of rounded and imbricated pebbles also evidence paleo-shorelines of the Lake Garda. They may be found at several sites and elevations ranging from 1 to *ca*. 15 m, resting on lacustrine terraces, relict abrasion platforms, or cemented as gravel patches on rocky cliffs. Of particular significance is a beach deposit found at about 3 m above the lake level at Riparo Valtenesi (Sasso di Manerba del Garda), on top of which a settlement of fishermen, Early Neolithic in age, was found (Barfield 2007). The lacustrine gravels supporting the Neolithic settlement and also found in the surroundings were dated to 9730 ± 70 ^{14}C yr BP (TO-4767) and 10,290 ± 80 ^{14}C yr BP (TO-4902) on the basis of single shells of freshwater gastropods (*Bithynia tentaculata)* (Fig. 10), corresponding to 11.0–12.4 ka calibrated age (Baroni in Barfield 2007; Baroni 2010).

Calcareous rims made up by algal stromatoliths and other organisms including freshwater gastropods are among the best indicators of lacustrine relict levels on the rocky coasts of the upper lake, where they developed from 1 to 5.7 m above the present lake level. These horizontally arranged concretion levels overhang the lake and depict the upper limit of the wet zone along the rocky coast (Cavallin et al. 1997; Baroni 2010). AMS dates of single shells from freshwater gastropods (*Bithynia tentaculata* and *Theodoxus fluviatilis*) found in the calcareous rims furnished ages ranging from 10,070 ± 70 (TO-4136) to 6140 ± 60 (TO-4766) ^{14}C yr BP (Cavallin et al. 1997), corresponding to calibrated ages ranging from 11.3–11.8 ka and 6.9–7.2 cal yr BP.

Fig. 14.8 The high cliff at the northern margin of Manerba Sasso with evidence of wave-cut notches in *background*, abrasion platform and erosional caves in *foreground* (*photo* C. Baroni)

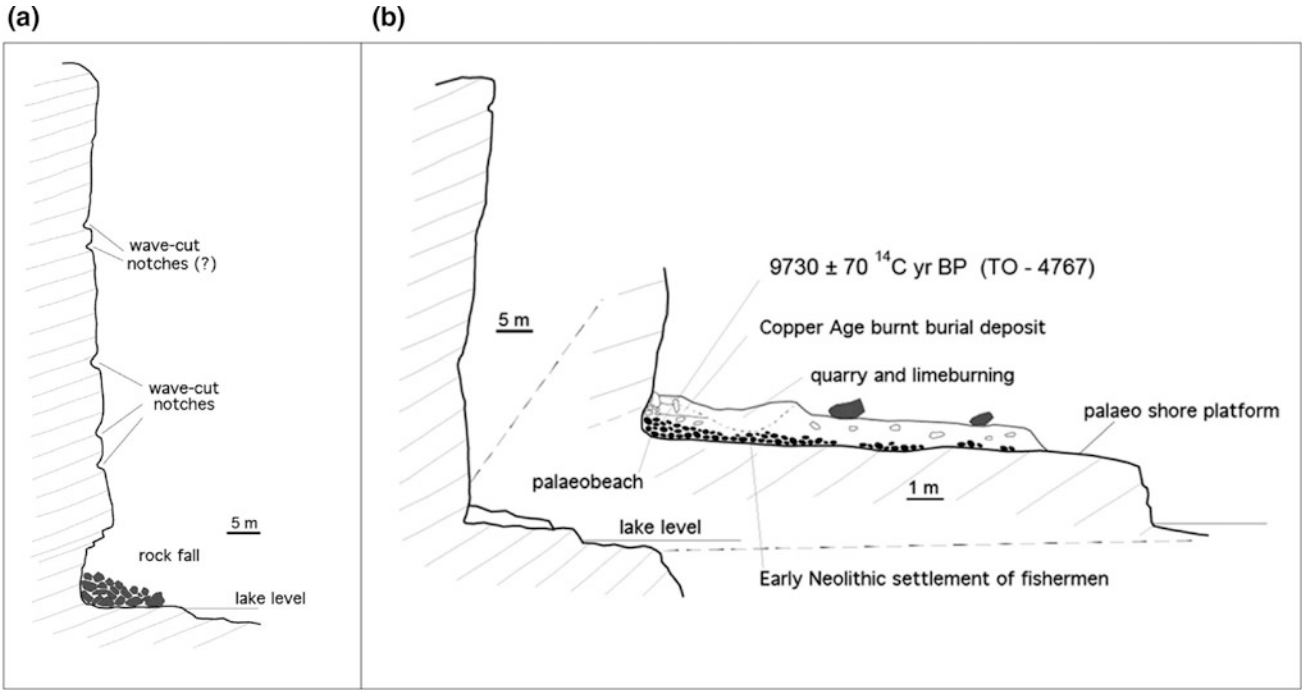

Fig. 14.9 **a** Section of the high cliff at the northern margin of Manerba Sasso with relict wave-cut notches and rock fall at the cliff toe. **b** Section through the paleo-beach at Manerba Sasso; radiocarbon date obtained from freshwater shell (*Bithynia tentaculata)* collected in the beach pebbles (modified after Baroni 2010)

Since at least the Early Neolithic the lake level has never exceeded the height of 68 m (*ca.* +3 m above the present lake) as documented by several archaeological settlements in the perilacustrine area (Aspes et al. 1998; Barfield 2007). Nevertheless, fluctuations of the Lake Garda level from some decimetres to not more than 1 m are documented during the ancient and middle to recent Bronze Age (4.1–3.5 ka BP, calibrated age) as registered in different settlement stages of pile-dwellings (Lazise, San Felice, Gabbiano di Manerba, Moniga, Cisano, etc.). Stratigraphic evidence of settlement stages are recognizable below the present lake level and witness lower than present levels as well documented at Lazise 'la Quercia' pile-dwelling. At this site, underwater excavation conducted by the Museum of Verona revealed various phases of occupation and abandonment of the pile-dwellings, which are clearly related to lowering and subsequent risings of the lake level (Aspes et al. 1998).

Along the western coast of the Lake Garda, shorelines of the same age may be found at different elevations and relative uplift of about 1 m of the shore to the north of Salò in respect to the Manerba-Sirmione area took place between *ca.* 12–10 ka and the present (with a mean estimated rate of *ca.* 10 cm/1000 years) as inferred by ^{14}C dates obtained from relict shorelines and beaches along the coastal margin of Lake Garda respect to their elevation (Cavallin et al. 1997; Baroni 2010).

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Geomorphological Processes and Landscape Evolution of the Lagoon of Venice

15

Aldino Bondesan

Abstract

The Lagoon of Venice, extending along the northern Adriatic coast in northeastern Italy, is the most important Italian lagoon. The delta systems of the Po, Adige and Brenta rivers delineate the lagoon from the south, whilst the Sile and Piave rivers border the lagoon in the north. The lagoon is closed by the barrier islands of Lido and Pellestrina and the spit of Cavallino. Inside the lagoon, several landforms typical of this peculiar environment are present: islands, salt marshes, tidal flats, fluvial deltas, tidal channels, sand dunes, ancient coastlines and man-made forms such as landfills, fish farms, coastal defences and artificial channels. Due to protracted human interference with natural processes, the Lagoon of Venice may be considered today as an artificial environment.

Keywords

Lagoon • Salt marshes • Venice • Adriatic Sea

15.1 Introduction

The Lagoon of Venice is the largest Italian lagoon and the most important heritage of the system of estuarine lagoons that for thousands of years and until the last century extended along the coast of the Adriatic Sea between Trieste and Ravenna, in northeastern Italy. The term “lagoon” is derived from the Italian *laguna*, which refers specifically to the Lagoon of Venice.

The lagoons are subjected to highly dynamic coastal processes, responsible for a fragile balance between terrestrial and marine processes, where, very often, an important role is played by humans. In fact, despite the history of significant environmental changes that occurred during the middle and late Holocene, the current setting of the Lagoon of Venice is mainly the result of a series of human interventions, especially those implemented in the last five centuries.

15.2 Geographical Setting

The Lagoon of Venice is located in the Gulf of Venice (northern Adriatic Sea), along the coastal fringe of the Venetian–Friulian Plain. The lagoon basin forms an arc about 55 km long and 8–13 km wide. It is separated from the open sea by a narrow coastal strip consisting of a series of barrier islands (Fig. 15.1). From the ENE, the spit of Cavallino is the largest one, which in the past was nourished by the mouth of the Piave River. It is followed by the two barrier islands of Lido and Pellestrina, while further south the lagoon is separated from the sea by the left wing of the fluvial delta of the Brenta River (Fig. 15.1).

The inner boundary that separates the lagoon from the mainland is in most cases marked by artificial hydraulic works. Figure 15.2 shows the lagoon boundary, the so-called *Conterminazione lagunare*, which is more an administrative border than a geographical one. It was fixed with 99 stones in 1791 by the Venetian Republic and was updated by the Magistrato alle Acque (Water Authority) at the end of the 1990s.

On both sides of the lagoon, a system of river mouths debouch into the Adriatic Sea. To the south, the large Po

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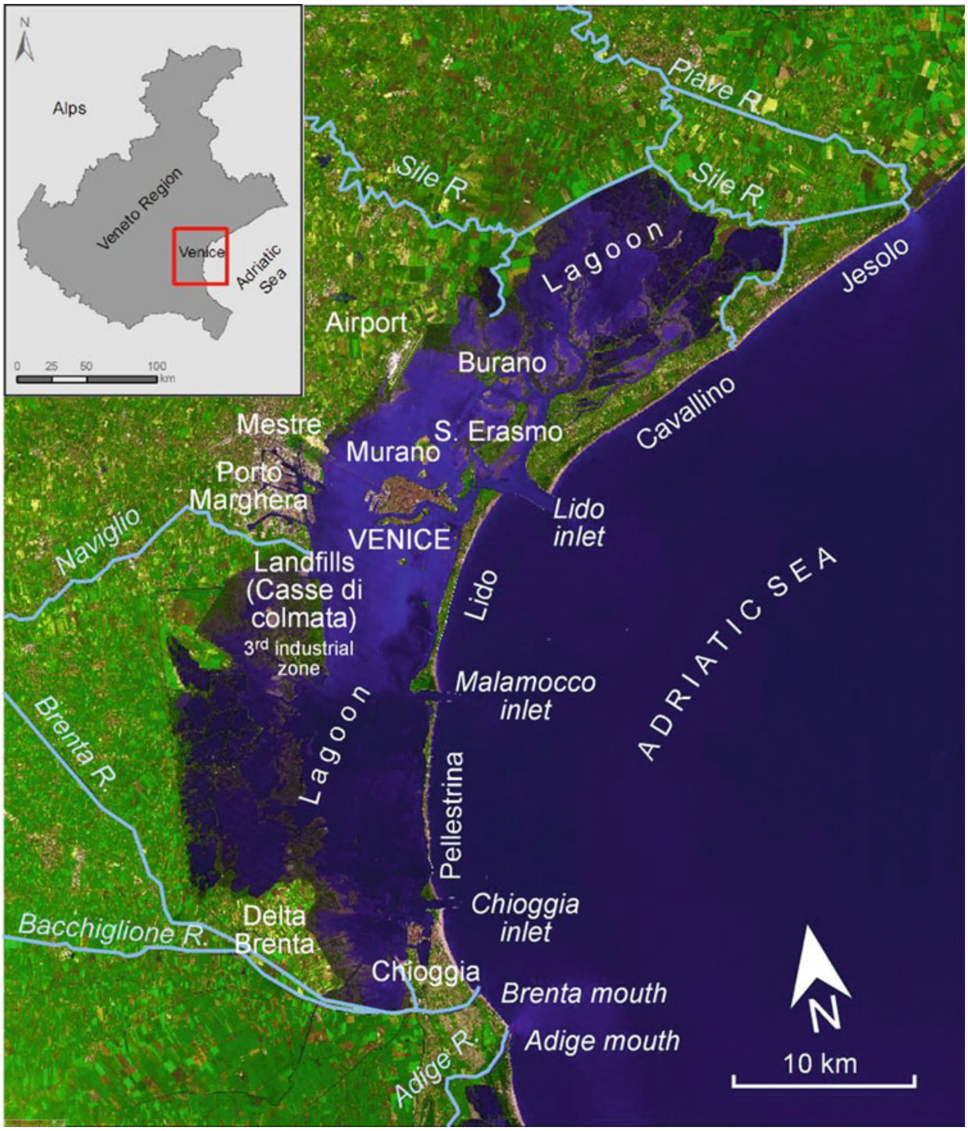

Fig. 15.1 Location map. Satellite image of the Lagoon of Venice and its mainland (Aster Image, 9 December 2001)

delta juts out into the sea; between the delta and the lagoon, the Adige and Brenta rivers (which also receive the waters of the Bacchiglione River) bring sediments to the southern part of the lagoon. To the north, the Sile, which occupied an old riverbed of the Piave in 1683, and the Piave rivers are delineating the lagoon, the latter with clearly identified fluvial ridges and deltas. Even in historical times, the Brenta and Sile poured their waters into the lagoon, but they have gradually been diverted outside it over the last five centuries.

Inside the lagoon basin, in addition to Venice and Chioggia, which are the two major groups of islands, there are other inhabited islands of appreciable size, such as Murano, Burano, Torcello and Sant'Erasmo. The others are smaller and almost all uninhabited.

The periodic ebb and flow of the sea water in connection with the cycle of the tides occurs via three tidal inlets at Chioggia, Malamocco and Lido.

15.3 Geomorphological Evolution

The Lagoon of Venice is part of the Venetian–Friulian plain formed by deposition by large river systems alternating with marine transgression. This sequence was mainly driven by the glacial and interglacial phases related to global climate cycles that occurred during the late Pleistocene and Holocene.

The central stretch of the Veneto plain consists of three alluvial megafans. The westernmost megafan was built by the Brenta River and stretches roughly in the NW–SE direction from the Brenta valley to the Venetian mainland. To the east, it borders the megafan of the Piave of Montebelluna, formed when the river was entering the plain west of Montello hill. Montello is located at the eastern end of the apex of the current Piave alluvial fan (megafan of the Piave of Nervesa).

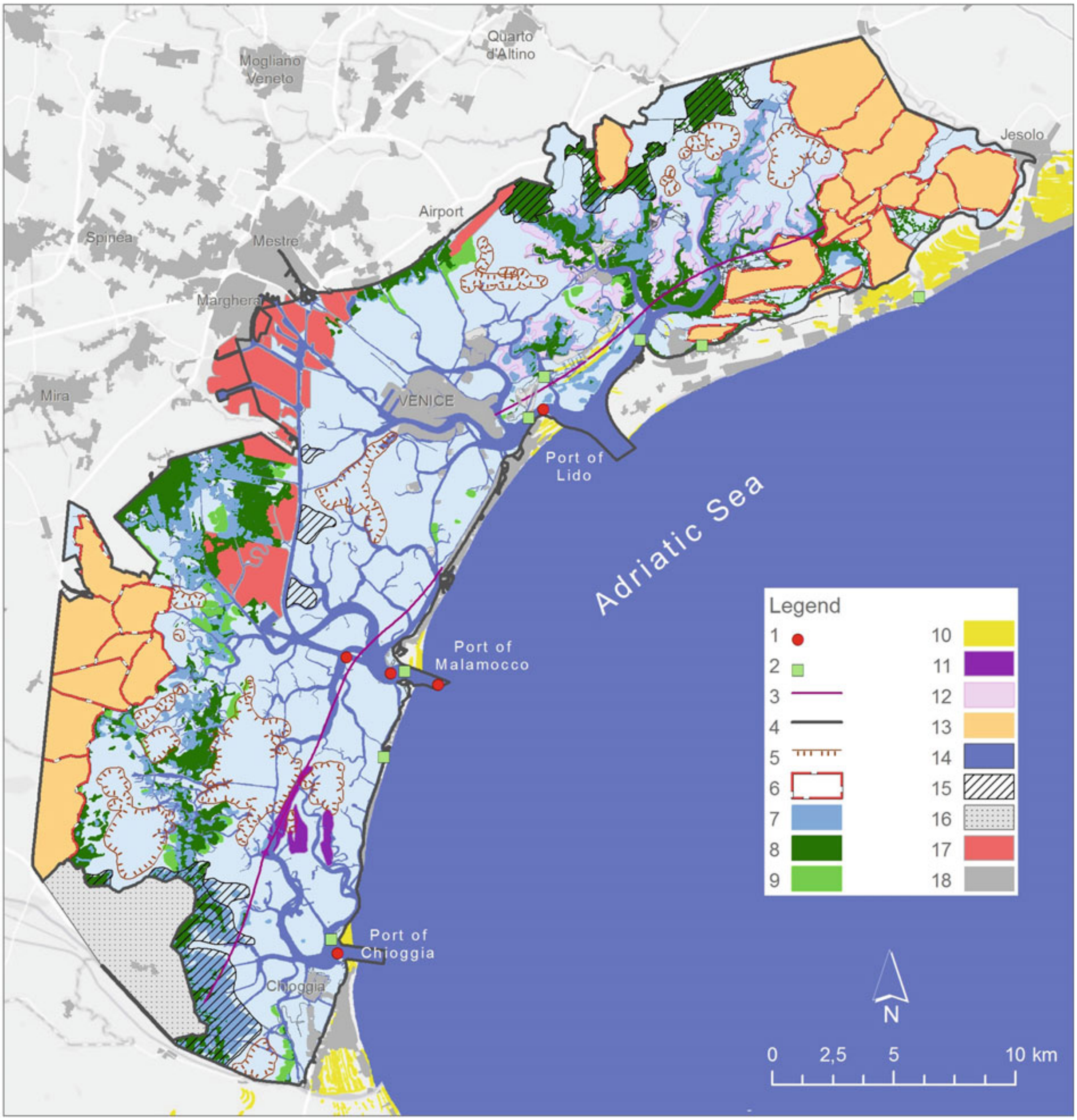

Fig. 15.2 Geomorphological sketch map of the Lagoon of Venice. Legend: *1* lagoonal inlet pool; *2* ancient lagoon inlet; *3* ancient coastline (5 ka BP); *4* ancient administrative lagoon boundary (*Conterminazione lagunare*); *5* depression in lagoon floor; *6* embankments; *7* tidal flat; *8* salt marsh; *9* artificial salt marsh; *10* sand dune; *11* relict of ancient barrier island; *12* lagoon tidal delta; *13* fish farm; *14* lagoon channel; *15* fluvial delta inside the lagoon; *16* reclaimed lagoon surface (Delta Brenta, 1840–1896); *17* landfill; *18* urbanized area

The plain to the west of the central and southern part of the Lagoon of Venice represents the terminus of the Holocene depositional system of the Brenta. This system is bordered to the north by the late Pleistocene deposits of the Brenta and to the south by the Holocene deposit of the Adige, with smaller contribution from the Po. The morphogenetic activity of the Bacchiglione is forced inside the large hollow formed by the juxtaposition of the Brenta system with the Adige system (Fontana et al. 2008, 2010; Carton et al. 2009).

The top of the Pleistocene deposits is marked by a paleosol—locally known as *caranto*—that contains carbonate concretions that are centimetres thick. This separates the Last Glacial Maximum (LGM) alluvial deposits from the overlying back barrier ones. Its top is an unconformity surface marking the Holocene–Pleistocene boundary between 4 and 7 m below mean sea level within the Lagoon of Venice (Donnici et al. 2011).

The formation of the lagoon took place after the marine transgression started at the end of the last glacial period, which reached its maximum in the Upper Atlantic (5–6 ka BP). In the Lagoon of Venice, the coastal wedge is quite thin and short, while most of the post-LGM deposits are lagoonal. Radiocarbon dating has shown that the paralic sediments along the margins of the lagoon are 1–2 thousands of years older than in Venice itself, where a structural high is present and lagoonal deposits range in age from 5.5 to 4.7 ka BP (Ammerman et al. 1995; Serandrei-Barbero et al. 2001, 2002). Alluvial and swamp deposits were buried by the marine ingression around 6.8 ka BP in the northern basin (Canali et al. 2007) and around 6 ka BP in the southern one (Favero and Serandrei-Barbero 1980).

After the maximum marine transgression, which went beyond the present coastline (Fig. 15.3, line A), a regression phase began, probably helped by the contribution of sediments from the Brenta in the southern sector of the lagoon and more to the south by the Adige and the Po. In the areas behind the line of maximum ingression, swamps and bogs formed as an effect of flooding and stagnation of fresh water (5–6 ka BP). In a relatively short period, the coastline moved forwards about 5 ka BP, towards the alignment of Motte Cucco–Peta de Bo–Val Grande (Fig. 15.3, line B). Upstream of this ancient shoreline, the first lagoons formed; from about 5 ka BP to mediaeval times we saw gradual development of the lagoon basins, fostered mainly by the stability of the coastline and the fact that the areas behind the barrier islands were not directly affected by the clastic contributions of rivers.

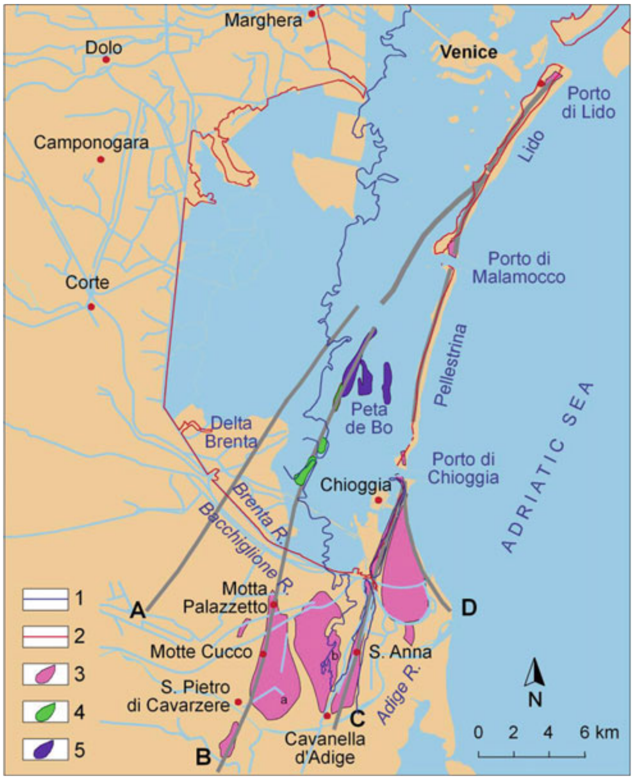

Fig. 15.3 The variations of the coastline in the southern part of the Lagoon of Venice. Legend: *Line A* limit of the maximum Holocenic ingression, after Favero and Serandrei-Barbero 1980; *line B* coastline of San Pietro di Cavarzere–Motte Cucco–Motta Palazzetto–Peta de Bo; *line C*: coastline Cavanella d'Adige–Sant'Anna–Chioggia; *line D*: present coastline; inner margin of the lagoon and coastline derived from historical cartography: *1* sixteenth century; *2* seventeenth century; *3* barrier island and complex of dunes, levelled or in elevation; ancient barrier island derived from: *4* historical cartography; *5* satellite images (modified after Bondesan and Meneghel 2004)

Between 2.8 and 2.5 ka BP the coastline rapidly moved forward along the Cavanella d'Adige–Sant'Anna–Chioggia line (Fig. 15.3, line C), where it remained until mediaeval times. Subsequent advancement of the coastline was probably caused by the Po River, but it was the Adige River which played a major role in sedimentation along the southern margin of the Lagoon. Also the Brenta River markedly contributed to coastal progradation, especially after an artificial fluvial diversion occurred at the end of the nineteenth century.

On the northern side of the lagoon, shoreline position was more stable and shoreline progradation started around 3 ka BP, induced by the action of the Piave River mouth (Amorosi et al. 2008). A marked advance was driven by the construction of the jetties at San Nicolò Port when, starting from 1872, a 2 km wide beach formed in about 80 years.

15.4 Landforms

The landforms inside the Lagoon of Venice can be classified according to the morphogenetic processes that have shaped them. Hence, alluvial, lagoonal and coastal features may be distinguished. These forms can be further classified according to bathymetry as subtidal zones located below the level of the average low tides; intertidal zones, alternately submerged and emerged; and supratidal zones (high tide platforms), submerged only by the highest tides (Fig. 15.2).

15.4.1 Alluvial Landforms

Within the Lagoon of Venice, alluvial and relict landforms inherited from continental environments are found. Among these, *fluvial ridges*, which are partially or completely submerged, form positive features inside the lagoon. These landforms are related to fluvial sedimentation due to repeated overbanking during floods. They can be relict forms determined by a natural or artificial withdrawal of the lagoon rim (which led to a partial submergence of the ridge) or they may have been generated by the advance of continental fluvial ridges in the lagoon environment. They are present in parts of the coastal plain invaded by the waters that now form the lagoon bottom, where there has been no subsequent sedimentation.

The *fluvial deltas inside the lagoon* are built of deltaic deposits formed along the lagoon's inner margin. The rivers, which at various times have poured their waters into the lagoon, created inner deltas with their sediments, consequently reducing the water surface area. The sediments are poorly reworked and deposits are generally thin, in a fan shape along the delta channels.

Some of the *islands* closest to the inner lagoonal margin arose on the fluvial deposits of rivers entering the lagoon.

15.4.2 Lagoon Landforms

Lagoonal landforms are widespread, and some have local names that have sometimes been proposed as scientific terms in Italian scientific literature.

The salt marshes (It.: *barene*) are among the most characteristic morphological elements of the lagoon. They are loamy, sandy flats situated a few centimetres above the sea level, dominated by dense stands of salt-tolerant plants such as herbs, grasses or low shrubs that contribute to their conservation. Currently, the lower limit of survival of halophilic vegetation coincides with the average sea level. They match, though not always perfectly, the forms defined by the international terms of *haute slikke* or *schorre*. They are characterized by a somewhat varying size and shape, but often in the vicinity of the channels they have a raised edge and a more depressed central part, similar to a "bowl" morphology. In other contexts, their form is tabular, with depressed edges or edges inclined towards the ponds where they link up with the intertidal flat. Various types of salt marshes were distinguished by Favero and Serandrei-Barbero (1983), depending on their continental (morphological relicts of the alluvial paleoplain inundated by marine transgression and subsequently emerged) or lagoonal origin (deposits that have developed as a result of natural lagoonal processes) and on the evolutionary behaviour that characterizes them.

Salt marshes of lagoon channel (It.: *barene di canale*) are very peculiar and largely present in the northern basin of the Lagoon of Venice. They are part of the natural levées located on the edge of the lagoon channels whose morphology is characterized by the presence of a raised edge at the feeder and a surface that slopes towards the side away from the channel (Fig. 15.4). The term "*gengiva*" (*gum*) has been proposed for submerged channel levées.

The mud flats (It.: *velme*) are barren silty intertidal flats located just below the sea level and extending from the lowest portion of the intertidal zone to the marsh areas. They usually show a low slope inclination. They are indicated in the international scientific literature by the terms tidal flats,

Fig. 15.4 Salt marshes, tidal flats and tidal creeks during low tide (*photo* A. Bondesan)

marsh flats or *slikke*. These flat plains are limited by the network of lagoon channels that starts from the inlets and branch off into smaller courses.

For the subtidal forms, the term “swamp” (It.: *palude*) is locally used to indicate the portions of the lagoon bottom that are located below the average low tide level. Based on the morphology of the lagoon, other forms have also been identified, including depressions in the lagoon floor (generally less than 1–1.5 m) on which there is little deposition of lagoon sediments.

Water interchange occurs through three tidal inlets (It.: *bocca di porto* or *porto*), which identify three lagoon basins separated by underwater watershed lines, each of which has a dendritic network of lagoon channels that converges to each inlet. In former times, there were up to eight ancient tidal inlets, but these are now silted up.

The widest basin is that of the Port of Lido, which includes about 50% of the surface of the lagoon. The Malamocco basin includes about 30% of the lagoon and the Chioggia basin includes about 20%. At the inlets, also as a result of the construction of jetties, the ebb and flow creates strong currents that have dug lagoonal inlet pools. These are the deepest areas of the lagoon (approximately 50 m deep at Malamocco, 38 m deep at Chioggia, and 30 m deep at Lido).

The entire lagoon, including the subtidal zone, is crossed by a dense network of tidal channels representing the circulatory system of water coming into the lagoon from the tidal inlets and reducing their section inwards. The natural hydrographic network is defined by at least three orders of channels: (1) main channels that convey the fluvial or lagoonal water to the sea; (2) secondary channels that flow from the main channels draining or dispersing water within the lagoon basin; and (3) tertiary channels that depart from the main channels or, more frequently, from the secondary ones and meander between mud flats and salt marshes. The latter (*tidal creeks*) are usually delimited by smooth levées, often no more than 20 cm high. The *tidal creeks* are locally known as *ghebi*. They often feed small ponds of brackish water, indicated by the local term “*chiari”*.

The main channels have locally been recognized to be the legacy of an ancient river hydrographic system that existed before the marine transgression. In places, they are still linked with the tributaries of the lagoon.

The natural levées of lagoon channels are formed by sedimentary bodies on the sides of a channel, generated by the ebb and flow of tidal currents according to a genetic process similar to the formation of fluvial ridges in a continental environment. The contribution of sediments derived mainly from the tidal inlets form large salt marshes and tidal flats (Fig. 15.5).

The dendritic pattern of tidal channels that branch off from the inlets to the interior of the lagoon shapes a tidal lagoon delta *(“flood delta”)*, formed by the complex of islands, salt marshes, mud flats and natural levées of the lagoon channel. In this sense, the city of Venice and the large islands on the northern side of the lagoon are considered to be part of the great tidal lagoon delta of the Port of Lido inlet.

15.4.3 Coastal Landforms

Some islands and old barrier islands, now incorporated within the lagoon, have marine origin. A typical example is the island of Sant’Erasmo, a stretch of ancient coastline

Fig. 15.5 Salt marshes next to the lagoon channel along the Cenesa Canal in the northern Lagoon of Venice (*photo* A. Bondesan)

isolated inside the lagoon that subsequently formed in a more advanced seawards position, the Cavallino coast (a large spit protruding from the northeastern coastal plain) and the barrier island of Lido. Other ancient beach ridges have been identified on the lagoon floor using remote sensing, historical maps and underwater surveys.

Seawards, the Lagoon of Venice is bordered by barrier islands and spits, characterized by variable widths from a few dozen metres to a few kilometres; these are Pellestrina, Lido di Venezia and Cavallino. Sottomarina constitutes the left wing of a protruding fluvial delta of the Brenta River.

Sand dunes have formed along the beaches, especially close to the inlets and along the river mouths where the sedimentary load was particularly high. Starting from the beginning of the nineteenth century, all the beaches have been subjected to drastic erosion, partially countered by the construction of dams, jetties, coastal defences and artificial nourishments.

15.5 An Artificial Landscape: Human-Induced Transformations

Human intervention in the lagoon environment commenced with the first human occupation, starting from Roman times along the lagoonal rim and from the fifth century AD in the town of Venice (Fig. 15.6), when the islands started to give refuge to Romanised people fleeing the Hun invasions.

The lagoon extent was regulated by the presence of river deltas and lagoon inlets, being controlled in their evolution by river sediment loads and tidal dynamics. After the twelfth century, the lagoon inlets were menaced by the progressive shallowing of water due to sand deposition caused by sedimentary drift converging in front of the lagoon from the side fluvial deltas (mostly the Piave and Adige rivers) and by silting up of the lagoon basin, mostly due to internal sedimentation of the Brenta and Sile rivers. For that reason, the Republic of Venice undertook an epic struggle against the rivers, diverting them outside the lagoon or turning them far aside. The projects were only partially carried out, mostly during the sixteenth and seventeenth centuries, changing not only the morphology of the surrounding alluvial plain and the coastal margin but also altering water dynamics and the pace of erosional processes. In order to prevent the lagoon from turning into a marshland, Venetian hydraulic projects reversed the natural evolution of the lagoon, in time causing progressive erosion of the main landforms, the coasts and the lagoon bottom (Bondesan and Furlanetto 2012).

Anthropogenic forms in the Lagoon of Venice have important, quite invasive, presence. Most of the islands of the lagoon are in fact associated with human intervention, which contributed to their elevation and conservation though defensive works (Fig. 15.7).

In the last two centuries, many transformations have been induced by humans. Peculiar features of the lagoon include the following. Fish farms (It.: *valli da pesca*) occupy an area

Fig. 15.6 Aerial view of Venice. San Marco Square on the *right* (*photo* A. Bondesan)

equal to 16% of the water surface. They represent large lagoonal areas surrounded by embankments used for traditional fish farming, where water exchange is artificially regulated and natural processes are slowed down or halted (Fig. 15.8). Hydraulic reclamation for agriculture changed large parts of the inner margin, especially on the southern side of the lagoon where the Brenta River used to enter into the lagoon before its final deviation at the end of nineteenth century. Landfills are largely present in most of the islands and the industrial site of Porto Marghera. In the twentieth century, the Marco Polo International Airport was constructed inside the lagoon, occupying large tidal flats.

Among the lagoon islands, the large reclaimed areas known as *casse di colmata* have to be mentioned for their impact on the lagoon environment. Their construction took place from the 1920s to the 1960s, to accommodate the expansion of the industrial port and the vast complex of factories of Porto Marghera facing the lagoon. The industrial port is today connected to the Malamocco inlet by the Malamocco-Marghera Canal. This canal has an average depth of 15 m. Some of the most serious causes of degradation of the lagoon are due to its existence. In fact, it has increased the volume and speed of tidal inflows and outflows, resulting in the intense and rapid dismantling of the lagoon bottom.

Materials resulting from the excavation of the channel were used in the 1960s to create reclaimed areas for the Third Industrial Zone (never completed). In addition to the strong impact that the reclaimed areas had and still have on the lagoon, the fundamental problem is that these extended "artificial islands" have affected the quantity and quality of water exchange. In 1986, the first measures were approved for the hydro-morphological recovery of the site to restore some of the previously existing channels.

The gradual increase in sea level and the reduced longshore drift caused the pronounced erosion of the Venetian beaches, which the Republic of Venice has tried to protect since 1300 AD. The efforts to defend the littoral against the aggressive action of the sea culminated in the eighteenth century with the construction of the *murazzi* (large stone walls).

The barrier island of Pellestrina is the most slender island between Malamocco and Chioggia (Fig. 15.7c). In the early 1990s, it was reduced in some places to a width of a few tens of metres, making the Lagoon of Venice extremely fragile (it was bypassed by the waves in the surge that occurred in 1966).

In 1994, enormous artificial nourishment consisting of about 4.6 million cubic metres of sand was accomplished along approximately 9 km of coastline for an initial width of

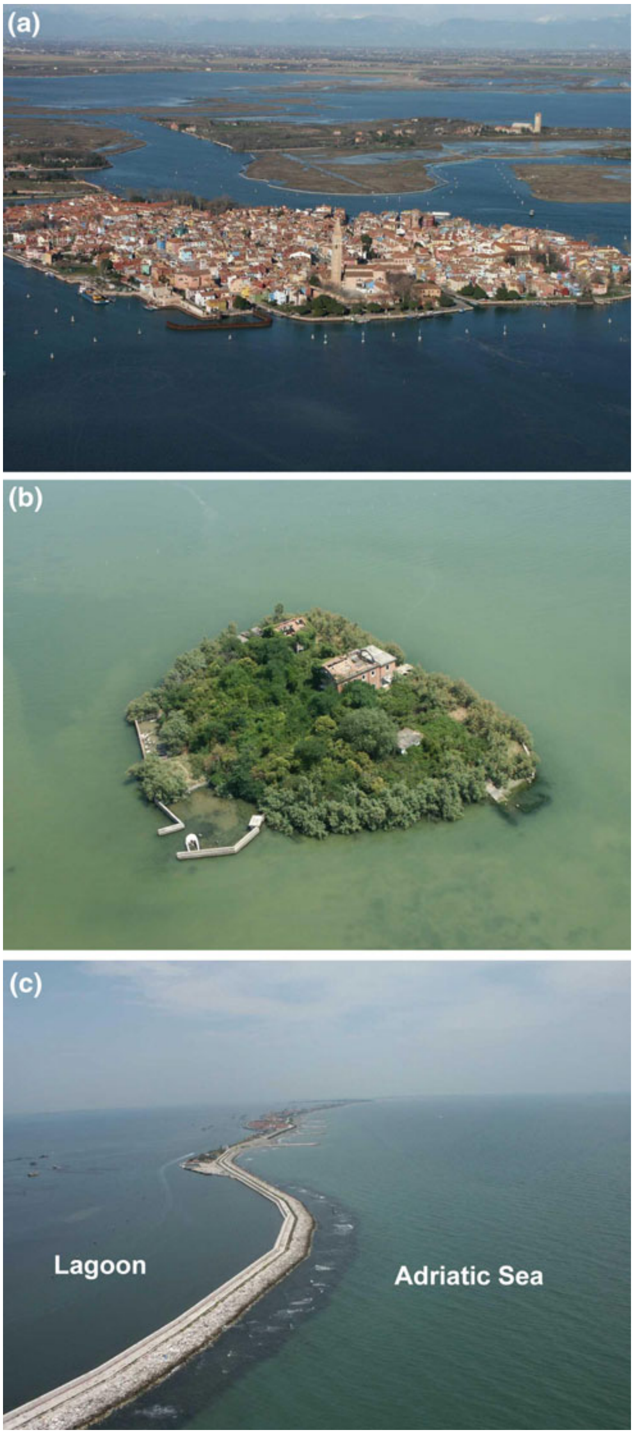

Fig. 15.7 Islands of the Lagoon of Venice. **a** Burano Island. The lagoon border is in the background, and the Alps are in the distance. **b** A typical small lagoon island (abandoned by people). They are usually artificially elevated with sediment accumulation and protected from erosion by concrete or stone walls. **c** The barrier island of Pellestrina is extremely narrow along its southern stretch (*photos* A. Bondesan)

Fig. 15.8 Fish farms in the southern basin of the lagoon (Valle Averto). In the foreground is the system of pools for fish recovery, and in the background is the network of embankments (*photo* A. Bondesan)

Fig. 15.9 Exceptional tide peaks are causing increasingly frequent flooding of Venice (*photo* DeepGreen/www.shutterstock.com)

about 100 m. This work, unprecedented in Europe, was completed in March 1999. The sand came from a submarine quarry located about 20 km off Malamocco in deep water from 20 to 24 m. This sand consisted of sediments belonging to transgressive coastal deposits. The intervention was supported by maritime works, such as jetties connected to a submerged berm, in order to form an organized structure in cells that can more effectively slow down erosion of sand.

Situated in the enclosed Gulf of Venice, the lagoon is subject to high variations in water levels due to extreme tides and low atmospheric pressure. These tides regularly flood much of Venice (Fig. 15.9). In the last decade, a huge effort was made to safeguard the Lagoon of Venice through the MOSE system (*MOdulo Sperimentale Elettromeccanico*, Experimental Electromechanical Module), which is an integrated system consisting of rows of movable gates installed at the Lido, Malamocco and Chioggia inlets that can temporarily isolate the Lagoon of Venice from the Adriatic Sea during high tides. MOSE is designed to protect Venice and the lagoon from tides of up to 3 m and from sea storms. The works to realize MOSE changed morphology at the tidal inlets and the jetties. Other defensive measures include construction of complex coastal defences, raising of quaysides and restoration through artificial re-nourishment of salt marshes and mudflats, subject to pronounced erosion during the last century, using the sediments excavated from canals.

15.6 Land Subsidence of Venice

Venice has suffered from both natural subsidence, ranging between 0.5 (Kent et al. 2002) and 1.3 mm/year (Carbognin et al. 2010) during the Quaternary period, and anthropogenic subsidence, particularly as an effect of over-exploitation of artesian aquifers for industrial water supply beginning in the 1930s and reaching its maximum from the 1950s to 1970s, when it doubled. The closure of the artesian wells in the 1970s resulted in a slight rebound (2 cm) and slowing down of anthropogenic subsidence. The subsidence recorded at the end of the last century was 1–3 mm/year along the coastline and 2–4 mm/year at the furthermost northern and southern boundaries (Carbognin et al. 2010). The elevation loss since 1897 is about 26 cm; 3 cm is the result of natural subsidence, 9 cm is the result of anthropogenic land subsidence and 14 cm is the result of an increase in the eustatic sea level. The subsidence caused an increase in the frequency and amount of flooding as well as erosion of the lagoon intertidal areas and the littoral (Brambati et al. 2003).

15.7 Conclusions

The Lagoon of Venice is characterized by complex morphology, with very different environments from the mainland and the sea, and contains constantly evolving landforms. Largely protected from silting by the Venetians in past centuries, it is now threatened by erosion caused by breaking waves and tidal forces. Man's interventions have been a decisive factor in a process that allowed preservation of the lagoon over the centuries. In this sense, the Lagoon of Venice is today a sort of open laboratory where human action drives or counters natural processes that challenge its survival.

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The Po Delta Region: Depositional Evolution, Climate Change and Human Intervention Through the Last 5000 Years

16

Marco Stefani

Abstract

The Holocene depositional evolution and landform development of the Po River delta area are hereafter illustrated. Eustasy, climate and a growing degree of human intervention largely influenced the delta history. During late phases of the post-glacial transgression, two large estuarine bays developed. About 3000 years ago, the growth of a rectilinear coastline, under high energy meteo-marine conditions, closed the bays. Several generations of wave-dominated delta lobes then prograded into the sea. The modern delta was induced 400 years ago by the digging of an artificial canal and records very fast environmental modification. The present-day framework is largely artificial in nature and subject to a growing degree of environmental dangers, such as river and sea water flooding. Significant landscape values are nevertheless surviving in the region.

Keywords

Depositional dynamics • Climate change • Human settlement • Holocene • Po Delta • Adriatic Sea

16.1 Introduction

The Po is the largest river of Italy, forming a wide alluvial plain (Pianura Padana) and reaching the Adriatic Sea through a splay of delta distributary channels. The Po River delta area of northern Italy (Fig. 16.1) records a widespread transgressive-regressive evolution of Holocene age. Through the last 5000 years, several generations of delta lobes advanced for 30–40 km into the northern Adriatic Sea, laterally shifting over 90 km of latitude (Fig. 16.2). Only a younger portion of the progradational units keeps a geomorphic expression and can be directly examined in outcrop, since the sediments older than about 4000 years are all buried. The region records major palaeogeographic change, from estuarine bays, through rectilinear wave-dominated coastlines, to jagged delta lobe shapes. The palaeogeographical evolution was largely influenced by the changing climate framework and by the growing anthropic intervention, an influence well-recorded inland by the Po River system (Marchetti 2008). This contribution is focused on the role of climate fluctuations and human activity in the changing depositional style of the sedimentary units outcropping in the coastal plain of the Po River. Reconstruction of the evolution is particularly detailed for the modern delta lobe, grown since the beginning of the seventeenth century AD, because of the wealth of historic documentation, integrated with the physical evidence.

The delta is developed in a tectonically active depositional basin, at the junction between the buried Apennine chain and the Venice monocline (Pieri and Groppi 1981). The structural framework induces tectonic subsidence, largely enhanced by sediment compaction and anthropogenic alteration (Bondesan et al. 1997). The fast subsidence was over-compensated, in the past, by the vast sediment input of the Po River, which is now severely reduced. The northern tributaries of the Po, deriving from the Alps and often flowing out of large lakes, provide the largest water contribution, but are comparatively poor in sediment; the streams

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Fig. 16.1 Geographic location of the Po Delta area. Base satellite image from 2015 Google, Image Landsat; Data SIO, NOAA, U.S. Navy, NGA, GEBCO

flowing from the highly erodible Apennines generate the majority of the sediment input. The Po is about 650 km long and presently has a catchment surface of about 71,000 km^2. During earlier Holocene times, its drainage basin was much larger, because former tributaries are now independently reaching the sea. The Po presently provides a mean water discharge to the sea of about 1500 m^3/s, its flux regime recording an increasing variation in amplitude. The registered flood maxima exceed 10,000 m^3/s (years 1951, 2000) and the summer minima are lower than 275 m^3/s (2012). Before the human alteration, flux fluctuations were minor in magnitude than the modern ones, but nevertheless important, inducing a punctuated dynamics of sedimentation, well recorded by the delta sedimentary successions. The Po Delta lobe protrudes into the semi-enclosed Adriatic Sea, characterized by eutrophic waters, by a maximum tidal range of about one metre, and by a comparatively reduced wave activity. The more frequent waves, triggering the northward long-shore drift of coastal sands, are induced by the SE wind (*Scirocco*); the strongest storm waves are generated by the NE one (*Bora*). The near shore marine current forms the western portion of an anticlockwise circulation cell, supporting the southward transport of suspended sediments.

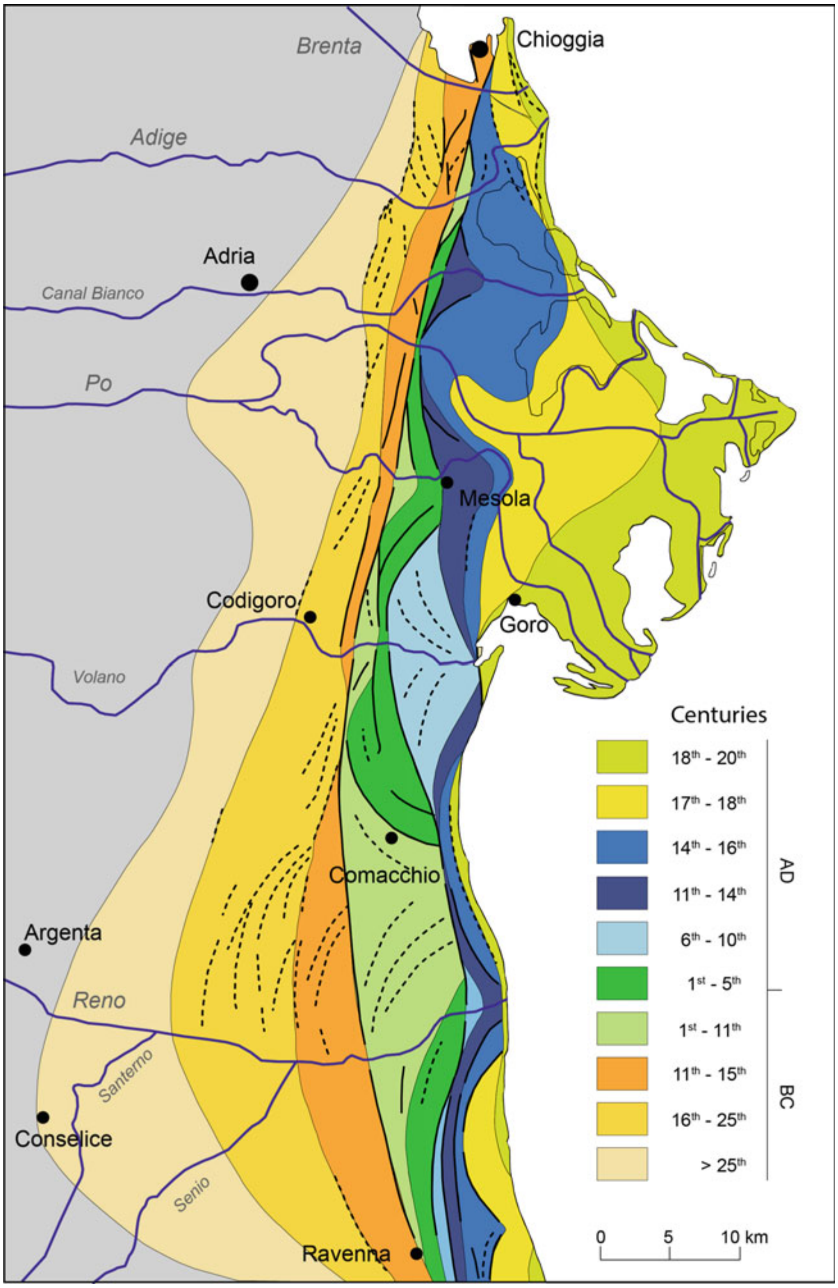
16.2 From the Synglacial Sea-Level Low-Stand to the Post-glacial Maximum Transgression (18,000–3000 Years BC)

During the Last Glacial Maximum (LGM), the eustatic sea level was about 120–130 m lower than the modern one, large Alpine glaciers reached the plain, and gravel-sand units accumulated within braided river systems across large portions of the present-day Po Plain and northern Adriatic Sea (Coreggiari et al. 1996). In the present delta region, coarse sands accumulated into cold, middle alluvial plain environments, about 300 km upstream from the ancient coast (Stefani and Vincenzi 2005). Climate warming then triggered the retreat of the Alpine glaciers, well before the major melting phase of the polar caps. At early stages of glacier retreat, the development of large Sub-Alpine lakes, followed by mountain reforestation, sharply decreased the sediment input into the Po Plain. To the north of the Po, fluvial waters were abundant, but poor in sediment load, and they were therefore able to induce widespread terrace erosion and apical incision of alluvial fans (Fontana et al. 2014). In this phase, fluvial sedimentation ceased across large areas of the plain in the modern delta region. Global melting of the continental ice then induced eustatic rise and worldwide transgression. In the present-day Po coastal area, renewed sedimentation was triggered only by the last phases of sea-level increase (8000–5000 years BC). Sediment accumulation restarted under continental conditions, soon to shift towards brackish and estuarine environments.

16.3 Maximum Transgression and Early Sea-Level Highstand (3000–1000 Years BC)

The melting speed of continental ice eventually slowed down, stabilizing the eustatic sea level. In the modern coastal region, relative sea-level rise and sedimentation compensated each

Fig. 16.2 Progradational evolution of the Po Delta coast in the last 5000 years, from the maximum transgression to the present. Note the considerable change in the geographic framework, from early highstand delta-estuarine bays to rectilinear coastline, and then from wave-dominated lobes to the modern artificial, digitate shape. *Dashed lines* indicate discontinuous delta-front sand ridges, *continuous lines* depict pronounced palaeo-coastlines



other on the maximum transgression line (Fig. 16.2). At the time, the delta-estuarine gulfs reached the most inland position, to the north and south of Comacchio, where they were floored by flat sand beds (Amorosi et al. 2003; Stefani and Vincenzi 2005), recording both storm waves and tidal currents. A continuous coastline was lacking and marine environments graded landward into wide brackish lagoons. Marine systems reached areas 40 km to the west of the present-day coastline and brackish waters regions that are now more than 70 km inland. At about 2000 years BC, two Po delta-estuarine mouths were active, well to the west of the present-day coastline (Fig. 16.2). Coastal sands accumulated there, under the combined action of storm waves and tidal currents. In a slowly subsiding anticline area, these sediments are still visible at the surface, forming the older outcropping unit of the coastal region (Fig. 16.3). The vast majority of the coeval sediments is however buried into the subsurface.

During the Bronze Age, between 2000 and 1000 years BC, an increased wind and wave activity supported a major environmental innovation, generating a new kind of depositional system through the growth of coastal spits and large barrier islands, which eventually merged together, to form a continuous coast (Figs. 16.2 and 16.4). The development of a rectilinear coastline can be traced across the whole of the northern Adriatic region, from the Apennine rocky coast

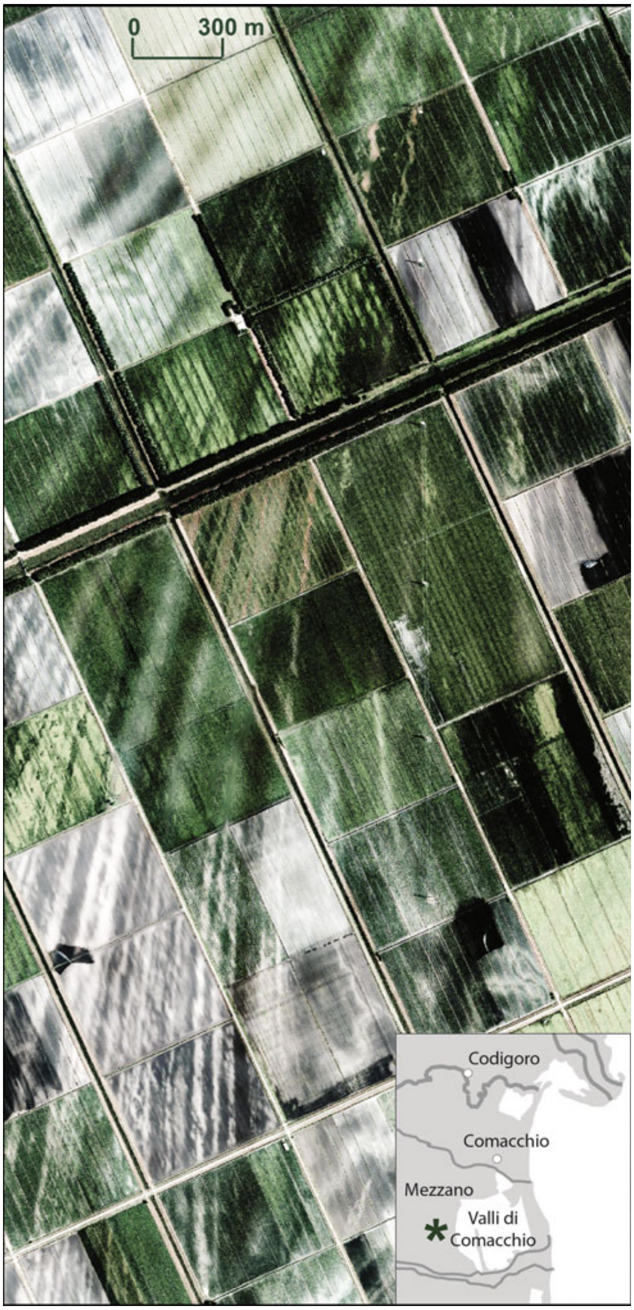


Fig. 16.3 Satellite image acquired in the visible spectrum, depicting some of the oldest outcropping sand bodies of the Po Delta plain, in the reclaimed Valle di Mezzano area, southwest of Comacchio. Image filtered and modified from 2015 Digital Globe

(south of Rimini) to the Friuli region. The active long-shore sand drift closed the former delta-estuarine bays and generated the barrier islands enclosing the Venice Lagoon (Bondesan and Meneghel 2004). The largest aeolian dune field (Figs. 16.4, 16.5, 16.6 and 16.7) of the Adriatic region (Italba-Massenzatica; Bondesan 1990) dates back to this time and it is still exceeding 13.5 m in elevation above the surrounding plain. The dunes are higher than any other Holocene counterpart of the delta area. This palaeogeographic evolution correlates with an active meteorological and oceanographic framework, well witnessed by the subsurface storm-layers distribution, suggesting a length of sea waves doubled than the present-day one, and by the accumulation of sand-gravel beds, drifted northward from the Apennine coast to the Comacchio area, under the action of strong SE wind (*Scirocco*). Climate change towards cooler and dryer conditions is also witnessed by Po and Venetian plain deposits (Veggiani 1994; Accorsi et al. 1996; Bondesan and Meneghel 2004), where it is associated with fluvial network reorganisation, lowering of the phreatic water table and the widespread abandonment of archaeological sites, marking the termination of the Bronze Age Terramare Civilisation, dated at between 1200 and 900 years BC. The dune fields dating back to this late Bronze Age time remain a striking feature within an otherwise wide, flat landscape of the delta plain and are therefore known as *monti* (mountains). These well drained sites provide the core area for the production of a peculiar sand soil wine (Vino Fortana DOC, "Vini del Bosco Elìceo").

16.4 Several Generations of Wave-Dominated Deltas (1000 BC–1600 AD)

From about the ninth to eighth century BC onwards, climate warming occurred in the coastal region (Veggiani 1994), associated with a sharp reduction in storm activity. The diminished long-shore drift supported the growth of several generations of protruding lobes (Figs. 16.2 and 16.4). In this phase, the massive sediment input filled up the lagoon space in the Emilia-Romagna area, while the paucity of sediment has preserved the Venice Lagoon to the present. During the first half of the first millennium BC, a major delta channel of the Po flew to a northern position, reaching the ancient port of Adria (Fig. 16.8).

In the second half of the same millennium, the main distributary channel (*Eridanus*) shifted to the south of the modern Comacchio site, supporting the growth of a very large delta lobe. The fluvial framework remained comparatively constant between about sixth century BC and fifth century AD (Fig. 16.8), during a relatively warm and stable climate phase. Between 350 years BC and 50 AD, the main Po channel advanced for about 12 km, as suggested also by the comparison of the Pseudo Sillace's and Strabo's geographic descriptions. At the north side of the delta lobe, the Etruscan port town of *Spina* developed since the late sixth century BC, soon reaching major importance, but the fast delta progradation afterwards made the port activity difficult, to the point that the port town was almost abandoned by the second century BC.

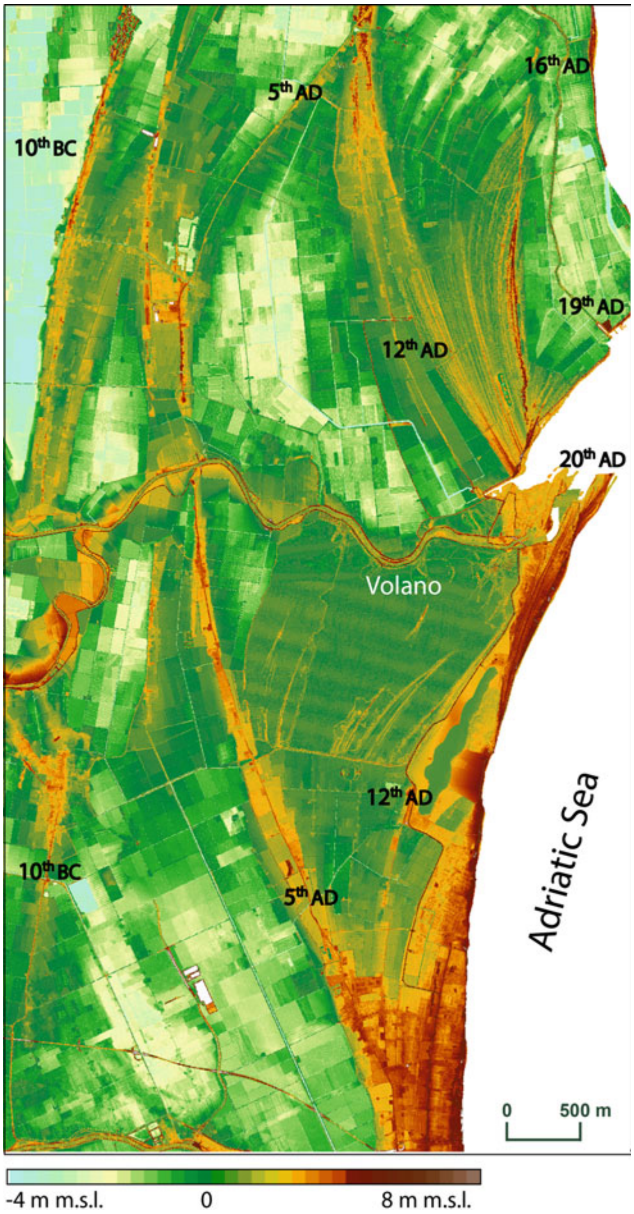


Fig. 16.4 LIDAR elevation model of the coastal plain, to the southwest of the present-day Po Delta lobe. Colours depict topographic elevation. Several coastal sand ridges, deposited through the last 3000 years, are visible. Data kindly provided by the Geological Service of the Regione Emilia-Romagna

Through Roman times (second century BC–fifth century AD), fluvial stability was enhanced by the first massive phase of artificial intervention. At that time, erosion and sediment input increased due to widespread deforestation, agriculture practises and river embankment. Large land reclamation canals were dug and river segments straightened, such as the Po channel downstream of Voghenza (Roman name: *Vicus Aventiae;* Stefani 2006) and the Santerno one (*Vatrenus*), at Filo d'Argenta (Fig. 16.8). The Reno (*Rhenus*) and Senio (*Sinnius*) rivers and all the streams in between were at the time tributaries of the Po, whereas they are now reaching the sea independently (Figs. 16.1 and 16.8). The larger fluvial basin and the large sediment input combined to support the massive growth of a Po (*Eridanus*) delta lobe, to the south of Comacchio, for the first time prograding beyond the modern coastline position. The ancient names of all the distributary channels of this delta are known from literary sources (Fig. 16.8).

Between 400 and 600 years AD, the demise of Roman infrastructures brought back wide areas to almost natural conditions, during a confuse period of war and invasions, while a moister and cooler climate developed (Veggiani 1994). Across the alluvial plain, wide swamplands arose and the Roman occupation surface was often rapidly buried by sediments (Cremaschi and Gasperi 1989). The whole of the Apennine tributaries, from the Secchia River to the Adriatic Sea, were disconnected from the Po and formed inland lake deltas. The former Po Delta distributaries were deactivated, and two new channels started to diverge at the future site of Ferrara, feeding two new delta lobes, to the north (Volano) and south (Primaro) of the abandoned Roman delta (Fig. 16.8). At the root of the Volano lobe (Figs. 16.4 and 16.5), the important Benedictine Abbey of Pomposa was founded near the seashore during early Mediaeval times, but the adjacent coastline then rapidly prograded for about 8 km, over a 500 year interval. From the twelfth century AD onwards, the main channel of the Po shifted northward, opening the present-day fluvial axis, thus generating a new lobe (Fig. 16.8). Climate was warmer and coastal progradation rates slower than during the previous early mediaeval phase. In the coastal area, gravity driven land reclamation works were performed under supervision of the Pomposa Abbey.

During the Renaissance, in the sixteenth century, a sharp increase of human intervention impacted the coastal area. An attempt to force the Reno River to reach the sea through the southern distributaries of the Po caused the termination of these channels (Volano and Primaro), because the large sediment load of the Reno silted up the confluence area, interrupting any further water flow (Bondesan et al. 1995). The two abandoned riverbeds then acted as natural dams, preventing fresh water and sediments from reaching the interspaced depression, which progressively became the salty, deepening lagoon of Valli di Comacchio (Fig. 16.8). It partially escaped the modern land reclamation works and presently forms the largest inland brackish water area of Italy. Meanwhile, the main delta channel supported the progradation of a large northern lobe (Po delle Fornaci), near the Adige River mouth (Fig. 16.9). Eventually these two deltas merged together, supporting fast progradation towards the Venice Lagoon.

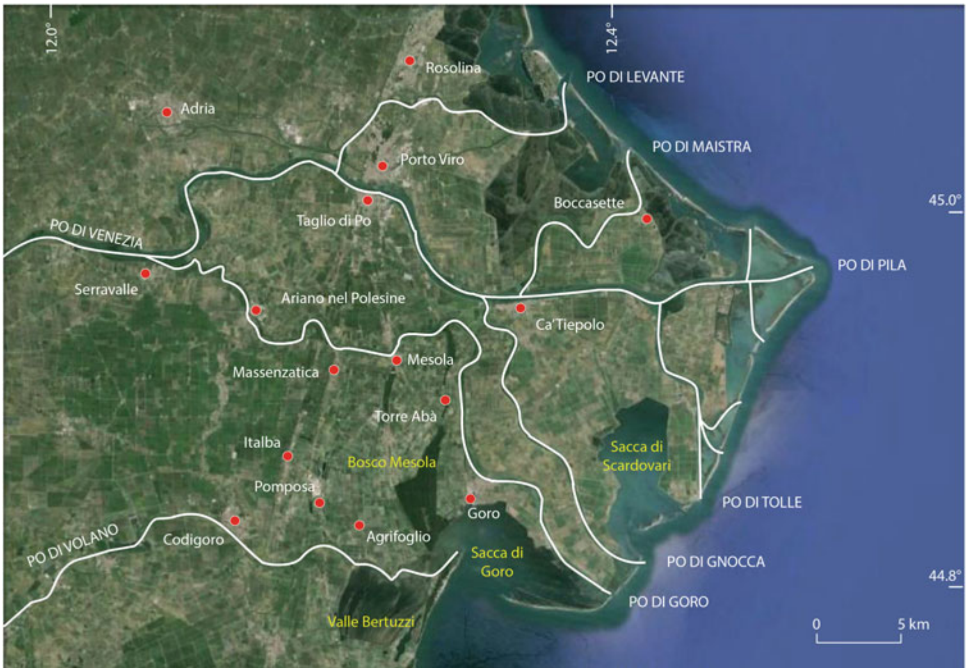


Fig. 16.5 Present-day geographic configuration of the Po Delta area, with location of the place names referred to in the text. Base satellite image from 2015 Google, Image Landsat; Data SIO, NOAA, U.S. Navy, NGA, GEBCO

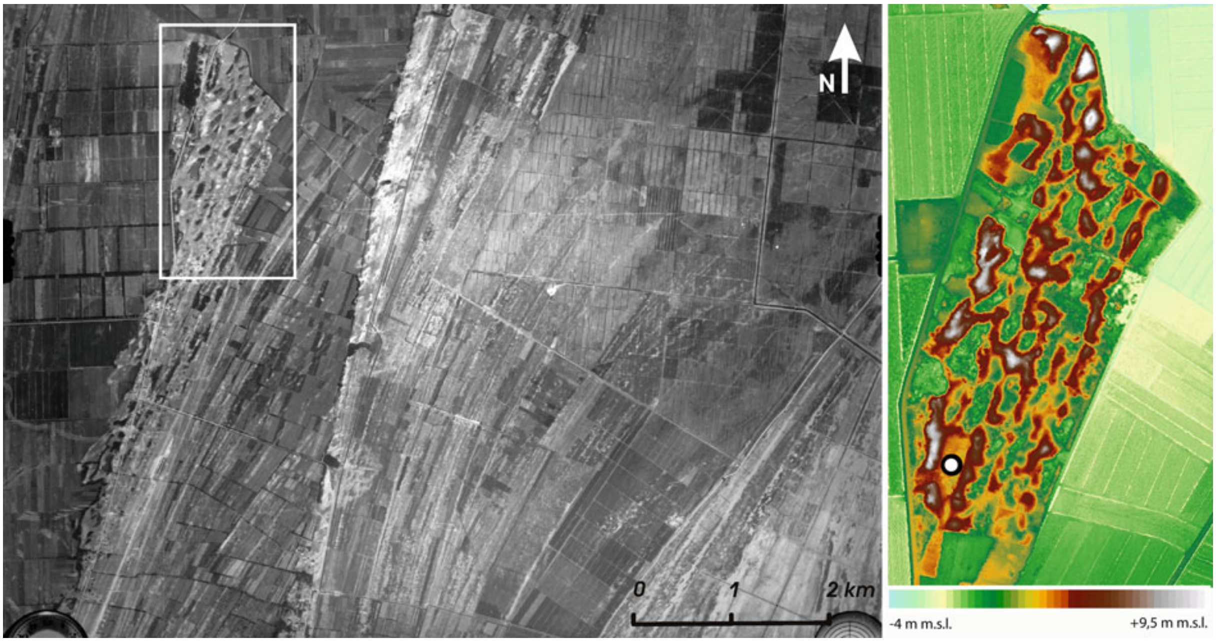


Fig. 16.6 Aerial view of the delta sand plain in the northeastern portion of the Ferrara Province, acquired by a R.A.F. reconnaissance plane during the late 1944, prior to the widespread anthropic alteration of the area. In the box, the LIDAR elevation model of the dunes, acquired in the year 2008, shows some sand excavation damage. The *white dot* visible in the elevation model indicates the location of Fig. 16.7

Between 1564 and 1580, an imposing land reclamation work was attempted in the coastal area, by order of the Duke of Ferrara (Alfonso II d'Este), drying about 400 km^2, to the south of the main Po fluvial channel. A 330 km long network of canals was dug and the inland waters were induced to reach the sea through two terminal mouths, under

Fig. 16.7 Field view of the southwestern portion of the Italba-Massenzatica dune field, partially covered by a recently grown poplar wood. Dunes reach 13.5 m of elevation above the adjacent delta plain. See *white dot* in Fig. 16.6 for location. Note man for scale (*circled*)

gravitational forcing. However, compaction of dried peats and organic clays induced fast subsidence across the reclaimed area, reversing the topographic gradients of the canals and eventually frustrating any effort to keep the area dry. The long canals and the spectacular ancient sluice buildings are however still well visible in the Po Delta area (Torre Abà and Agrifoglio, Fig. 16.5), providing important historic landmarks.

16.5 The Fast Growth of the Man-Induced Modern Delta Lobe (1600-1900 AD)

The evolution of the modern delta is hereafter for the first time reconstructed in detail (Fig. 16.9). The growth of the present-day lobe was induced, at the very beginning of the seventeenth century, by an artificial canalisation, triggering fast progradation. The modern delta rapidly evolved from a cuspidate lobe to articulated, poly-lobe deltas, rich in a large number of rapidly shifting distributary channels and lacking aeolian dunes and continuous beach systems.

At the end of the sixteenth century, the delta was fast prograding northward, approaching the inlets of the Venice Lagoon. At the time, the Republic of Venice was performing major hydraulic works, aimed at preserving the navigation, fishery and military-protection functions of the lagoon by preventing the sedimentary infilling of the area. The rivers of the Venice region were forced to directly reach the sea, bypassing the lagoon. Meanwhile, immediately to the south of the Po Delta lobe, the Estense government of the Ferrara State was planning a port at Mesola, potentially threatening the Venice interests. The Estense power was however soon to be forced out from the Ferrara Duchy, in 1598, relinquishing the region to the State of the Church. The resulting power vacuum allowed the Venetian government to artificially force the Po Delta channels southward. The diversion was planned to prevent the sedimentary closure of the southern tidal inlets of the Venice Lagoon, but also to smother with sediment the Mesola Port and the reclamation canals of a potentially hostile neighbour. The diversion was very successful in triggering the fast progradation of the modern delta lobe.

At about the year 1600 (Gabbianelli et al. 2000), the Po Delta almost reached the southern inlet of the Venice Lagoon (Bocca di Chioggia), and a narrow interdistributary bay separated the main northern lobe (Po delle Fornaci) from the smaller southern one (Po dell'Abate). Between May the 5th 1600 and September the 16th 1604, a large canal was dug at Porto Viro, to connect the main Po channel with the interdistributary bay. The canal was about 4500 m long, 600 m wide and 10 m deep. An attempt was also performed to close down the northbound channel by building a dam. In the year 1612, the main distributary channel was the man-induced one, the Po Novo, which had already prograded for more than 15 km, while the underfed northern lobe started to retreat. In the year 1650, the main Po channel was the Donzella one, also known as Gnocca, fast prograding southward. At the time, the erosional retrogradation of the northern lobe had almost reached the present-day coastline and the adjacent delta plain started to be flooded by salty waters. During the seventeenth century, the new delta progradation closed the mouth of the northern canals of the former Estense land reclamation. By the end of the century, almost the whole of the reclaimed region was therefore re-flooded.

A renewed northward progradation trend took place at about the year 1700 (Po di Grignola), because of the failed attempts to close the northern distributary channels of the Po. At the time, the coastline developed a poly-lobe shape, with well developed interdistributary bays and a poorly defined coastline. During the early eighteenth century, the delta growth speeded up because of an augmented sediment

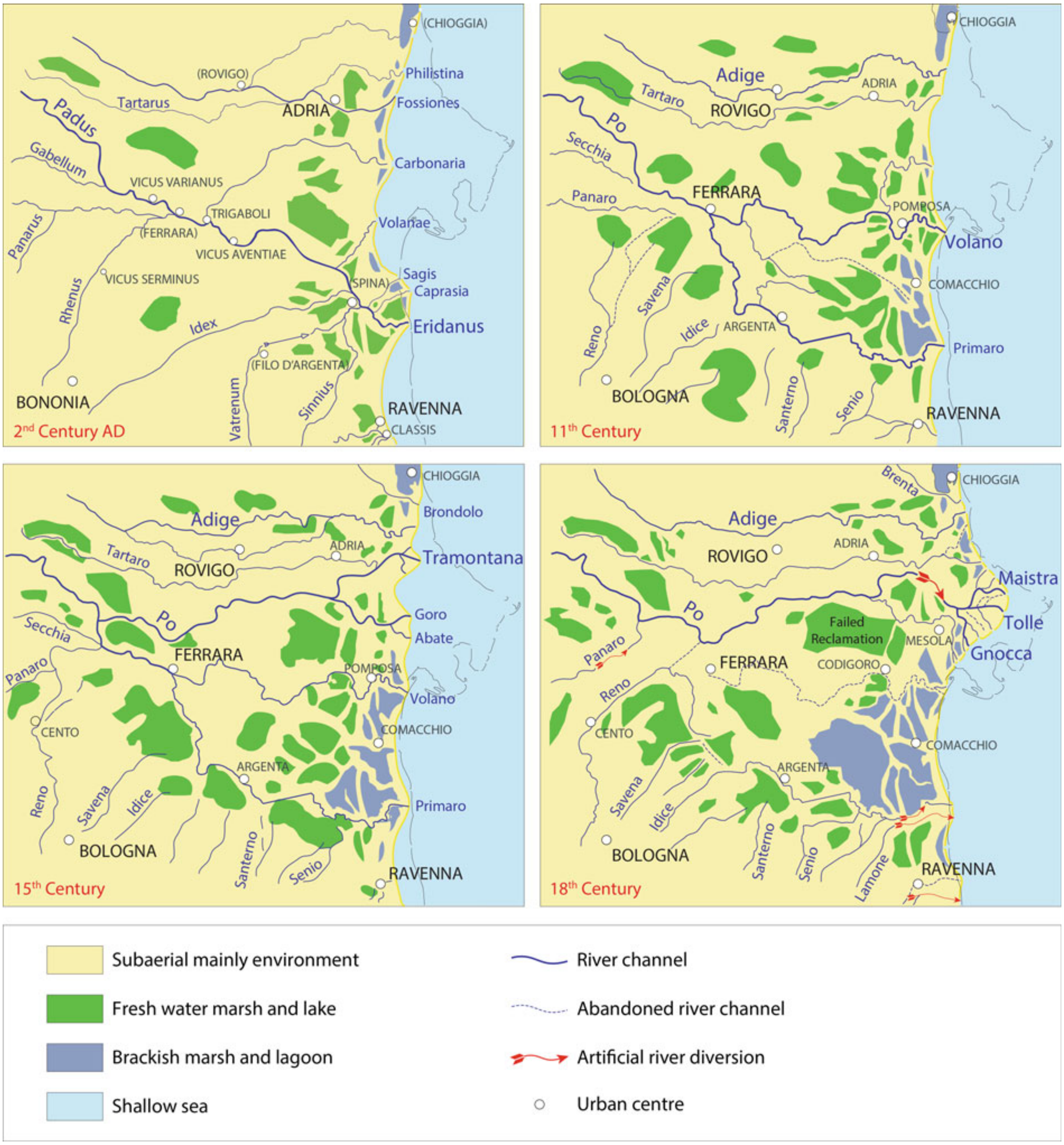


Fig. 16.8 Schematic reconstructions of the drainage evolution in the Po coastal plain, from Roman to modern times. In the oldest reconstruction, toponyms known form the ancient Latin literature are used. Note the impressive magnitude of the paleogeography change (modified after Bondesan 1990 and Stefani and Vincenzi 2005)

input, supported by climate evolution towards cooler conditions, the retreat of the mountain woods and the advance of Alpine glaciers. The sea wave activity also probably increased. Over the short period of a few years, a major geographic change took place. In the year 1735, a continuous delta front developed, smoothed by the coastal sand drift, associated with the growth of small aeolian dunes. The major distributary channels were eastbound (Asenìn and Tolle channels); to the south, the ancient Po di Volano lobe was largely flooded, and the former wood and vineyard areas (Bosco Eliceo) gave way to salty lagoons. In the year 1758, after a pause in progradation, the advance of the southern mouths restarted to dominate the delta evolution. In the year 1790, the central channels became the dominant ones, two of them corresponding to the modern channels of Pila and Tolle. The fast progradation rapidly recreated a digitate

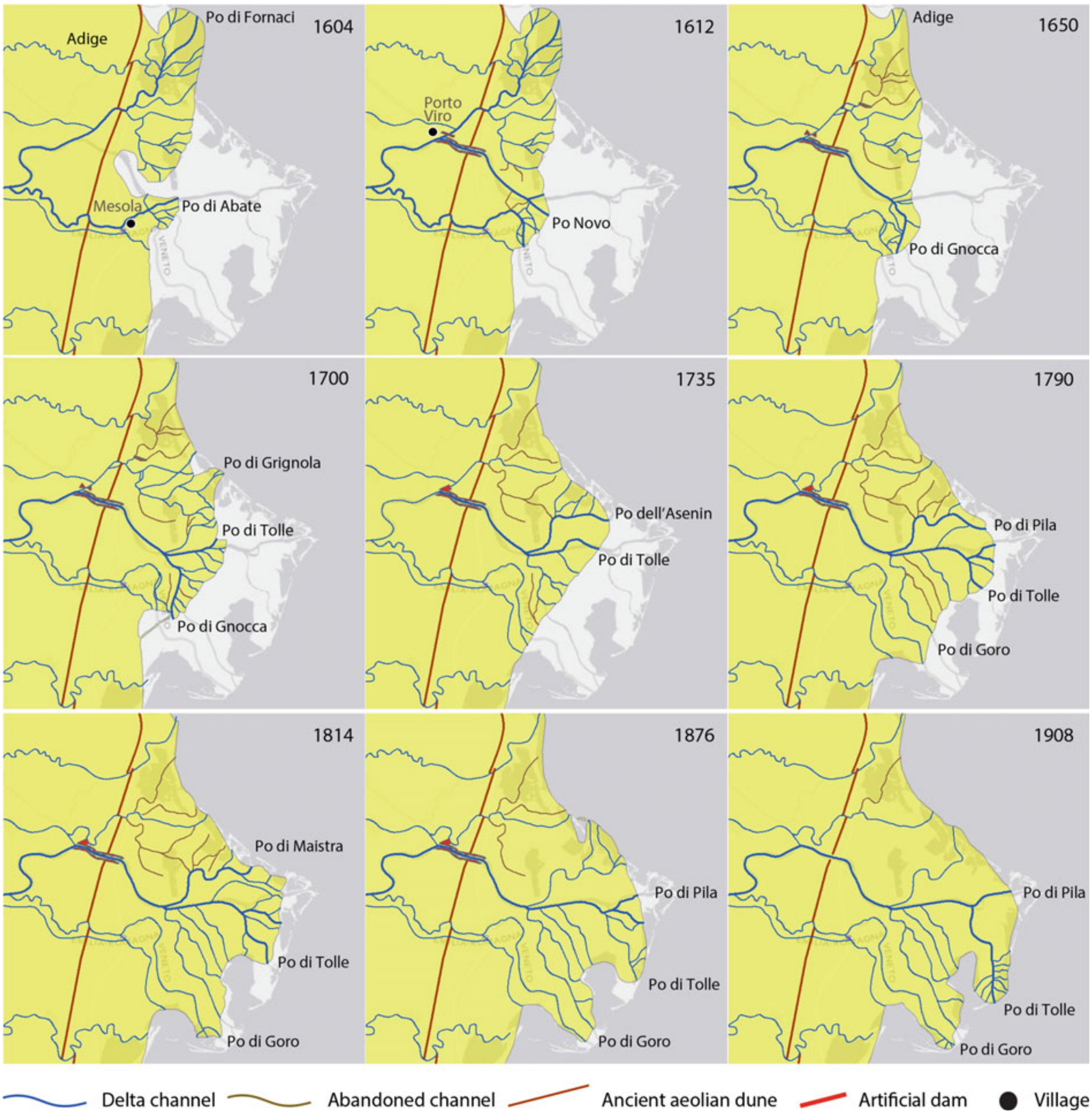


Fig. 16.9 Reconstruction of the modern delta lobe growth, since the beginning of the seventeenth century

shape of the delta, with embryonic interdistributary bays (Sacca di Scardovari and Sacca di Goro), as visible in the year 1814. During the second half of the nineteenth century, the Po di Maistra was for the last time keeping its importance, as visible in the 1876 map. At the time, the Po di Tolle channel was fast prograding towards the very south. At the start of the new century, the northern channel was already confined to a minor role and the major discharge was through the centrally placed Pila mouth. During the first half of the twentieth century, the delta was still prograding, generating a strongly digitate shape, recording a progressive sediment starvation of the delta system.

16.6 The Present-Day Artificial Framework

During the last 150 years, water scooping supported the widespread land reclamation of the vast majority of the delta top region. The landscape of the southern portion of the modern delta is therefore mainly flat and artificial in nature, compartmentalized by the high river embankments; in the northern portion, coastal lagoons and deltaic spits are however preserved, generating a "natural" landscape of high value (e.g. Boccasette). Some fascinating environments have survived in partially natural conditions, such as the aeolian dune field and lagoons in the northern portion of the delta,

Fig. 16.10 Former coastal wood at the southern margin of the Bosco Mesola, progressively covered by the salty waters of the Sacca di Goro interdistributary bay because of the fast subsidence and sediment starvation. For location, see Fig. 16.5

near Rosolina, the delta bay of Goro, the coastal wood of Bosco Mesola, the salty lagoons of Valle Bertuzzi and the larger lagoon area of the Valli di Comacchio.

The massive anthropogenic alteration is however overwhelming. Continuous river embankments were built, forcing rivers to become suspended over reclaimed areas, which are well below sea level. Natural subsidence was considerably accelerated, to values even exceeding 3–4 m per century, by the combined effect of land drying and subsurface water and methane pumping (Bondesan et al. 1997). The granular sediment input to the coastal environments has almost stopped over the last 50 years because of the massive anthropogenic alteration of rivers, such as dam construction and sand excavation from riverbeds. The combination of these factors induced erosion and marine transgression to largely took over progradation, throughout the region (Fig. 16.10). Only massive coastal protection works and artificial damming prevent the Po River delta from being rapidly re-conquered by sea. River and coastline man-induced rigidity, accelerated subsidence, interruption of the fluvial sediment input, climate change, river and sea water pollution and eutrophication combine to make the environmental management of the fragile coastal area difficult. A retreat of the human activity from large delta top areas therefore looks unavoidable in any foreseeable future.

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17

Landscapes and Landforms Driven by Geological Structures in the Northwestern Apennines

Luisa Pellegrini and Pier Luigi Vercesi

Abstract

The northwestern Apennines present a very complex geomorphology, strictly related to the recent tectonic evolution of the orogenic chain (Upper Oligocene—Lower Miocene to present). In this chapter, some unique and representative landform assemblages related to tectonic structures located in the area between the Scrivia and Trebbia valleys are described. Morphological aspects are also highlighted in relation to lithological/structural elements of local or regional importance, some of which have driven significant river diversion. The peculiar features of these landforms hold the pieces of the geological and geomorphological evolution of the entire area and are spectacularly exposed and clearly visible along beautiful valleys.

Keywords

Selective erosion • Synclinal mountain • River diversion • Entrenched meanders • Northern Apennines

17.1 Introduction

The extremely varied landscape of the northwestern Apennines is the result of geomorphological modelling influenced by the presence of rock types of diverse erodibility in a very complex tectonic setting. The tectonic evolution of the area took place in the Neogene and Quaternary, involving alternating phases of intense activity (e.g. the Tortonian, Intra-Messinian, Mid-Pliocene phases) and phases of relative quiescence. The effects of these phases are clearly visible in the contemporary morphology of mountains and valleys, where a series of different geomorphic features allows for the reconstruction of a complex landscape evolution, including the development of a hydrographic network with a very peculiar pattern. Therefore, fluvial diversions, superimposed rivers (entrenched meanders), steep escarpments, or gorges are common in this sector of the Apennines.

There are many locations where landforms, such as hanging valleys, monadnocks, etc. are strictly related to regional tectonic structures (anticlines and synclines) and to their lithology. Obviously, all these structures had clearly influenced the fluvial morphology, which shows straight trends, aligned elbows, asymmetrical valleys, erosion steps with the formation of paleo-surfaces, polygenic landslides, centrifugal patterns, etc. Selected unique examples will be described and discussed in this chapter, aiming at highlighting how the geomorphological evolution has been conditioned through time by various geological settings.

17.2 Geographical Setting

The area is located in the northern portion of the Apennines, east of the Scrivia Valley, west of the Trebbia Valley and north of the Po River—Ligurian Sea watershed (Fig. 17.1). This watershed runs about 10 km away from the Ligurian coastline and is about 1200 m high (except Mt. Aiona, 1695 m a.s.l.). It should be noted that the highest peaks are not situated along the watershed itself, but they can be found

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about 25 km north of it, forming a massif about 1600–1700 m high (e.g. Mt. Lesima, 1724 m; Mt. Chiappo, 1699 m; Mt. Ebro, 1700 m; Mt. Antola, 1597 m). North of the massif elevations progressively decrease, the mountains become hills and finally the Po Plain opens up and the altitudes drop to 50–70 m.

The area is crossed by many rivers and streams, which form a kind of radial pattern with the massif formed by Mt. Antola, Mt. Ebro, Mt. Chiappo and Mt. Lesima in the centre. This pattern is due to structural setting and differential uplift. Neotectonic phases, in particular, the uplift of the central area of the chain, and favourable, very wet climatic conditions have caused intense fluvial erosion, many river diversions and captures.

Rivers on the northern slopes of this massif, which flow into the Po River, have two preferential directions: northwest (Staffora, Curone and Scrivia rivers) and northeast (Tidone and Trebbia rivers). This configuration follows the shape of the structural arc in this part of the Apennine area. Only the first reach of the Staffora River and some minor streams (e.g. Versa and Scuropasso rivers) flow northward.

Climate shows an average annual temperature of 12 °C in the less elevated areas and of 8 °C at the highest elevations. Rainfall is about 675 mm/year on the plain, 785 mm/year in the hills and 1420 mm/year in the mountains. The monthly pluviometric regime shows two maxima, in November (absolute maximum) and May, and two minima, in July (absolute minimum) and January (Maggi and Ottone 2003).

17.3 Geology and Structure

The Apennine orogen was generated by the closure of the Liguria-Piemonte Ocean (Eoalpine phase) and subsequent continental collision between the European and Adriatic tectonic plates (Mesoalpine phase). This chain has an

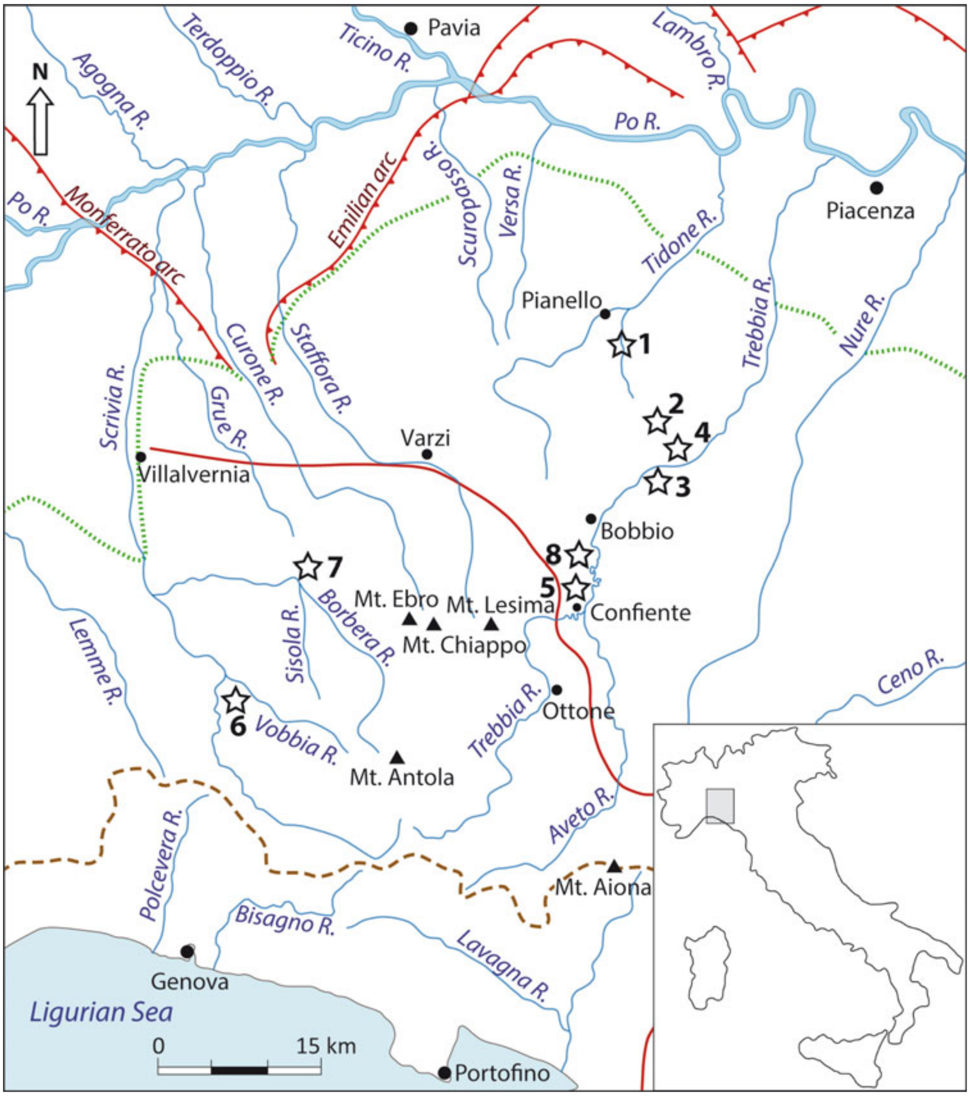

Fig. 17.1 Geographical setting of the northwestern Apennines. The *brown dashed line* indicates the divide between the Po basin and the Ligurian basins; the *green dotted line* shows the Po Plain boundary; the *red lines* represent tectonic lines (*lines with triangles* are main post-Tortonian thrusts, modified after CNR 1991). The *stars* indicate: *1* Rocca d'Olgisio syncline mountain; *2* Pietra Parcellara ophiolite; *3* Mt. Barberino ophiolite; *4* Caverzago slope; *5* Brugnello slope; *6* Castello della Pietra peak; *7* Borbera River diversion; *8* Trebbia River entrenched meanders and Bobbio windows

eastward vergence (Adriatic vergence) which is due to the post-Oligo-Miocene tectonic phases, and related to the westward subduction of the Adriatic plate. According to this model, the opening of the Ligurian-Provenzal Basin in the Upper Oligocene—Lower Miocene, and later opening of the Tyrrhenian Basin (Upper Miocene) can be both explained as back-arc tectonic extensions, induced by the Apennine subduction, and as the source of the *boudinage* structure of the Alpine prism (Laubscher 1988). Today's geological structure of the Apennines, with its northeast-vergent nappes stacked upon the Adriatic plate, arises from these latest geodynamic phases, started in the Upper Oligocene—Lower Miocene and showing landforms very different from one another.

17.4 Landforms

The landscape of the area is very complex, with contrasting landforms and frequent morphological changes. These changes are mostly related to different lithology and regional tectonic structures, heritage of the tectonic setting of the Apennine chain.

17.4.1 Structural Landforms

In stable tectonic settings, morphology only reflects erosional/depositional processes, which can be more or less intense depending on the climatic condition and the initial topography of the area. By contrast, in the Apennines tectonic evolution is still active and the connection between landforms and tectonics is the primary element that marks the landscape. Examples include faults juxtaposing completely different lithologies on the two sides, resulting in asymmetrical valleys (Staffora Valley); active synclines with deformed highly resistant sedimentary successions, which are fractured in the axial zone (Rocca d'Olgisio syncline); arching and isostatic movements deforming stacked nappes and taking the same stratigraphic units to different topographic levels (Mt. Barberino ophiolitic group).

An exemplary case of a hanging syncline is the Rocca d'Olgisio ridge (cf. Pellegrini et al. 2010) which is located southwest of Piacenza, close to Pianello Val Tidone. It is an extraordinary site of high geological value, cut in the middle by the Chiarone stream, with a SSE–NNW direction. At the western end of the structure, the fortress of Rocca d'Olgisio stands in a striking position, over a high arenaceous spur (Fig. 17.2).

The structural and lithological setting played a fundamental role in shaping the Rocca d'Olgisio syncline, where the "relief inversion" phenomenon is related to the superposition of resistant and weak successions. Therefore, the syncline is built up of turbiditic sediments of the Ranzano Formation in the upper part, and in the Monte Piano Marls in the lower part. The conglomeratic sandstones (Ranzano Formation), highly resistant to erosion, allowed the structure to stand in a dominant position with respect to the general landscape, whereas anticlines can be recognized in the more erodible marls of the Val Luretta Formation to the north, and in the Palombini Shales and the pelitic-arenaceous succession of the Scabiazza Sandstones to the south (Fig. 17.3), both subject to considerable erosion.

Also, topographic maps show peculiar erosional features of the Rocca d'Olgisio syncline, due to central depression of the WNW–ESE-oriented fold axis and the periclinal closures of two lateral culminations. These two terminations display different morphologies: the western one has a very gentle pitch and the limbs of the folds are almost parallel, while the eastern one has a steeper pitch and the pattern of the outcrops is almost circular.

Therefore, the area shows all typical conditions for shaping of a "canoe valley" such as resistant rocks above weak ones, folded structures (with an Apennine trend of their axes), folded structures with a WNW–ESE strain trend, geomorphological evolution that led to the erosion of the upper parts of the relief (axial culminations) and "relief inversion". We can define the elongated shapes as a "canoe valley" because of the similarity with this type of boat. In the above-described area, the anticlines, squeezed and faulted, are more intensely affected by erosion that has reached the weakest rocks. When this happens, erosion increases its intensity and speeds up, while the lower parts of the synclines, formed by competent rocks, are still resistant to erosion. This selective erosion has generated a landscape where synclines are the most elevated morphological features.

The evolutionary model of the area has many similarities with the one proposed in 1965 and taken up in 1985 by Oberlander to explain the morphology of the Zagros Mountains. Although the tectonic evolution has been different, the peculiarity of the frequently undulating axes of the folds (plunging folds), the lithological alternation of resistant and weak rocks, and the young orogenic developments have led to a similar morphological evolution. The drainage pattern is discordant with the geological structure (Chiarone stream) and is comparable to Oberlander's (1985) transverse streams with superimposition controlled by structures such as the "drainage inheritance" of Summerfield (1991).

In more detail, the canoe valley of the Rocca d'Olgisio is 4.5 km long and 1 km wide in the central part and reaches the maximum altitude of 610 m in the northwestern periclinal culmination. The effects of selective erosion can be recognized at different scales, from relief modelling in the topographic outline to the tiny details of sculpting and

Fig. 17.2 View of the structural landform of Rocca d'Olgisio from southeast (*photo* L. Pellegrini)

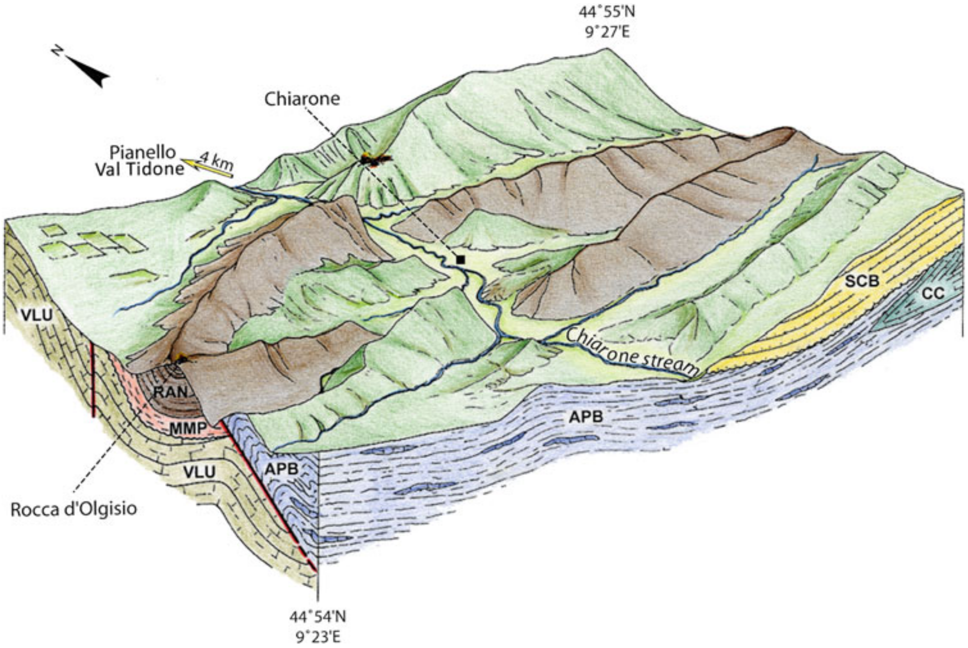

Fig. 17.3 The Rocca d'Olgisio "canoe-shaped" syncline. Three dimensional sketch of the structure. *RAN* Ranzano Formation; *MMP* Monte Piano Marls; *VLU* Val Luretta Formation; *SCB* Scabiazza Sandstones; *APB* Palombini Shales; *CC* Calpionelle Limestone (modified after Pellegrini et al. 2010)

chiselling. The inner side of the "canoe" corresponds to the pelitic facies of the Ranzano Formation and has gentle morphology, while the outer rocky faces are steep, with escarpments up to 200 m, carved in the conglomeratic-arenaceous strata. Lithological features of these strata, partially lightly diagenized, the exposure of the face scarp slope, together with the particular microclimate of the area, have led to the excavation of variously sized hollows, such as tafoni, caves, and alveolar structures with honeycomb appearance, due to differential weathering.

This area is also of high naturalistic interest, because some rare and unusual vegetable species, not found elsewhere in the Northern Apennines, grow here spontaneously thanks to the particular microclimate and soil conditions, consequence of the southward exposition, and local geometry of the arenaceous slopes. A southward exposition, or a nook, protected from winter rain, develops a microclimate that is excellent for these plants, which need warmth and plenty of sun. Moreover, degradation of the arenaceous terrain has produced favourable soil (sandy or very well drained, with a pH about 6–7.5) for the growth of some vegetable species uncommon in this portion of the Apennines. Therefore, it is possible to see the unusual presence of dwarf Indian figs (*Opuntia compressa,* Salisb.) of North American origin, some cork oaks (*Quercus pseudosuber,* Santi) and amaryllis, protected by the current laws, the yellow amaryllis (*Sternbergia lutea,* L.*)* very rare in the Emilian region, some species of wild orchids, like the "spider flower" (*Ophris Sphegodes,* Miller) and the "pyramidal orchid" (*Anacamptis pyramidalis,* L.).

17.4.2 Lithological Control on Erosion: Relief Due to Selective Erosion

Lithology and structures strongly influence erosional processes that are much faster if the rock is erodible. Resistant rocks usually emerge as isolated peaks when they are in contact with weak rocks. The selective erosion of Pietra Parcellara, Pietra Perduca (very close to Pietra Parcellara), Mt. Barberino, Caverzago, Brugnello and Castello della Pietra peak are very significant examples.

17.4.2.1 The Pietra Parcellara Ophiolite

The Pietra Parcellara (Fig. 17.4), Pietra Perduca and Mt. Barberino elevations in the Trebbia Valley are large fragments of serpentinized lherzolites (ophiolites) which stand out against the mild landscape of the Palombini Shales Formation. Effects of selective erosion are very clear when related to lithological changes and have repercussions in making use of the soil and in the spontaneous vegetation distribution.

Groundwater reservoir originated in the ophiolitic masses leaks and soaks the clays underneath. This downgrades the geotechnical properties of the pelitic rocks, together with the erosion at the base of the slope, due to lateral erosion of the Trebbia River. Erosion and degradation of the pelitic rocks have caused the formation of some huge landslides.

17.4.2.2 Mt. Barberino Ophiolitic Relief

Mt. Barberino (Fig. 17.1) ophiolitic relief is also surrounded by pelitic deposits with gentle and moderately inclined slopes and is deeply carved by the Trebbia River, which flows in a gorge. This gorge is the result of a superimposed/antecedent phenomenon. It was a consequence of the latest phases of rising of the chain that did increase the stream power enough to deeply erode these more resistant rocks. Upstream of the obstruction, the valley, carved in weak rocks, is wide and terraced alluvial deposits fill its bottom (Bobbio plain). Phases of deposition and incision of these alluvial deposits were emphasized by the ophiolitic obstacle and by the phases of its erosion.

17.4.2.3 Caverzago Slope

Elevated position, which made the neighbouring areas more visible, has affected human behaviour in choosing where to settle since ancient times. In fact, worship or defensive churches and castles have been built on the top of structural landforms.

Fig. 17.4 The Pietra Parcellara ophiolitic relief stands out in the *background*; in the *foreground*, the foot of a large landslidein clays (*photo* P.L. Vercesi)

In the Trebbia Valley, for example, the oratory of Pietra Perduca is nestled in the fracture of an ophiolitic block, close to Pietra Parcellara, and the church of Caverzago (Fig. 17.5), northeast of Barberino, is located on the edge of a steep scarp. This scarp was shaped in turbiditic successions and, even if they are relatively easy to crumble, they have relatively endured through time.

17.4.2.4 The Brugnello Slope

Similarly, south of Bobbio, in the Trebbia Valley, the church of Brugnello (Figs. 17.6 and 17.9a) stands on the edge of a precipitous scarp, more than 150 m high and shaped in the erodible Brugnello Shale Member (the arenaceous components prevail against the shales). The position of this church, and those of Caverzago and the Castello della Pietra, underlines just how the religious or strategic settlement choices are linked to specific landforms.

17.4.2.5 Castello Della Pietra Peak

In the Vobbia Valley, a right tributary of the Scrivia River, there is a spectacular and dramatic peak and on top of it, the Castello della Pietra towers (Fig. 17.7). The peak is similar to the Meteora in Thessaly (Central Greece). In this case, selective erosion focused on planes of weakness, in correspondence to vertical faults. The latter have irregularly cut the highly resistant rocks belonging to the Savignone Conglomerates Formation, which have been intensely fractured and are now arranged in bands of variable thickness, from a few centimetres up to some metres; in some cases, the

Fig. 17.6 Church and village of Brugnello built on an ancient fluvial surface at the edge of a high scarp carved by the Trebbia River (*photo* L. Pellegrini)

Fig. 17.5 The Caverzago church, dominating the Trebbia River bed, is set on an ancient fluvial surface that has been partially eroded. Beside the church, the ruins of the castle, collapsed because of the scarp retrogression, are still recognizable (*photo* P.L. Vercesi)

Fig. 17.7 The Castello della Pietra was built on top of the lower of the two rocky peaks. The highest reaches an altitude of 625 m a.s.l. and rises up 210 m from the valley bottom (*photo* L. Pellegrini)

formation is shaped in huge isolated spurs. The Castello della Pietra has been included among the list of Italian national monuments.

17.4.3 River Diversion

The Villalvernia-Varzi-Ottone-Levanto tectonic lineament (Fig. 17.1) influences the evolution and the trend of the Staffora Valley. The influence is very clear in the medium reach of the Staffora River, where the river suddenly drifts towards west and then north. From a general point of view, the river axis shows abrupt drift-diversion, or a fluvial elbow, mimicking the trends of other rivers of the same sector (Fig. 17.1). These common features in the river are visible in the collisional zones of the tectonic arcs, such as the Emilian tectonic arc and the Monferrato tectonic arc (CNR 1991).

The Borbera Valley has a very peculiar hydrographic pattern (Pellegrini et al. 2003). The Borbera River, a right tributary of the Scrivia River, flows in a SE–NW direction. Near Pertuso, 1.5 km north of the confluence with the Sisola River, it twists sharply to the west (Fig. 17.8). Changing its direction, the stream abandons a zone of weak rocks and crosses more resistant ones. Moreover, the Borbera Valley (downstream from the confluence with the Sisola River to Pertuso) shows a rather wide riverbed (Fig. 17.8a) and very asymmetric valley slopes. The right side of the valley, carved in flysch, has a gentle slope; the left one has a much steeper slope and is developed in more resistant conglomerates.

Along the valley floor, extensive terraced alluvial deposits stretch out. Where the Borbera River crosses the conglomerates, in the east-to-west reach, "young" landforms can be seen with entrenched meanders and gorges.

Comparative analysis of the morphological and morphotectonic elements described above allowed to propose a scheme for the recent evolution of the area. An original river flowed from SSE towards NNW, going on to the valley of the present Grue River (Fig. 17.8b). The headward erosion of a stream flowing to west, and located west of Borbera Valley, caused capture of the Borbera River. In all likelihood, this capture have been helped by differential tectonic uplift of Mt. Gavasa area and by a tectonic lineament located in the present Borbera gorge close to Pertuso. The evidence of the former Borbera Valley is represented by the scarp flanking the Merlassino area and which is the continuation of the scarp south of the Pertuso elbow (Fig. 17.8b, c). Since the scarp height is generally the same southward and northward of the elbow, the diversion must have occurred quite recently. Traces of the bottom of the former Borbera Valley is no longer visible because of the earth flows affecting the Merlassino area.

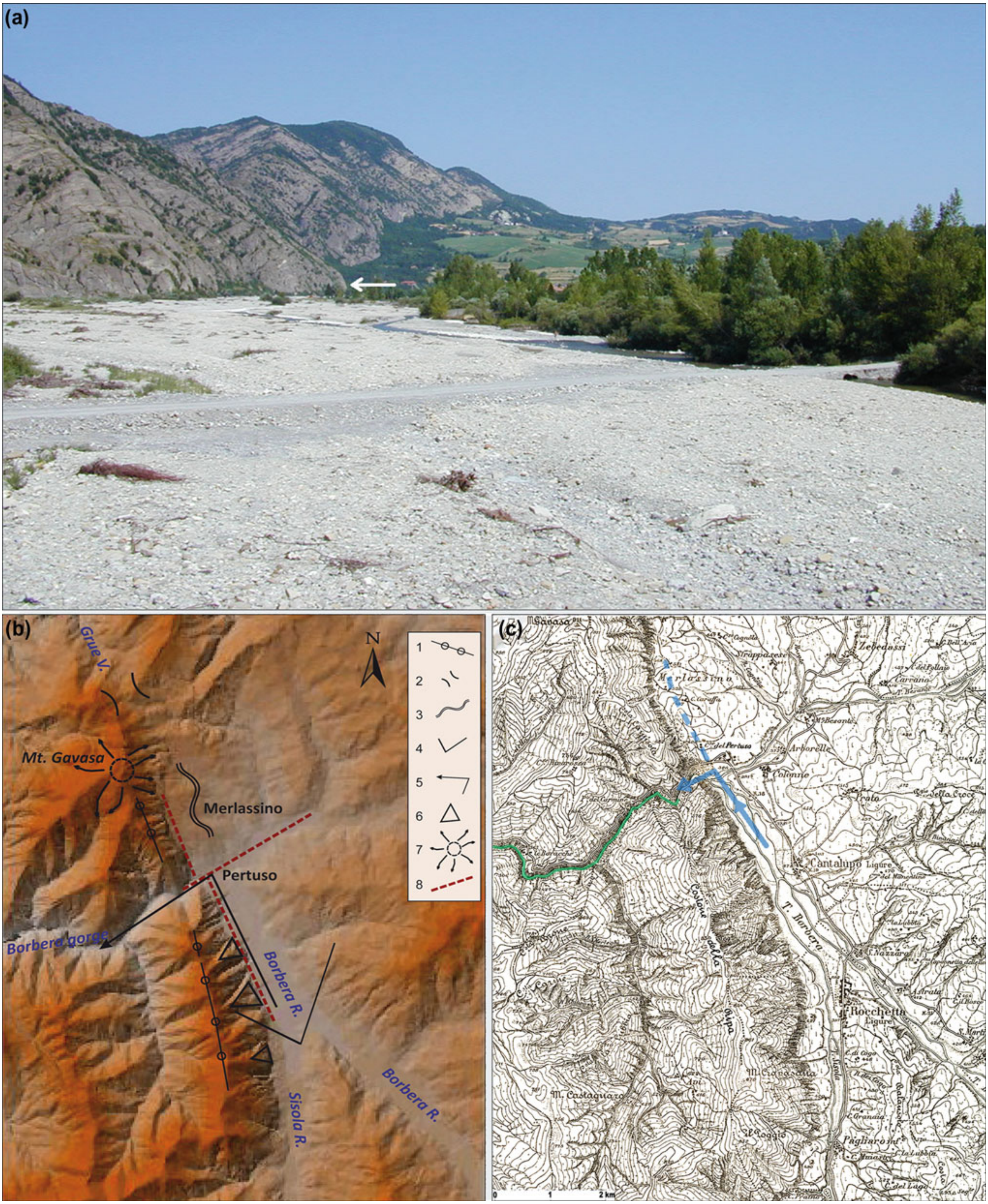

Fig. 17.8 **a** In the foreground, the Borbera River large channel that carries flows towards the background of the photo (by L. Pellegrini) and then turns to the *left* (*white arrow*). **b** Lineaments and morphotectonic elements on hillshaded terrain model, related to diversion (Pertuso area): *1* rectilinear crest or spur; *2* saddle; *3* landslide; *4* asymmetric valley; *5* diversion elbow; *6* triangular facet; *7* centrifugal drainage pattern in the uplift area; *8* lineament (modified after Pellegrini et al. 2003). **c** Topographic map (after Marinelli 1948) of the area of the Borbera diversion. The *blue arrow* indicates the Borbera diversion and the *dashed blue line* is its ancient course. The *green line* highlights the headward erosion of the captor river

Fig. 17.9 **a** Aerial image of entrenched meanders of the Trebbia River from Marsaglia to Bobbio (*photo* G. Bertolini). **b** terrestrial view of the San Salvatore meander cut in the San Salvatore Sandstone of the Lower Miocene (Tuscan nappe) in the heart of the Bobbio tectonic window (*photo* L. Pellegrini)

17.4.4 Incised Meanders

The deep gorge carved by the Trebbia River (Fig. 17.9a), south of Bobbio, not only has displayed important geological structures to the view, such as the tectonic window of Bobbio, but also shows extraordinary entrenched meanders.

The origin of these meanders is related to the reactivation of erosional activity of the Trebbia River, after the relief had undergone levelling (pediplanation), likely during the middle-late Pliocene. This levelling is proven by widespread ancient surfaces, located on top of the water divides or along the slopes. The surfaces are now isolated but well recognizable (see, for example in Fig. 17.9a, Moglia, Rossarola, Brugnello, Telecchio).

Flowing across a gentle and slightly undulated paleolandscape, the Trebbia River channel was a meandering one, with a very high sinuosity index. When the tectonic uplift forced the Trebbia River to start downcutting again, the river did not change its style; it remained meandering highlighting in this way the phenomenon of superimposition.

The magnificent meanders of Confiente, Brugnello and of San Salvatore (Fig. 17.9b) are carved in highly resistant lithology, such as siltstone and sandstone, or sandstone and conglomerate. The high slopes exhibit evidence of several stages of erosion with stronger gradients towards the valley floor (rock-cut terraces).

17.4.4.1 The Tectonic Window of Bobbio

The «Bobbio tectonic window» (Ludwig 1929; Elter 1994) in the Trebbia Valley extends from about Ponte Organasco (close to Marsaglia) to Bobbio and offers a view of the Northern Apennine structural frame.

The Northern Apennines developed through successive tectonic phases and their structure shows various tectonic units piled upon one another, stacked up and shifted towards the northeast (from the Lombardy to the Emilia-Romagna regions), whilst they were originally located in more southwestern areas. The result of this stacking and migration was a fold and thrust tectonic style of the chain.

The internal structures, migrated from west to east, now lie in the western part of the continental margin of the Apula plate. The allochthonous Ligurian Units of oceanic origin currently form the uppermost nappe system of the Northern Apennine stack and have migrated on the Tosco-Umbrian Unit, which represents the deformed and unstuck foreland of the Apula plate.

The Ligurian Units nappe is locally incised, giving the chance to observe the underlying units. This is the case of the tectonic windows of Bobbio, and the other ones such as Salsomaggiore, in the Parma Apennines to the east.

Along the valley bottom of the Trebbia River, which is deeply incised into all the tectonic units, it is possible to see all lithologies and structures of the tectonic window of Bobbio along the slopes of the valley, with the younger unit in the lower part and the progressively oldest lithologies towards the top, separated from one another by thrusts.

17.5 Conclusions

An area characterized by very diverse geological and morphological features, which gave birth to a very unusual landscape, has been described in this chapter. It is interesting to recognize and understand the connections between landforms and tectonic and lithological setting of the area. Therefore, an analysis of local landforms inserted and linked within the regional geological context of the area can be very helpful in understanding landscape evolution.

Many landforms described here can be considered as geomorphosites and therefore included in valorisation programmes. Actually, there are two parks in the area: the Antola Park and the Trebbia Fluvial Regional Park. The Antola Park was established in 1995, based on regional law. The protected area includes the high Trebbia Valley and the Vobbia Valley, with specific reference to the “Castello della Pietra”. The Trebbia Fluvial Regional Park is located in the lowest reaches of the valley and is aimed primarily at protecting relict environments in plain and hilly settings, which are important natural habitats for native flora and fauna.

A project for the establishment of a geotouristic itinerary in the Trebbia Valley (particularly referred to the middle section of the valley) is ongoing, aiming at the assessment of sites with high scientific and aesthetic values such as the entrenched meanders, the Pietra Parcellara and others, described in this chapter.

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18 Fingerprints of Large-Scale Landslides in the Landscape of the Emilia Apennines

Giovanni Bertolini, Alessandro Corsini, and Claudio Tellini

Abstract

Impressive depletion and accumulation landforms created by the millennial evolution of large-scale landslides are distinctive features of the landscape of the Emilia Apennines (Northern Italy). They are complex earth slides and earth flows that can be tens of hectares wide and can involve millions of cubic metres of clayey deposits originated by the failure and weathering of weak rocks such as clayey flysch and mélanges. These landslides have originated in large number since the upper Pleistocene. It is estimated that they now cover up to 20% of the mountain areas of the region. They typically alternate periods of dormancy that can be centuries long, to periods of reactivation that can last for a single season or several years. Upon reactivation, they rejuvenate landforms that outstand impressively from the surrounding landscape and cause severe damages to infrastructures. The chapter presents some relevant examples of these landslides and related hazard and risk issues.

Keywords

Landslides • Landslide reactivation • Hazard and risk • Emilia Apennines

18.1 Introduction

In the Late Pleistocene and Holocene, landslides have been a major geomorphic factor in the development of the landscape of the Emilia Apennines, the sector of the Northern Apennines of Italy stretching from the Reno to the Trebbia rivers (Regione Emilia-Romagna) (Fig. 18.1). Impressive long-term persistent erosional and accumulation features related to large-scale earth slide—earth flow phenomena are clearly distinguishable in the landscape of Emilia Apennines. The aim of this chapter is to present selected typical landslide features that mark the landscape of the Emilia Apennines and to pinpoint how their evolution during the millennia has left a very distinguishable fingerprint in the landscape and how their recurrent reactivation influences troublesome coexistence between socio-economic activities and natural landscape evolution.

18.2 Geographical Setting

The Emilia Apennines have an area of approximately 9000 km^2 from the Reno to the Trebbia river basins in the northeast-facing slope of the Northern Apennines (Fig. 18.1). Administratively, they fall within the Regione Emilia-Romagna, from the Province of Bologna to the Province of Piacenza. The main peaks are located along the SE–NW watershed of the Apennines (Mt. Corno alle Scale,

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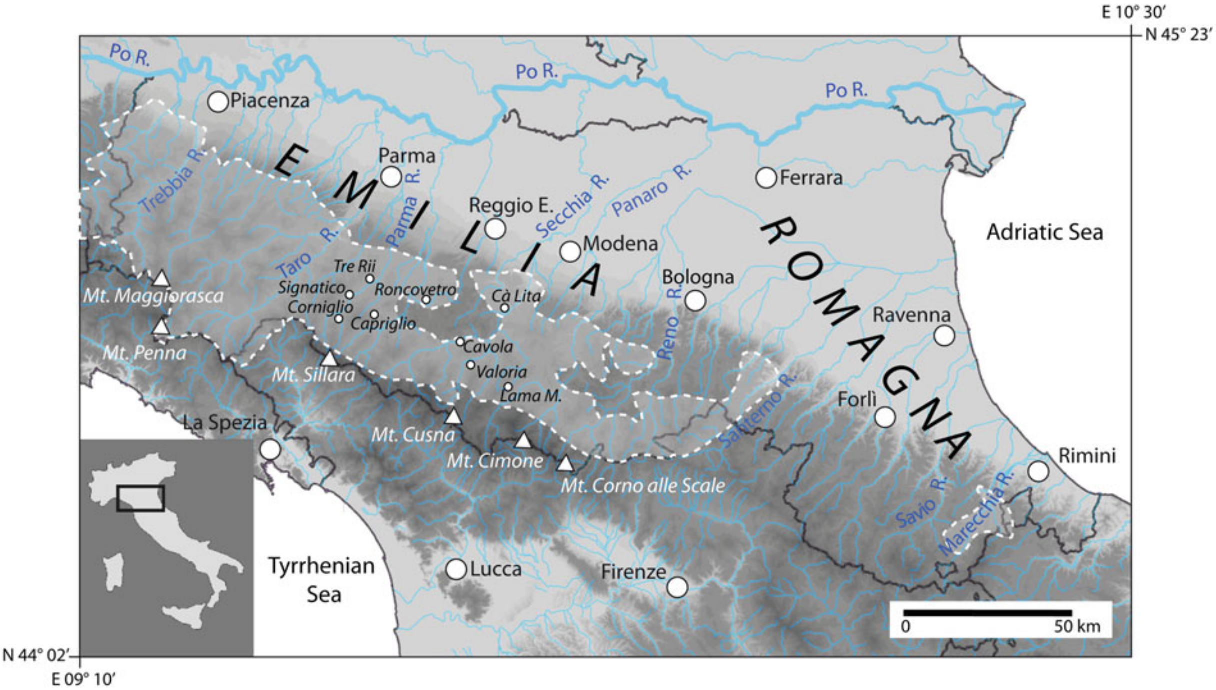

Fig. 18.1 Geographical and geological setting of the Emilia Apennines showing the landslides cited in the text (*italic black*). The *dashed line* outlines areas formed by clayey formations (usually named “Argille Scagliose” and “Helmintoid Flysch”, Late Cretaceous to Eocene in age) which are the most landslide-prone units in the Emilia Apennines

1945 m a.s.l.; Mt. Cimone, 2165 m; Mt. Cusna, 2121 m; Mt. Sillara, 1867 m; Mt. Penna, 1735 m; Mt. Maggiorasca, 1799 m). Main river valleys and, consequently, secondary mountain ridges have a NE–SW trend. Average elevation in secondary mountain ridges is between 1600 and 1000 m and elevation decreases toward the northeastern boundary of the mountain chain, which is marked by Quaternary alluvial fans.

Climate is generally “sub-continental” and locally “cool-temperate”, according to the Köppen classification system. Rainfall is very variable due to the fact that the watershed of the Northern Apennines tends to block moist air masses arriving from the Tyrrhenian Sea. Rainfall varies from approximately 1800 mm/year along the watershed to only 800 mm/year at the transition to the Po Plain. It is mostly concentrated in autumn and spring months, while during winter a significant snow cover is deposited in the most elevated sectors of the chain. Wind hits mostly from the west and south, activated by Atlantic depressions swapping across the upper Tyrrhenian Sea. During winter, northeastern currents of artic-continental provenience are quite common, determining prolonged cold conditions and significant snowfall even at very low elevations. Average annual temperature is between 4° and 12 °C, with summer temperatures around 20 °C or higher and winter temperatures around 5 °C and episodically as low as −20 °C.

18.3 Geological Setting

The Northern Apennines are constituted by allochthonous stratigraphic sequences superimposed during several tectonic phases in the Cenozoic (Bettelli and De Nardo 2001). Most of these rock units are made up of arenaceous and calcareous flysch and of chaotic mélanges (submarine olistostromes or tectonic mélanges). In both cases, rock masses have an abundant or prevailing clayey component. Their degree of tectonization is high, with pervading shear surfaces observable at any scale. These formations are usually parts of the Ligurian and Sub-ligurian Domains (Late Jurassic—Early Eocene in age) and were in the past also known as “Helmintoid Flysch” and “Argille Scagliose” (Auctt.) (Fig. 18.1). These formations can be classified as weak rock masses of significant structural and lithological complexity. Their poor mechanical resistance and the presence of groundwater makes these rock masses particularly prone to landslides. The lithological character of landslide bodies, generally made of thick clayey deposits with gravels and blocks, is due to the post-failure weathering of claystone, sandstone and limestone rock fragments. These deposits are in residual strength conditions and, as such, can be quite easily mobilized by slope movements.

18.4 Landforms Related to Large-Scale Landslides

Due to geological and paleo-climatic factors, the landscape in the Emilia Apennines is very diverse. At higher altitudes, slopes are steep and made of marly and arenaceous flysch formations. They are characterized by the presence of glacial landforms and deposits, which formed during the Late Pleistocene, and by gravitational debris covers deposited during the Holocene. At intermediate and lower altitudes, slopes are relatively gentle due to the presence of clayey flysch and mélanges. Locally, these slopes are characterized by the presence of plateaux made of sandstones and calcarenites that stand high above the surrounding gentle slopes made of clayey rocks. Late Pleistocene periglacial conditions have determined a landscape dominated by alluvial and gravitational features. Particularly widespread are landforms associated to complex large-scale earth slides—earth flows that have developed from the Last Glacial Maximum to date. The specificity of the "landslide landscape" of the Emilia Apennines has been acknowledged by the "*Geological Landscape Map of Emilia-Romagna*", published by the Geological Survey of Emilia-Romagna (Bertolini et al. 2009). It is highlighted that the official landslide inventory map of the Emilia Apennines includes over 70,000 landslides (Regione Emilia-Romagna 2013). The inventory map indicates that landslides cover up to 20% of mountain areas of the region and, in some municipalities, more than 50% of the territory. In many cases, this is due to the presence of several large-scale complex earth slides—earth flows, often adjacent to one another, forming a typical landslide-related landscape (Fig. 18.2). It is estimated that this type of phenomena makes up for approximately 90% of the recognized landslides and that at least 1300 of these landslides exceed one million cubic metres in volume and, often, sliding surfaces are located at depth of tens of metres (Bertolini and Pellegrini 2001).

Radiocarbon dating of organic matter (principally wood) trapped in some landslides and lacustrine deposits correlated to slope movements, indicates that while some phenomena

Fig. 18.2 The Cavola (*right*) and l'Oca (*left*) landslides forming a typical landslide-related landscape in the Emilia Apennines, with several adjacent large-scale landslides affecting most part of the slopes (Reggio Emilia Province, *photo* G. Bertolini, 2014). A detailed analysis of their internal stratigraphy reveals that the Cavola landslide body was built up from 4000 to 3000 years ago, showing a mean accumulation rate of 4.5 cm/year (Bertolini 2007). During the twentieth century, this landslide was partially reactivated four times

can be as old as 30,000 years BP, the majority of landslide deposits have been accumulated in the last 15,000 years and, prevalently, in specific periods of the Holocene during which climatic conditions worsened in terms of precipitation (Bertolini and Tellini 2001; Soldati et al. 2006; Bertolini 2007). As a consequence, it can be speculated that most of the large-scale landslides that mark the landscape of the region are of prehistoric age. Historic records and recent reports indicate quite clearly that the vast majority of reported landslide events can be referred to the partial or total reactivation of pre-existing landslides, while first-time failure landslides are quite rare. Upon reactivation, velocity of these landslides can vary from very slow (few cm/day) to moderate (m/day) according to the scale proposed by Cruden and Varnes (1996). In dormant conditions, these landslides can still undergo extremely slow movements (1–2 cm/year) (Bertolini and Pellegrini 2001).

The causal factors are primarily lithological, structural and hydrogeological, while topographic gradient and land use seem to have a more limited influence (most landslides develop at slope gradients ranging from 8 to 11°—which is the usual slope angle of clayey and flysch formations—and densely wooded areas, grassland or cultivated areas are affected by slope movements in approximately similar extent). More specifically, reactivation events are caused by hydro-mechanical processes at the slope scale, and involve groundwater recharge, progressive weathering of the affected fractured bedrock and loss of shear resistance in bedrock and landslide deposits (Ronchetti et al. 2010). The mechanisms associated with large-scale reactivation of these landslides include: (i) failure at the crown zone, (ii) undrained loading of pre-existing landslide deposits, (iii) downslope failure propagation of the entire landslide body (Bertolini and Pizziolo 2008).

In a landscape-oriented perspective, it is helpful to distinguish between landslides that have been apparently dormant for long periods of time and landslides that have been recently reactivated in paroxysmal events. In the first case, landslide-related landforms are still evident to skilled geologists and geographers, but they might be not so evident to unexperienced eyes. As an example, the catastrophic Lama Mocogno landslide of 1579, is now largely covered by vegetation and partially remodelled by anthropogenic activity, so that only an experienced eye can recognize and interpret convex morphology of the source area and lobate landforms of the main landslide body (Fig. 18.3). The same applies, for example, to the Tre Rii landslide (Fig. 18.4).

On the other hand, in case of recently reactivated landslides, landforms associated with slope movements can be rejuvenated by significant retrogression, enlargement and

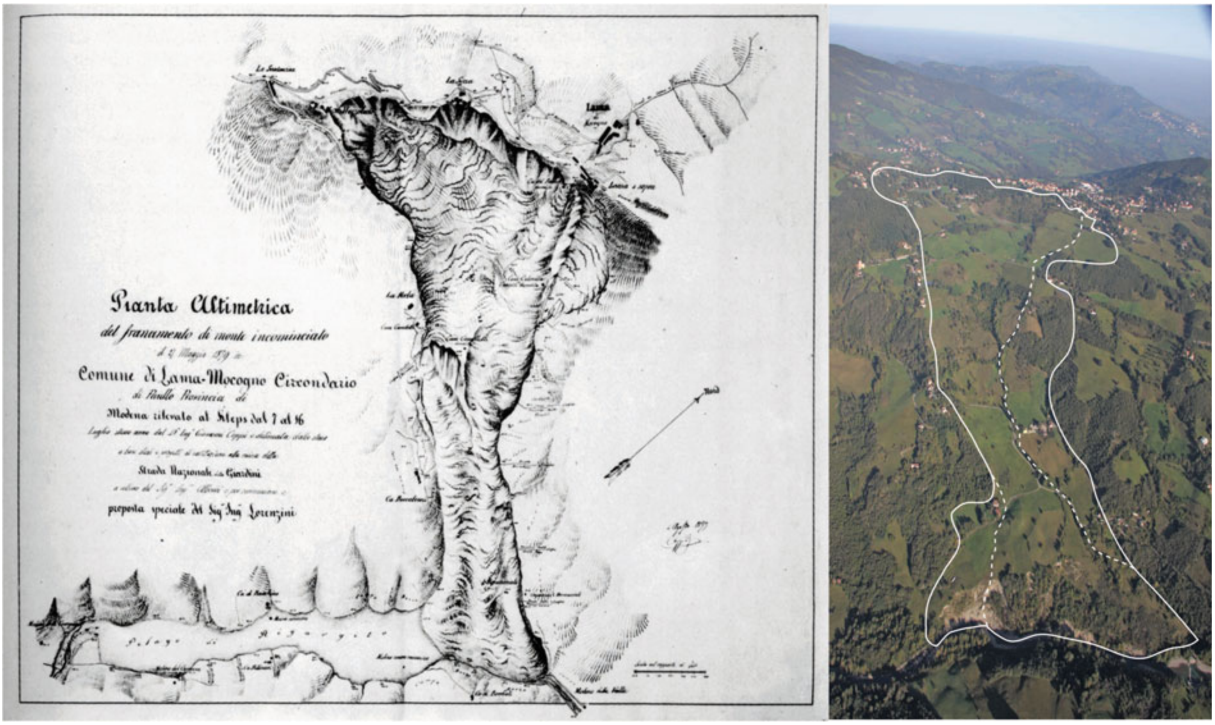

Fig. 18.3 The Lama Mocogno landslide (Modena Province, *photo* G. Bertolini, 2014): present state compared with the map of the 1579 reactivation. Map produced by G. Coppi in the nineteenth century

Fig. 18.4 The Tre Rii landslide (Parma Province, *photo* G. Bertolini, 2014) has been dormant for a long period of time and the large fan-shaped landslide body was built up by pre-historic and historic reactivation events (8665 to 8610 and 1300 to 1520 years BP, Tellini and Chelli 2003)

forward advancement of the landslide. In such cases, the landslide area outstands impressively from the surrounding landscape, making it evident even to the eye of non-specialists. Examples of this kind are the Corniglio landslide, reactivated in 1994 and 1999 (Larini et al. 2001) (Fig. 18.5); the Valoria landslide, reactivated in 2001, 2005 and 2009 (Fig. 18.6); the Roncovetro landslide, reactivated between 1994 and 1999 and ever since active (Fig. 18.7); the Ca' Lita landslide, reactivated in 2002 and 2004 (Fig. 18.8); the Signatico landslide, reactivated in 1977 and frequently partially active (Fig. 18.9) and, finally, the Capriglio landslide, reactivated in 2013 (Fig. 18.10). These prominent examples of recently reactivated landslides show features that might be considered as typical of an "early" or—better—"rejuvenation" stage of development in the multi-millennial gravitational evolution of the slopes which are affected. In some cases, continuous or recurrent activity is probably co-determined by the inflow of highly mineralized groundwater mixed with methane uprising along regional fault lines along which the landslides are located (e.g. Roncovetro landslide in Bertolini 2010 and Ca' Lita landslide in Cervi et al. 2012).

18.5 Hazard and Risk Issues

Dealing with the risk associated with large-scale landslides such as these described above is not an easy task. In prevention, hazard assessment and mapping, one has to address the problem of estimating return periods of reactivation events of individual landslides. In some cases, the return period of reactivation can be roughly assessed on the basis of available historical archives (Regione Emilia-Romagna 2014). Such archives contain reports about hundreds of known reactivation events which occurred in the last centuries. Many of the older records refer to events that damaged villages which were built, since the ninth century, on top of landslide deposits. The awareness of recurrent slope stability problems, with return periods in the range of centuries or decades, has led decision makers to officially declare tens of villages to be transferred or to be consolidated. Nonetheless, an objective difficulty in estimating return periods remains for the majority of landslides, for which no historical record is available. Therefore, land-use regulations are based on inventory maps, distinguishing active and dormant landslides, rather than on hazard maps,

Fig. 18.5 The Corniglio landslide (Parma Province, *photo* G. Bertolini, 2001) was fully reactivated in the 1994–1996 period, after being historically active in 1740 and 1902 as well as in the sixth, seventh and sixteenth centuries (Tellini and Chelli 2003). The complete reactivation of 1996 was initiated by retrogression of the main scarp and landslide toe advance for about 50 m as a bulk, almost damming the Parma River (Larini et al. 2001)

Fig. 18.6 The Valoria landslide reactivated in 2001, 2005 and 2009 (Modena Province, *photo* A. Corsini, 2009). Before reactivation in 2001, the slope was fully covered by a dense woodland (Ronchetti et al. 2007). During the 2001 reactivation, as well as in 2005 and 2009, clayey material flowed at velocities up to 10 m/hour. The total displacement in each single event was in some sectors even higher than 100 m (Daenhe and Corsini 2013)

Fig. 18.7 The permanently active Roncovetro landslide (Reggio Emilia Province, *photo* G. Bertolini, 2012). The activity of the landslide is probably determined by the inflow of highly mineralized groundwater mixed with methane, coming from the subsurface (Bertolini 2010)

Fig. 18.8 The Ca' Lita landslide, reactivated in 2002 and 2004 (Reggio Emilia Province, *photo* G. Bertolini, 2012). During the 2004 event the landslide toe advanced for more than 400 m, filling a previously existing gully (Borgatti et al. 2006; Corsini et al. 2009). The activity of this landslide is probably co-determined by the inflow of highly mineralized groundwater mixed with methane uprising along a regional fault line (Cervi et al. 2012)

indicating intensity and return period of expected phenomena. This makes cost-benefit analysis impossible in land-use planning and, consequently, land-use regulations do not generally prohibit new settlements on dormant landslides. Moving on to the forecast phase, it should be acknowledged that cumulated rainfall thresholds are presently used for general wide-area warning purposes in the Emilia Apennines (Berti et al. 2012). However, it is impossible to know specifically which landslide, among thousands in the Emilia Apennines, is actually going to resume activity for a rainfall event above warning threshold. This makes site-specific response actions impossible. Ideally, since reactivation of a landslide proceeds initially at a rather slow rate, site-specific continuous monitoring systems can be effectively used, in association with evacuation plans, in order to reduce risk to people. In practice, early warning systems can be used only in a limited number of cases which generally are restricted to landslides that have recently resumed activity in paroxysmal phases. Extending this approach to thousands of landslides of the Emilia Apennine is utopia. Finally, in the response phase, structural and deep drainage works aimed at slope consolidation are possible and, actually, have often been among the preferred risk mitigation measures. However, they are extremely costly and technically complex, due to the huge dimensions of landslides, significant thickness of landslide bodies, hydro-mechanical complexity of processes and deposits (Borgatti et al. 2008). Moreover, they require a proper maintenance programme, an effort that is not generally properly financed.

Fig. 18.9 The Signatico landslide, reactivated in 1977 (Parma Province, *photo* G. Bertolini, 2014). There were several previous reactivation events: ninth century, 1710, nineteenth century and 1906, causing formation of a dammed lake (Tellini and Chelli 2003)

Fig. 18.10 The Capriglio landslide reactivated in 2013 (Parma Province, *photo* G. Bertolini, 2013). Reactivation caused retrogression of the scarp by about 300 m and advancement of the toe for about 1 km, which filled an existing river gully

18.6 Conclusions

Arcuate scarps, that are hundreds of metres long and accumulation areas that are tens of hectares wide, are the fingerprints of millennial activity and morphological evolution of large-scale landslides in the Emilia Apennines. Since historic times, especially from the ninth–eleventh century AD, several villages in the Emilia Apennines have been built on top of landslide deposits, mostly because they constitute flatter zones with a soft clayey substratum that makes cultivation and settlement easier than in the surrounding steep and rocky stable slopes. Evidently, at the time of village establishment, these ancient landslides must have been dormant for periods of time long enough for locals to loose memory of previous catastrophic reactivation events. This recurrent loss of memory about disastrous landslides has actually continued until the beginning of the twentieth century, when the first structured reports of historical landslides were compiled, consisting mostly of events occurred in post-medieval times during the so called Little Ice Age (Almagià 1907). Nowadays, the historical archive of landslide events (Regione Emilia-Romagna 2014) contains many hundreds of known reactivation events which occurred in the last centuries.

As some of these landslides will inevitably reactivate in the future, as they did in the past centuries, scientists and decision makers are faced with the difficult task to find a way to cope with their recurrent activity in terms of prevention, forecast and response policies. This might involve improvement of land-use planning by including hazard maps that account for the relative probability of reactivation of these phenomena, implementation of monitoring that would help to assess both triggering conditions and precursory movements more precisely and, possibly, development of forecasting event scenarios and improvement of evacuation and risk management plans. It might also involve application of new approaches for evaluating or re-evaluating potential benefits of structural mitigation works and allocation of resources for their maintenance as well as for the maintenance of a more widespread monitoring network. Finally, it might also require a more incisive action for effective relocation of some villages and roads that, after all, might be the most cost-effective measure to undertake. Significant steps have been made along these lines of actions in the last decades but other crucial ones are still to be made. Certainly enough, these landslides will persist in the landscape of the Emilia Apennine for some millennia ahead and, for the time being, we should be aware of this type of potentially destructive processes. Actually, considering the large size and high thickness of some landslides deposits, it is quite evident that in some periods in the past these landslides must have been even much more active than in the last decades. Therefore it can be concluded that landslides are hazardous, but they are also part of the natural system and it is up to mankind to find ways to adapt rather than grumble about the occurrence of landslides. In the meantime, we might also be allowed to be intellectually fascinated by their features that witness the impressive magnitude of gravitational slope processes that, from the Late Pleistocene until today, have profoundly shaped the landscape of this geologically complex mountain area.

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Mud Volcanoes in the Emilia-Romagna Apennines: Small Landforms of Outstanding Scenic and Scientific Value

19

Doriano Castaldini and Paola Coratza

Abstract

Mud volcanoes are emissions of cold mud due to the ascent to the surface of salty and muddy waters mixed with gaseous (methane) and, in minor part, fluid hydrocarbons (petroleum veils) along faults and fractures. In the Emilia-Romagna Apennines (Northern Italy) mud volcanoes are closely linked to the active tectonic compression associated with a thrust of regional importance. They are mostly cone shaped and show variable geometry and size, ranging from one to few metres, and are located in 19 sites in the northwestern part of the Apennines. The mud volcanoes of the region have been known since a long time and have always aroused great interest due to their outstanding scenic value. In the past, the mud volcano emissions have been used in many ways: the mud was applied for cosmetic use and the natural oil was much appreciated for its balsamic and purgative properties. In the last decades, the mud volcanoes have represented relevant tourist attractiveness.

Keywords

Mud volcanoes • Geotourism • Emilia-Romagna Apennines

19.1 Introduction

Mud volcanoes are usually cone-shaped landforms constructed by the extrusion of mud, rock fragments, fluids (such as saline water and fluid hydrocarbons) and gases. The normal activity of mud volcanoes consists of gradual and progressive outflows of semi-liquid material. Explosive and paroxysmal activities are responsible for ejecting mud and decimetric to metric clasts.

The occurrence of mud volcanoes is controlled by several factors, such as tectonic activity, sedimentary loading due to rapid sedimentation, the existence of thick, fine-grained plastic sediments and continuous hydrocarbon accumulation (cf. Dimitrov 2002). Mud volcanoes have variable geometry and size, from one to two metres to several hundred metres in height. These features, expression of a remarkable natural process initiated deep in the sedimentary succession, are distributed worldwide, both inland and offshore. They can be found in a wide variety of tectonic settings, including passive continental margins, continental interiors, as well as transform and convergent plate boundaries. Anyhow they typically predominate at converging plate boundaries and are disseminated all along the Alpine-Himalayan, Pacific and Caribbean mobile belts.

The principal gas emitted by mud volcano eruptions is thermogenic methane, generated within the sediments at depths often greater than 10 km. It is commonly accepted that overpressure generated by methane-rich fluids is one of the main driving mechanisms triggering mud volcanism (Dimitrov 2002). Despite their name, morphology and the resemblance in the activity are the only characteristics of mud volcanoes that link them with magmatic volcanism. They generally exhibit a typical cone form, although of smaller dimension than the magmatic relatives, but other forms, such as sharp cones, flat and plateau cones, dome shapes, calderas, can be distinguished. Mud volcanoes appear to be generally characterised by a gentle activity, but they may occasionally experience impressive explosive

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eruptions, with violent ejection of mud and rock blocks often accompanied by flames produced by self-ignition of the methane contained in the mud.

Mud volcanoes show a high scenic value and are well known from many areas of the world such as Azerbaijan, Mexico, Venezuela, Colombia and Ecuador. In Europe they can be found in Italy, Albania and Romania. They are quite common in Italy, with the most spectacular ones located in Emilia-Romagna and in Sicily. Italian mud volcanoes are generally characterised by relatively small apparatuses, and occur along the external compressive margin of the Apennine chain (Martinelli and Judd 2004). They are clustered in three main geographical groups: northern Apennines (Pede-Apennines margin of Emilia-Romagna), central Apennines (eastern Marche and Abruzzo) and Sicily. Moreover, there are also few mud volcanoes offshore in the central sector of the Adriatic Sea (Fig. 19.1).

The mud volcanoes of Italy have been known for a long time and have always aroused great interest. They were first described by Pliny the Elder, at around 50 AD, in his monumental “Naturalis Historia”. Others in the following centuries described the mud volcanoes with fantastic attributes of impressiveness and spectacularity (e.g. the naturalists Spallanzani, at the end of the eighteenth century, and the Abbot Stoppani at the end of nineteenth century).

19.2 Mud Volcanoes in the Emilia-Romagna Apennines

Mud volcanoes of relatively small size (≤ 500 m^2), but of high scientific interest and scenic value, punctuate the northwestern sector of the Pede-Apennine front of Emilia-Romagna, between Parma and Bologna, representing almost 30% of all those present on the Italian territory (Figs. 19.1 and 19.2). They are genetically linked to the ascent of salty and muddy waters mixed with gaseous (methane) to the surface and, in minor part, with circulation of fluid hydrocarbons (petroleum veils) along tectonic discontinuities produced by the overthrusting of the Apennine chain front. Their local name “Salse“ results from the high “salt” content of the muddy waters whose origin is related to the presence of the sea that occupied the present Po Plain till about one million years ago and that deposited clays which nowadays outcrop in the hilly sector of the Apennines.

The shape of the mud ejection apparatuses depends on the density of the muddy mixture: if it is dense, cones (single, double or multiple) of height ranging from a few decimetres to some metres may develop; if the muddy mixture is liquid, ground level-pool mud volcanoes (diameters ranging from a few decimetres to some metres) are formed. The cones have the classic shape of a volcano, occupy roughly circular areas, and stand up above the general ground level. They intermittently emit gas bubbles and muddy water from a crater; these vary from a few centimetres to almost a metre in diameter (Fig. 19.3).

Mud volcanoes show a rather discontinuous activity; sometimes old apparatuses become dormant or even extinct whereas new vents can appear in other spots. Therefore, the morphology of mud volcano areas is constantly evolving with the formation of new craters whilst others cease their activity.

The clayey materials ejected from the craters cover the surrounding ground with mudflows; owing to their fluidity, mud flows can cover distances of up to 100 m from the vent. In the hot season, the shrinking of mud deposits creates typical polygonal mud cracks (Fig. 19.4).

From a geological point of view the Emilia-Romagna Apennines are a fold-and-thrust belt, characterised by complex structures and geodynamic evolution. The northern Apennines originated from the consumption of the Liguria-Piedmont oceanic basin, located in the western Tethys, and the consequent collision between the Adria plate and the European plate, which started in the Upper Cretaceous (Bosellini 2017).

The mud volcanoes occur above the hanging wall of the active Pede-Apennine thrust, and thus have their origin in the deformation associated with this regional structure (Manga and Bonini 2012). In this sector of the Apennines, the following main structural and stratigraphic units crop out (Fig. 19.2): (i) Ligurian Units made up of deep-sea sediments, including Jurassic Ophiolites, followed by thick sequences of Cretaceous to Eocene calcareous or terrigeneous turbidites; (ii) mainly terrigenous Epiligurian Succession of Middle Eocene to late Messinian, uncorformably resting on the previously deformed Ligurian Units; (iii) prevalently marly-clayey Late Miocene–Pleistocene marine rocks.

The morphology of this sector of the Apennines is strongly influenced by this sequence of lithotypes. In the surroundings of mud volcanoes, clayey terrains largely outcrop which are characterised by typical and locally spectacular “calanchi” landforms (badlands). They are typically shaped in clayey soils due to concentrated gully erosion. The landscape is also characterised by several landslides of different types, from shallow movements to large-scale displacements.

19.3 The Landscape of Mud Volcanoes in the Emilia Pede-Apennines

The mud volcanoes of the Pede-Apennine front of the Emilia-Romagna Region are mainly located in the Emilia sector (the northwestern one) and are associated with a SSW-dipping thrust.

Fig. 19.1 The geographical distribution of mud volcanoes inland (*red dots*) and offshore (*yellow dots*) in Italy (*data source* Martinelli and Judd 2004). The box refers to the mud volcanoes in Emilia-Romagna Apennines (see Fig. 19.2)

Here below only the mud volcano areas with scenic value (and easily accessible) are described (Fig. 19.2).

19.3.1 Mud Volcanoes of the Parma Apennines

The mud volcanoes of the Parma Apennines are located in three sites in which the formations of the Epiligurian Succession outcrop. In detail, in the hills of Parma Apennines the mud volcanoes of Rivalta, Torre and S. Polo d'Enza (n. 1, 2, 3 in Fig. 19.2) can be found. All these sites are modest in size and have no volcanoes with height of over 50 cm. Noteworthy are the first two mud volcano fields which occur in elliptical depressions (approximately coincident with the axis of an WNW–ESE trending anticline) interpreted as mud calderas (Bonini 2012). The Rivalta field is hosted in a sub-tabular mud-filled depression at an altitude between 320 and 325 m a.s.l.; active vents occur as small cones and bubbling pools in the depression central sector (Fig. 19.3a). The Torre field depression exhibits comparatively steeper scarps that connect to a gentler zone likely to represent the residual caldera floor. Fluid venting, consisting of bubbling mud pots, occurs in two zones corresponding to the apical part of small creeks entering the amphitheatre at about 330 m a.s.l.

In Rivalta and Torre sites, agricultural activity interferes with muddy emissions, with varying effects in space and time; in fact owing to their high fluidity, the ejected mud flows tend to create small swamps, which can disappear as a result of agricultural activity.

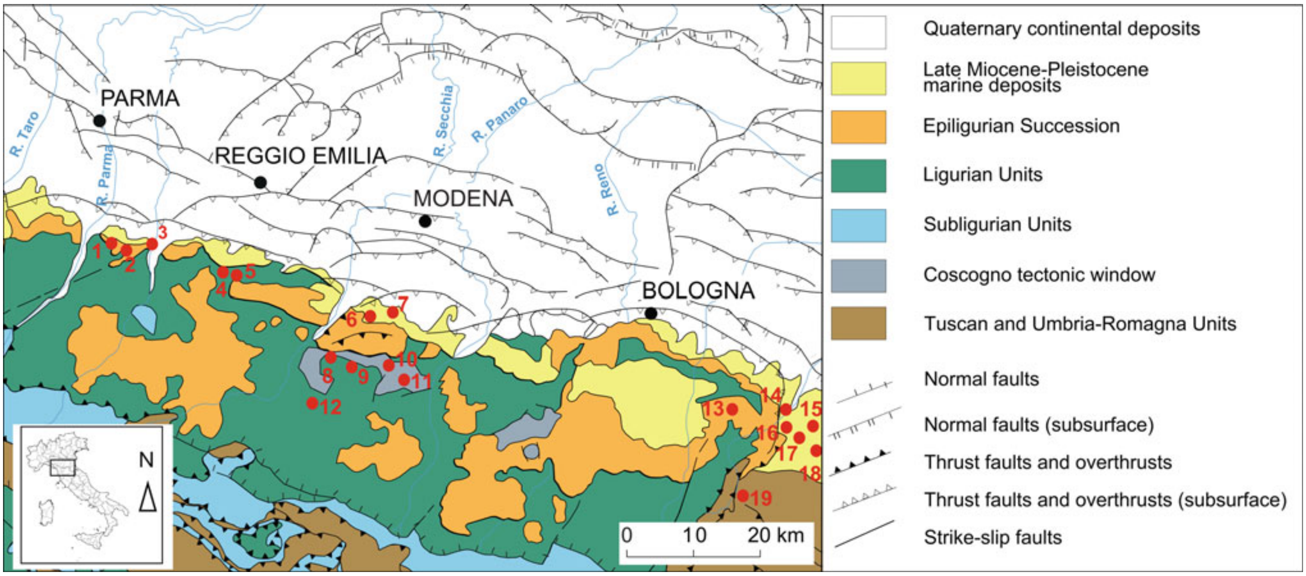

Fig. 19.2 Geological sketch map of the Emilia Apennines (modified after Remitti et al. 2012). Areas of mud volcanism (*red dots*): *1* Rivalta; *2* Torre; *3* San Polo d'Enza; *4* Casola-Querciola; *5* Regnano; *6* Montegibbio; *7* Nirano; *8* Montebaranzone; *9* Centora; *10* Madonna di Puianello; *11* Ospitaletto; *12* Canalina; *13* Sassuno; *14* San Martino in Pedriolo; *15* Bergullo; *16* Sallustra Valley; *17* Pedriaga; *18* Casalfiumanese; *19* Cà Rubano

19.3.2 Mud Volcanoes of the Reggio Emilia Apennines

The mud volcanoes of the Reggio Emilia Apennines are located in the Ligurian Units outcropping in the Viano district close to Regnano and Casola-Querciola hamlets (n. 4 and 5 in Fig. 19.2). The Regnano mud volcano is the second mud volcano field in size, surpassed in all Emilia-Romagna Apennines only by that of Nirano (Modena Apennines); it consists of mud breccias and mud flows spreading over an area of about 1 ha. The Regnano mud volcano field is found at an altitude between 420 and 430 m a.s.l., on the top of a slope which faces eastward. The apparatuses are aligned along normal faults which allow surface leakage of fluid derived from sources located at a depth between 3 and 6 km. The fault system associated with the Regnano mud volcanoes drains a Miocene reservoir which supplies formation water and thermogenic methane (Capozzi and Picotti 2002). The activity sometimes is quite remarkable and occurs in several vents. So much that the main mud ejection mouths assume a cone trunk shape and the relative mud flows remain as higher ground than the surrounding terrain (Figs. 19.3b and 19.4). The Casola-Querciola mud volcanoes are located in an almost flat zone (at about 440 m a.s.l.), a few kilometres far to northwest of Regnano and they are mainly level-pool mud volcanoes. A new mud ejection point, which was formed in July 2014, affects a secondary road causing problems to the local traffic. For both Regnano and Casola-Querciola areas, educational footpaths with panels were built in July 2015.

19.3.3 Mud Volcanoes of the Modena Apennines

In the Modena Apennines, mud volcanism occurs in a wide area (diameter of about 20 km) in which formations belonging to Ligurian Units, Epiligurian Succession and Late Miocene–Pleistocene marine deposits outcrop. In detail, mud volcanoes are found in six areas: Montegibbio, Nirano, Montebaranzone, Centora, Madonna di Puianello, Ospitaletto and Canalina (n. 6 to 12 in Fig. 19.2).

The Montegibbio mud volcano field, in the Sassuolo district (n. 6 in Fig. 19.2), is currently represented by few small pools of salty waters, with limited gas bubbling, rather than true mud volcanoes; such pools occur within a moderately elongated depression at an altitude of about 230 m a.s.l. Historical records report an extremely intense activity, characterised by emissions accompanied by explosions and by a large cone approximately 10 m tall, described by several authors. Even the eruption of 91 BC mentioned by Pliny is believed to have caused extensive damage to historical Roman settlements. Extensive clay deposits widespread downstream the Montegibbio mud volcanoes are evidence of this eruptive event. The decreased activity could be partly explained by the exploitation of subsurface fluids for supplying the adjacent Salvarola spa (Bonini 2009). The mud volcano that caused the large 1835 eruption (described in detail and mapped by nineteenth century authors) is now extinct and looks like a small hill which has its top at 281 m a.s.l. The 1835 eruption was accompanied by a seismic tremor that was perceived by the population up to several

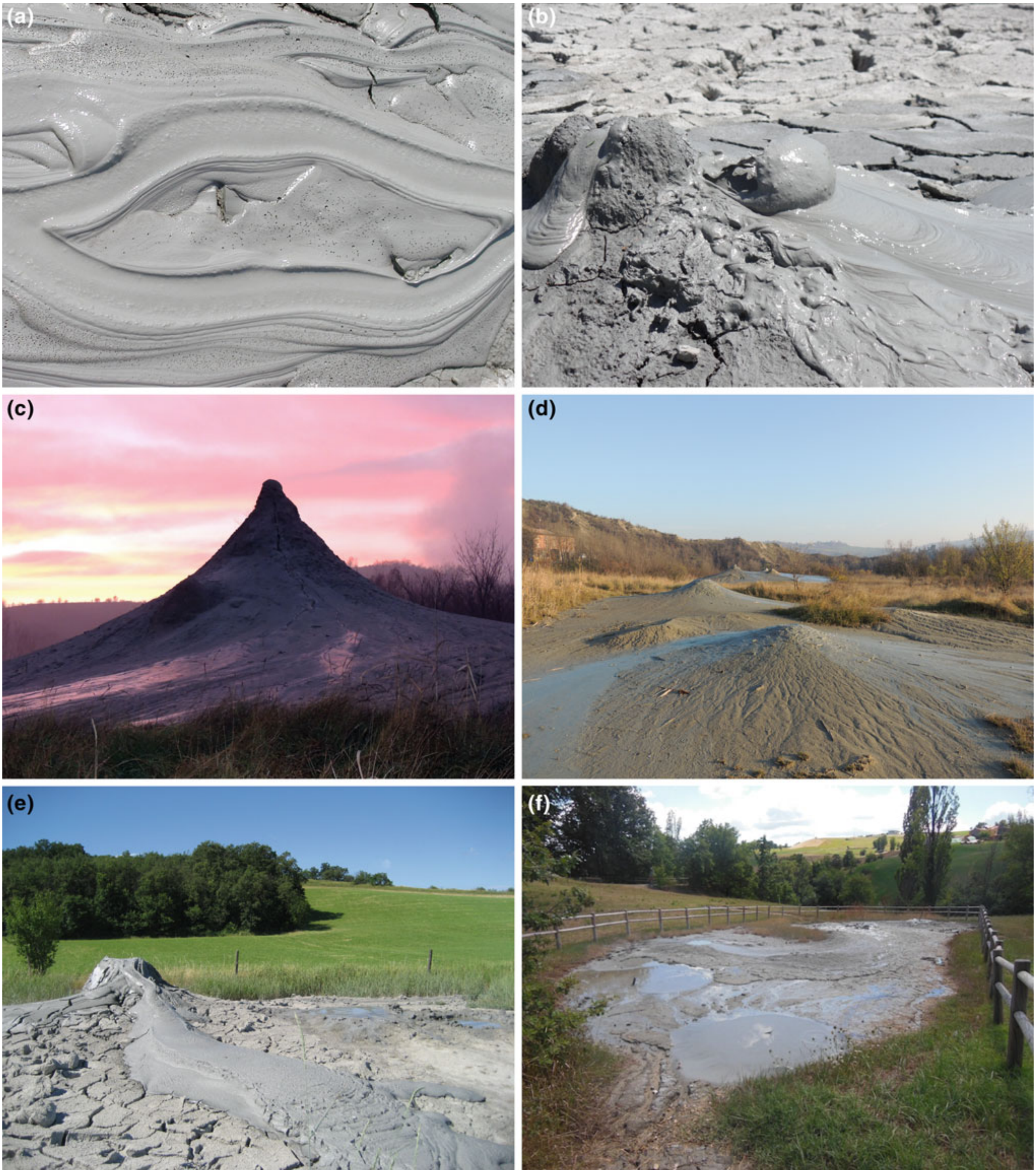

Fig. 19.3 Mud volcanoes in the Emilia Pede-Apennines: **a** close-up of ducted high-velocity flow at Torre mud volcanoes (Parma Apennines) (*photo* J. Valdati); **b** close-up of the main mud ejection mouth of the Regnano mud volcanism area (Reggio Emilia Apennines) (*photo* N. Borghi); **c** cone of the Nirano Natural Reserve mud volcanoes field at sunset (Modena Apennines) (*photo* L. Callegari); **d** panoramic view over some of the mud cones of Nirano Natural Reserve (Modena Apennines) (*photo* L. Callegari); **e** cone and mudflow in the Madonna di Puianello area (Modena Apennines) (*photo* C. Rebecchi); **f** level-pool mud volcanoes of Ospitaletto (Modena Apennines) (*photo* D. Castaldini)

Fig. 19.4 Main mud ejection mouths of the Regnano mud volcanism area in the Reggio Emilia Apennines (*photo* D. Castaldini)

kilometres away; the volume of mud emitted was estimated at 500,000 m^3, whereas the spout of ejection reached a height of 40 m and the eruptive deposit was distributed over an area of 30,000 m^2.

Particularly noteworthy is the Nirano mud volcano field (n. 7 in Fig. 19.2), located in the Fiorano Modenese district, which, with a surface area of approximately 75,000 m^2, is one of the best developed and largest mud volcano field of the entire Italian territory and among the largest in Europe; it is thus protected as natural reserve (Salse di Nirano) since 1982. The Nirano mud volcanoes are found at the bottom of an elliptical depression (Fig. 19.5), interpreted as a collapse-like structure (caldera) that may have developed in response to the emptying of a shallow mud chamber triggered by several ejections and evacuation of fluid sediments (Castaldini et al. 2005); the bottom of the depression is at *ca.* 200 m and the rim at 250 m a.s.l. The Nirano field is characterised by the presence of two main systems of faults/fractures, SW–NE and NW–SE oriented, respectively. They are highlighted by the arrangements of mud volcanoes, which show clear alignments, and by the elongated shape of the caldera (Castaldini et al. 2005; Bonini 2008).

There are several individual or multiple cones within the field of the mud volcanoes of Nirano (Fig. 19.3c, d), but it is not possible to provide the exact number of mud-ejecting points, because the morphology of this area is constantly evolving. In fact, they have a rather discontinuous activity; apparatuses become dormant or even extinct whereas new vents can appear in other spots. Nowadays, mud emission occurs clustered into five main venting areas constituted by cones as well as level-pool mud volcanoes. A mud chamber was identified at a depth of 25 m; this mud chamber could represent the last phase of mud accumulation before the final emission, not excluding the existence of deeper larger reservoirs (Accaino et al. 2007).

Other geomorphological features in the Natural Reserve of Salse di Nirano are badlands which are quite evident on many slopes (Fig. 19.5). The numerous facilities, excursion and educational footpaths with panels, equipped trails (one for people with disabilities), the Cà Tassi visitor centre and the Cà Rossa eco-museum, make the area accessible to all, supporting environmental education initiatives.

The Madonna di Puianello vents (n. 10 in Fig. 19.2) occur in two areas located in the Maranello district. The most important mud volcanism site is found near Casa Possessione, in a flat depression at the altitude of 440 m a.s.l. that probably represents a caldera-like feature (Bonini 2012). Actually, it is characterised by three main cones aligned in a WNW–ESE direction and three main bubbling mud level-pools. The mud ejection apparatuses (Fig. 19.3e) are located in a private property affected by agricultural activity from which are protected by wire mesh.

The Ospitaletto mud volcanism area (n. 11 in Fig. 19.2) is located in the Marano sul Panaro district at the bottom of a south-facing gentle concave depression at an altitude of about 525 m a.s.l. It is currently constituted by about a dozen of eruptive apparatuses with moderate activity: most of them are bubbling mud level-pools with diameter ranging

Fig. 19.5 Aerial view of the mud volcanoes of the Nirano Natural Reserve (Modena Apennines). The mud volcanoes (*grey spots*) are located at the *bottom* of an elliptical depression surrounded by badlands (*photo* G. Bertolini)

from about 0.1 to 1 m (Fig. 19.3f). The area is easy to reach by road and is outlined by educational panels.

The Centora, Montebaranzone and Canalina mud volcanoes (n. 8, 9 and 12, respectively, in Fig. 19.2) are nice examples of mud volcanism. Anyhow, they are difficult to be reached, and therefore less known and visited than the others sites.

19.3.4 Mud Volcanoes of the Bologna Apennines

In the Bologna Apennine front, seven mud volcano sites are located in the Umbria-Romagna Units, in the Epiligurian Succession and in the Late Miocene–Pleistocene marine deposits (n. 13 to 19 in Fig. 19.2) at altitudes ranging from *ca.* 50–500 m a.s.l. The most part of them have surface area <5 m^2 and are scarcely known. They are level-pool mud volcanoes with rather discontinuous activity. The only two Bologna Apennines mud volcanism areas described by previous authors are currently inaccessible as located in areas affected by landslides and badlands (mud volcanoes of Sassuno, n. 13 in Fig. 19.2) or hidden by the dense vegetation which covers the site where they are located (mud volcanoes of Bergullo, n. 15 in Fig. 19.2). One of the Bergullo vents is a 3 m diameter bubbling mud level-pools from which fluid is periodically exploited for supplying the near Riolo Terme spa.

19.4 Mud Volcano Eruptions and Earthquakes

From a general point of view, earthquakes have been considered to be a potentially important trigger for mud volcano eruptions (e.g. Martinelli and Panahi 2005; Bonini 2012), but mud volcanoes also erupt independently of seismicity.

Noteworthy is the occurrence of the above-mentioned giant mud volcano eruption, associated with the contemporaneous destructive earthquake of 91 BC that struck the Modena Pede-Apennine margin.

The relationships between seismicity and mud volcano activity have been testified by the strong seismic events that occurred in 2012 in northern Italy. In detail, in May 2012 a seismic sequence struck the lower central part of the Po Plain, located about 50 km NE of the Modena and Reggio Emilia Pede-Apennine front. The main shocks occurred on 20 and 29 May, with local magnitude 5.9 and 5.8, respectively. The seismic sequence, due to buried Apennine faulted folds, caused a number of fatalities and significant damage as well as many ground effects such as cracks, liquefaction-type phenomena and hydrological anomalies (Emergeo Working Group 2013). A few days before the onset of the seismic sequence, an anomalous activity was observed in some mud volcanism areas. In particular in Nirano, Ospitaletto, Puianello, Regnano and Casola-Querciola areas (Modena and Reggio Emilia Apennines), normally inactive or poorly active mud volcanoes became active or showed increased activity and new small vents formed (Manga and Bonini 2012).

19.5 Cultural Value and Tourism Attractiveness

The peculiar geological phenomenon of mud volcanoes makes this sector of the Emilia-Romagna Apennines a site of worship and interest since the Roman period. In particular the field of Nirano has been known since ancient times and has been studied by historians, scientists and travellers. The area where the Nirano mud volcanoes are located was called "the beautiful place", due to the high aesthetic value of hilly landscapes forming the foothills of the Apennines. Since the Roman period, the Nirano area was a dwelling place of organised groups that worked with ceramics and bricks, as testified by many historical sources and proved by the discovery of an ancient crockery furnace. Probably, as in other cults and places, the area of the Nirano mud volcanoes had represented in the past an ideal place where the phenomenon of leakage of water and mud was interpreted as a prodigy. In his "Naturalis Historia", Pliny the Elder, as other scientists later from the seventeenth century, described the *salse* with apocalyptic and spectacular attributes. In particular, he described the eruption of a mud volcano in the Modena district, with skyscraping flames and smoke, seen from a distance of about 10 km, during which the violent ejection of overpressured mud was accompanied by methane combustion. At the end of the nineteenth century, the abbot Stoppani compared the *salse*'s phenomenon to molehills out of which noises similar to "retching" came out, giving them the epithet of "cesspool volcanoes" (Stoppani 1876) (Fig. 19.6).

Mud volcanoes are interesting owing also to the ecological changes induced by the widespread deposition of sodium chlorine. Indeed, the herbaceous plants which colonise the soil around mud volcanoes make up the most complete example of halophilous vegetation.

In addition to arouse interest and curiosity, the mud volcanoes between Nirano and Sassuolo (Modena Apennines), were used in many ways in the past. The mud from the *salse* was applied for cosmetic use as mud masks and for mud baths at the ancient Salvarola Spa, near Sassuolo. Also, natural oil of the *salse* was much appreciated for its balsamic and purgative properties and sold by monks of San Pietro in Modena. Nowadays, the mud is used only in veterinary science to blaze up articulations of horses.

Besides their cultural value, the Emilia-Romagna mud volcanoes represent a tourist attraction as testified by an increasing number of visitors (about 70,000 visitors in 2015

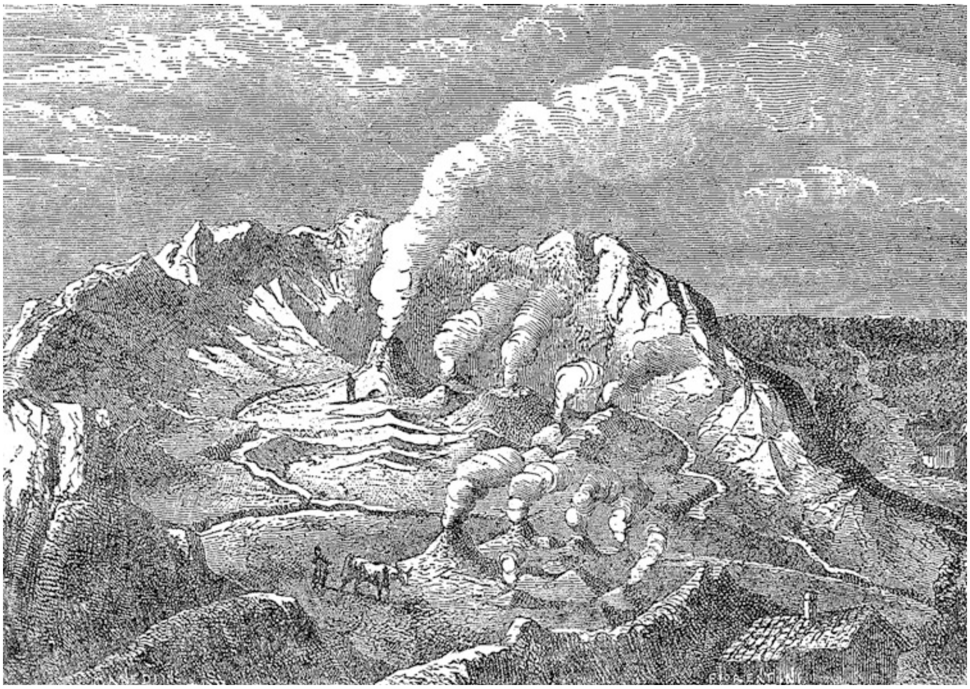

Fig. 19.6 The Salse di Nirano as illustrated in famous book "Il Bel Paese" by Abbot Antonio Stoppani (1876)

in the Salse di Nirano Natural Reserve). Numerous initiatives to improve access and enhance understanding have been developed in the last decades. In particular, tourist environmental maps, geotourism maps, books in hard copy and digital format, videos, virtual flights, multimedia and audio CDs have been implemented (e.g. Castaldini et al. 2011). These activities are targeted at various potential users, tourists, local residents, young people, schools, etc., and are aimed at the enhancement of geological and geomorphological aspects of the natural heritage making it available to the public.

Worthy of note is the 2015 initiative called the "Mud Volcanoes Route" for the promotion of the environment, art, wellness, tastes, technology and talent of the territory of districts of Viano (Reggio Emilia Apennines), Sassuolo, Fiorano Modenese and Maranello (Modena Apennines), in which part of the Emilia-Romagna mud volcano fields are located. The Mud Volcanoes Route is an emotional journey that connects places and excellences through the geological phenomenon of mud volcanoes.

19.6 Conclusions

Mud volcanoes are landforms of outstanding scenic value that are expression of a remarkable natural process initiated deep in the sedimentary succession. Although these features have a long history of investigation, in recent years interest in mud volcanism has increased for several reasons. A considerable impulse to investigations on this topic has been recorded in part because of petroleum exploration but also due to the role that mud volcanoes play in the global methane budget, a potent greenhouse gas.

Moreover, thanks to their scenic value, mud volcanoes generate tourist attraction; for example, the natural reserves of Northern Apennines of Nirano or the "vulcanii noroiosi" of Buzau (Eastern Carpathian foredeep, Romania) are relevant examples in Europe. Recently a growing interest in the heritage value of mud volcanoes has been observed in Emilia-Romagna, in relation to geoconservation and geotourism issues. In this context, in 2015 the above-mentioned Mud Volcanoes Route has been developed. The itinerary is outlined in a leaflet containing short explanation, photos and a map in which are located areas with mud volcanoes, castles, archaeological sites, historic and holy buildings and represents an initiative for the promotion of environment, art, wellness, tastes, technology and talent of the territory of these districts. Although the hazard from mud volcanoes is generally low, sometimes they may lead to sudden and violent eruptions and isolated casualties have been reported. Very notable cases in this regard are those of the Offida mud volcanoes (Ascoli Piceno, Marche Region), which at the end of 1959 exploded with a deafening roar, associated with a small earthquake and damaging some houses of the areas; or the most recent event that occurred in September 2014 in the Natural Reserve of Macalube di Aragona in Sicily where a mud volcano erupted, with an ejection of mud up to about 20 m above the ground and causing the burial of an adult and two children killing them. When a given geological site acquires a tourism value, it is necessary to assess the possible natural hazard processes which might threaten the safety of visitors (Soldati et al. 2008). In particular, fast-occurring processes might directly involve tourists in proximity of the site of interest or along access roads and footpaths. In this context, interdisciplinary research aiming at analysing the causes and understanding triggering mechanisms of paroxysmal and dangerous phenomena in the Natural Reserve of Nirano, are in progress, funded by the local municipality.

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The Outstanding Terraced Landscape of the Cinque Terre Coastal Slopes (Eastern Liguria)

20

Pierluigi Brandolini

Abstract

Due to a century-old agricultural practice, the coastal landscape of Cinque Terre (eastern Liguria, northwestern Italy) has been almost completely modified by slope terracing via reworking of millions of cubic metres of debris cover and the construction of thousands of kilometres of dry stone walls. Given their geomorphological-environmental value, as well as scenic and historical significance, the Cinque Terre represent one of the most outstanding examples of human integration with the natural landscape within the Mediterranean region, and have been recognised since 1997 as a World Heritage Site by UNESCO and included since 1999 within a National Park. Following the abandonment of farming over the last half a century, the terraced slopes have been progressively affected by crumbling of the dry stone walls and mass movements. As dramatically evidenced by the effects of the major rainstorm of October 2011, the Cinque Terre are currently at very high geomorphological risk and thus mitigation measures and conservation policies are urgently needed.

Keywords

Terraced slope landscape • Dry stone wall • Cultural heritage • Geomorphological risk • Cinque Terre • Liguria

20.1 Introduction

Due to its rugged morphology and a general lack of flat areas suitable for cultivation, the Liguria region in northwestern Italy is widely characterised, both along the coastal zone and inland, by slope terracing. Millions of cubic metres of debris cover have been reworked and thousands of kilometres of dry stone walls constructed. This impressive work of slope transformation is the result of a century-old agricultural practice, representing an outstanding example of human integration with the natural landscape (Terranova et al. 2002; Agnoletti 2013).

Located in easternmost Liguria (Fig. 20.1), the Cinque Terre are considered one of the most peculiar and dramatic examples of a terraced coastal landscape within the Mediterranean region. In fact, during the last millennium almost all the steep slopes of Cinque Terre, from the edge of the sea cliff and up to 400–500 m in elevation, have been modified by agricultural terracing, creating a highly unusual, man-made coastal landscape fully integrated with the geomorphological environment (Figs. 20.2 and 20.3). In many cases, terraces have been developed within earlier large coastal landslides and degradation scarps (Terranova et al. 2006).

Based on their environmental, scenic and historical significance, the Cinque Terre have been recognised since 1997 as a World Heritage Site by UNESCO and since 1999 have been included within the National Park of Cinque Terre.

Investigation of terraced areas has highlighted their positive role in improving slope stability via the construction of retaining dry stone masonry and the creation of drainage

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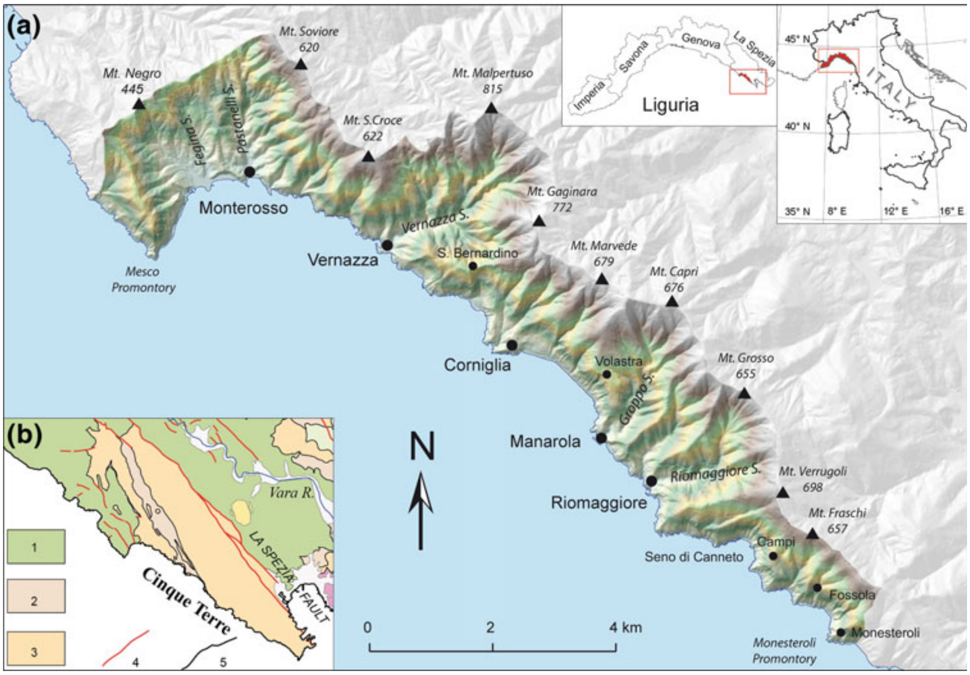

Fig. 20.1 Location of the study area. **a** Shaded relief map of the coastal area of Cinque Terre (derived from vector topographic base map 1:5000 scale—Regione Liguria). **b** Tectonic sketch map: (*1*) Ligurian Unit (Middle Jurassic–Paleocene); (*2*) Sub-Ligurian Unit (Paleocene–Early-Middle Eocene; (*3*) Tuscan Unit (Upper Oligocene); (*4*) main faults; (*5*) main overthrust (modified after Terranova et al. 2006)

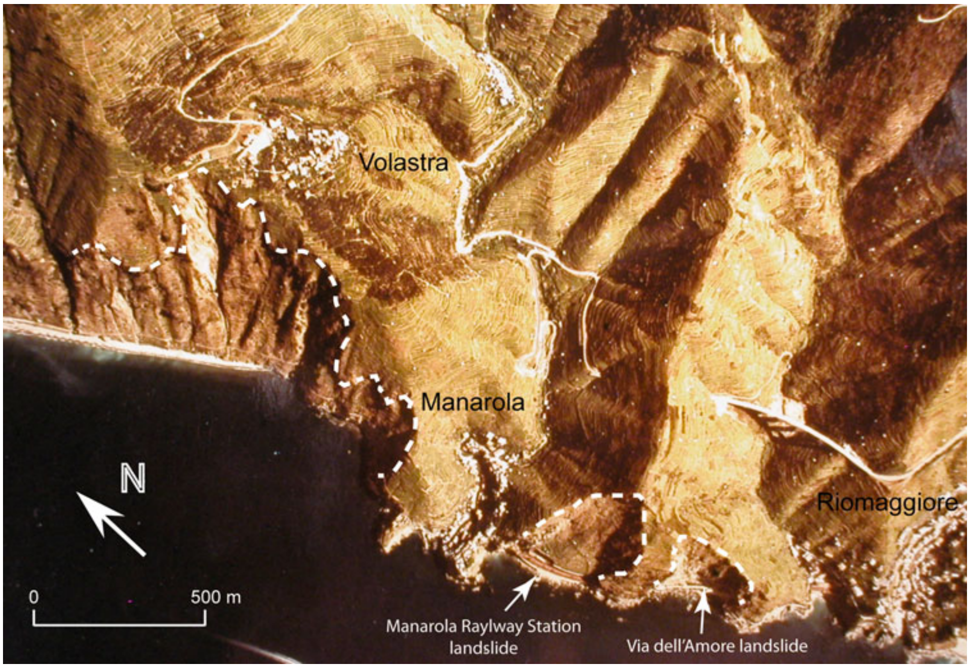

Fig. 20.2 Aerial photo of Cinque Terre coastal zone between Volastra and Riomaggiore, taken in 1973 (modified after Terranova 1984), showing the slope terracing developed from the edge of the sea cliff up to 400–500 m in elevation. In many cases, agricultural terracing has been constructed within earlier large coastal landslides and degradation scarps (highlighted in the picture by the *dashed white line*)

networks to ensure better control of shallow water erosion (Terranova 1984; Stanchi et al. 2012). At the same time, a lack of terrace maintenance due to farm abandonment led in only a few decades to instability phenomena, characterised by widespread soil erosion and slope movements. Abandoned terraced slopes are particularly susceptible to shallow landsliding, usually triggered by heavy rainfall events of short duration (Cevasco et al. 2013; Brandolini et al. 2016). Moreover, after high intensity precipitation, the materials mobilised by runoff and landslide phenomena have a considerable impact on the solid discharge, flow and energy of streams, causing floods that are increasingly affecting coastal settlements in Liguria (Brandolini et al. 2012; Faccini et al. 2012).

Following the exodus of farmers that has taken place over the past half century, the terraced slopes of Cinque Terre have been progressively abandoned and affected by degradation and crumbling of dry stone walls, with the loss of several hectares of terracing leading to rising geomorphological risk

Fig. 20.3 Panoramic view of the Cinque Terre from west: *in the foreground* the village of Vernazza surrounded by very steep and cultivated terraced slopes; *in the background* the ancient Macereto landslide and the Corniglia village located on a former marine terrace (*photo* Cinque Terre National Park Archive)

conditions (Brandolini et al. 2008; Galve et al. 2016). As dramatically evidenced by the effects of a major rainstorm event of October 2011, which resulted in hundreds of shallow landslides as well as a catastrophic flood, the Cinque Terre are currently ever more sensitive to intense rainfall (Galve et al. 2015).

Therefore, given the great environmental and historical value of Cinque Terre, which receive more than one million tourists every year, geomorphological risk mitigation measures and conservation policies are an urgent issue to preserve this extraordinary coastal landscape.

20.2 Geographical Setting

The toponym “Cinque Terre”, meaning “five lands”, is derived from the historical villages of Monterosso, Vernazza, Corniglia, Manarola and Riomaggiore, which lie in easternmost Liguria along a 20-km stretch of rocky coastline between the Mesco and Monesteroli promontories, in the province of La Spezia (Fig. 20.1).

Despite its seaside location, Cinque Terre exhibit characteristics typical of hilly-mountain areas, with very steep slopes, deeply cut valleys, and small watersheds with ephemeral streams. The narrow coastal zone of Cinque Terre is bounded to the north by a series of peaks ranging in altitude, from west to east, from 400 to around 800 m a.s.l. (Mt. Negro, 445 m; Mt. Soviore, 620 m; Mt. S. Croce, 621 m; Mt. Malpertuso, 815 m; Mt. Gaginara, 772 m; Mt. Capri, 786 m; Mt. Grosso, 655 m; Mt. Verrugoli, 698 m; Mt. Fraschi, 527 m). These mountains form a ridge oriented NW–SE, parallel and very close (from 1 to 3 km) to the coast, which represents the divide between Cinque Terre and the Vara valley. Consequently most of the slopes face southwest.

The villages of Monterosso, Vernazza, Manarola and Riomaggiore are mainly located along the coast adjacent to rivers and partly on the top of the sea cliff; only the hamlet of Corniglia is wholly located on a former marine terrace at an elevation of 100 m (Fig. 20.3). Scattered settlements are also present at between 300 and 500 m elevation on slope areas with favourable aspect.

The climate of the area is typically Mediterranean, characterised by warm and dry summers and mild winters. The annual mean temperature ranges between 14.5 and 15.5 °C, reaching a mean peak of 22–24.5 °C in July and August and a low of 7–8 °C in January. Annual mean rainfall is 1040 mm, with maximum rainfall typically occurring in December; a mean value of 224 mm has been recorded for this month at the Levanto gauge station for the period 1932–2011. Heavy rainfall events of short duration are very frequent in the area, with intensities greater than 150 mm/3 h and 200 mm/6 h as recorded during the period 1951–2011. Regarding the flooding event of 25 October 2011, a cumulative rainfall total of 382 mm in 24 h was recorded at the Monterosso gauge station, the highest levels ever observed in the entire Cinque Terre region (ARPAL-CFMI-PC 2012).

Thanks to its particular geological, morphological and climatic conditions, the Cinque Terre area is characterised by distinctive land-use practices, with almost all slopes terraced for cultivation of olive groves and especially vineyards. These practices have led to the development of a unique coastal landscape and terroir which is internationally renowned for the production of Vermentino and Sciacchetrà wines.

Beginning in around 1100 AD, man-made slope terracing has subsequently spread over an area corresponding to approximately 60% of the entire territory of the Cinque Terre (33 km^2), within the present day municipalities of Monterosso, Vernazza and Riomaggiore (Terranova 1984). The only unterraced areas are the upper slopes in the proximity of the ridge dividing Cinque Terre and the Vara valley, which are mainly covered by chestnut and holm oak forest.

Following the exodus of farmers which took place in the last century, the terraced areas have been progressively abandoned, causing a general increase in soil erosion and slope instability. Currently only around 20% of terraces are still cultivated (Terranova et al. 2002).

20.3 Geological and Geomorphological Setting

The Cinque Terre area is characterised by the presence of five tectonic units belonging to the Tuscan, Sub-Ligurian and Ligurian domains (Giammarino et al. 2002). These units form part of a wide overturned anti-form SW-verging fold, and are bounded to the northeast by a major normal fault (La Spezia fault). Structural and geo-lithological features generated by the emplacement of the Apennines—in particular its Plio-Quaternary tectonic uplift (Carmignani et al. 1994)—have directly influenced the geomorphological landscape, which in turn conditioned current land-use patterns.

The most widespread rock formation is flysch which comprises sandstones and clayey siltstones locally known as the Macigno Formation (upper Oligocene). This formation belongs to the Tuscan Nappe (Tuscan Domain) which crops out along almost the entire coast between Monterosso and the eastern border of Cinque Terre represented by the Monesteroli promontory (Fig. 20.1).

Regarding the Sub-Ligurian Domain, claystones with limestones and silty sandstone turbidites (Palaeocene), marly limestones with thin claystone interbeds (early-middle Eocene) and fine sandstone turbidites (upper Oligocene) belonging to the Canetolo Unit crop out in the central part of Cinque Terre, in particular within the Vernazza River catchment and along the coast between Corniglia and Manarola.

In the framework of the Ligurian Domain, quartzose and micaceous-feldspatic sandstones (upper Cretaceous-Palaeocene), claystones, calcarenites and marls (upper Cretaceous), clayey shales with siliceous micritic limestones (upper Cretaceous) belonging to the Gottero Unit, cherts, gabbros and serpentinites (medium Jurassic) belonging to the Bracco Unit, as well as claystones and limestones with olistolites of ophiolitic and granitic breccias (upper Cretaceous) belonging to the Mt. Veri Unit, are present in the westernmost sector of Cinque Terre between the Mesco promontory and Monterosso.

From a geomorphological point of view, the orientation of the coastline and the drainage pattern of the area are influenced on a large scale by tectonic lineations (fault and fracture systems), mainly striking NW–SE and NE–SW, but also N–S and E–W. Catchments in the Cinque Terre region are very small in extent, ranging from 1–3 km^2 (Fegina, Pastanelli, Groppo and Riomaggiore streams) to around 6 km^2 (Vernazza stream). As a consequence, and also due to the aforementioned proximity of the main divide between Cinque Terre and the Vara valley to the coast, the rivers are short with steep profiles and ephemeral hydrological regimes. Due to considerable erosive and sediment transport capacity, associated with the high intensity rainfall events which regularly affect eastern Liguria, many streams are incising their beds (Cevasco et al. 2012).

Thanks to its high slope steepness, with more than 50% of terrain characterised by gradients ranging between 30° and 40°, and its hydrological regime, the geomorphological landscape of Cinque Terre is dominated by gravity and running water processes. These terrestrial processes interact with marine erosion along the coast, resulting in the presence of several large coastal landslides and an almost continuous rocky sea cliff (Fig. 20.4).

Dramatic rock falls and degradation scarps are particularly common along the eastern slope of the Mesco promontory, affecting very thick (up to 15 m) and fractured sandstone strata of the Gottero Unit. Active large translational rock slides are currently observable along the coast between Vernazza and Corniglia; the edges of the associated scarps are located from between 100 m a.s.l. around the slope and sea cliff just to the east of Vernazza, to 280 m a.s.l. around the Macereto area (Fig. 20.3). The latter slides involve highly fractured layers, with the same prevailing bed attitude as the slope, of sandstones and clayey siltstones of the Macigno Formation (Tuscan Unit).

A large complex mass wasting process—locally known as the Guvano landslide and favoured by the tectonic contact between the Canetolo Unit (claystones with limestones and silty sandstone turbidites) and the Tuscan Unit (sandstones and clayey siltstones)—is still active along the coastal slope between S. Bernardino and Corniglia. The source area is located at around 350 m a.s.l. just below S. Bernardino, where rock falls and topples can be observed. This landslide evolved into a flow, forming a wide downslope accumulation extending to the shoreline (Fig. 20.4a).

An ancient mass movement, locally known as the Rodalabia landslide, occurred just east of the Corniglia promontory and involved an entire slope between 275 m elevation and sea level. This complex landslide resulted in extensive accumulation that affected around 500 m of coastline, currently characterised by the presence of agricultural terracing, sparse settlement and the Genoa-La Spezia railway line. Indeed, the latter was only made possible by the construction of huge retaining walls in 1870, which protect the landslide area from further sea wave erosion. Another ancient dormant landslide is present just eastward of the Manarola village, affecting the slope above the railway station (Fig. 20.4b).

One of the most hazardous mass movements is the landslide affecting the sea cliff between Manarola and

Fig. 20.4 Panoramic view of the main landslide areas present in the Cinque Terre within the terraced coastal slopes landscape: **a** the large complex mass movement known as Guvano landslide; **b** *on the right* the dormant landslide of Manarola; *on the left* shallow landslides and debris flows affecting the slope below Volastra; **c** *on the left* the active landslide of "Via dell'Amore"; *on the right* the degradation scarp which affect the slope below the Madonna of Mt. Nero Sanctuary (*photos* P. Brandolini)

Riomaggiore. Frequently reactivated, this landslide has caused severe damage and interruption to the most famous and spectacular tourist path in Cinque Terre, the "Via dell'Amore" (Fig. 20.4c). The landslide is complex and affects slopes up to 200 m a.s.l., mainly in the form of rock falls from sandstone and clayey siltstone bedrock outcrops (Tuscan unit) which are strongly tectonised by an articulated system of folds and joints.

Considering the intense rainfall that regularly affects the area and the high steepness of the slopes, which are typically characterised by eluvial-colluvial cover of only 1–2 m in thickness, shallow landslides and debris flows are widespread throughout Cinque Terre (Fig. 20.4b). Shallow landslides consisting mainly of earth and debris slides and often evolving into flows, with a failure surface represented by the contact between debris cover and bedrock, have particularly affected mostly abandoned or non-maintained terraced slopes in the areas of Vernazza, Volastra, Seno di Canneto, Campi, Fossola and Monesteroli (Terranova 1984; Cevasco et al. 2013). In the last few decades, these landslides have affected many hectares of vineyards and olive groves (Fig. 20.5c).

Almost the entire littoral zone of Cinque Terre is characterised by a spectacular rocky coast, cut by the action of prevailing sea storms from the SW (Libeccio) and SE (Scirocco). Most of these sea cliffs are active and have an edge of scarp typically ranging between 5 and 30 m, but reaching 100 m just along from the Corniglia promontory (Fig. 20.3).

Beaches in the region are few and small, and are associated with the main rivers (Fegina and Vernazza) or occur at the foot of some coastal slopes affected by active gravitational processes (Guvano, Campi and Monesteroli). A number of artificial beaches (Corniglia, Vernazza and Monterosso), currently in retreat, were created in 1870 and 1970 by nourishment with materials derived from the construction of tunnels on the Genova—La Spezia railway line (Fig. 20.2).

20.4 Landscape of Slope Terracing and Geomorphological Risk

During the last millennium, the geomorphological landscape of Cinque Terre has been almost totally modified by human activity via the construction of agricultural terraces within the steep slopes, from sea level up to 400–500 m. Early farmers reworked and retained the shallow colluvial cover by constructing dry stone walls, selecting the most suitable bedrock for cultivation. Not coincidentally, the borders of the terraced areas line up almost exactly with the geological contacts of the different formations which crop out in the region. In fact, vineyards and olive groves in Cinque Terre are found only on terraces built on sandstones and clayey siltstones (Tuscan Unit), claystones with limestones and silty sandstone turbidites (Canetolo Unit), clayey shales with siliceous micritic limestones (Gottero Unit) and claystones

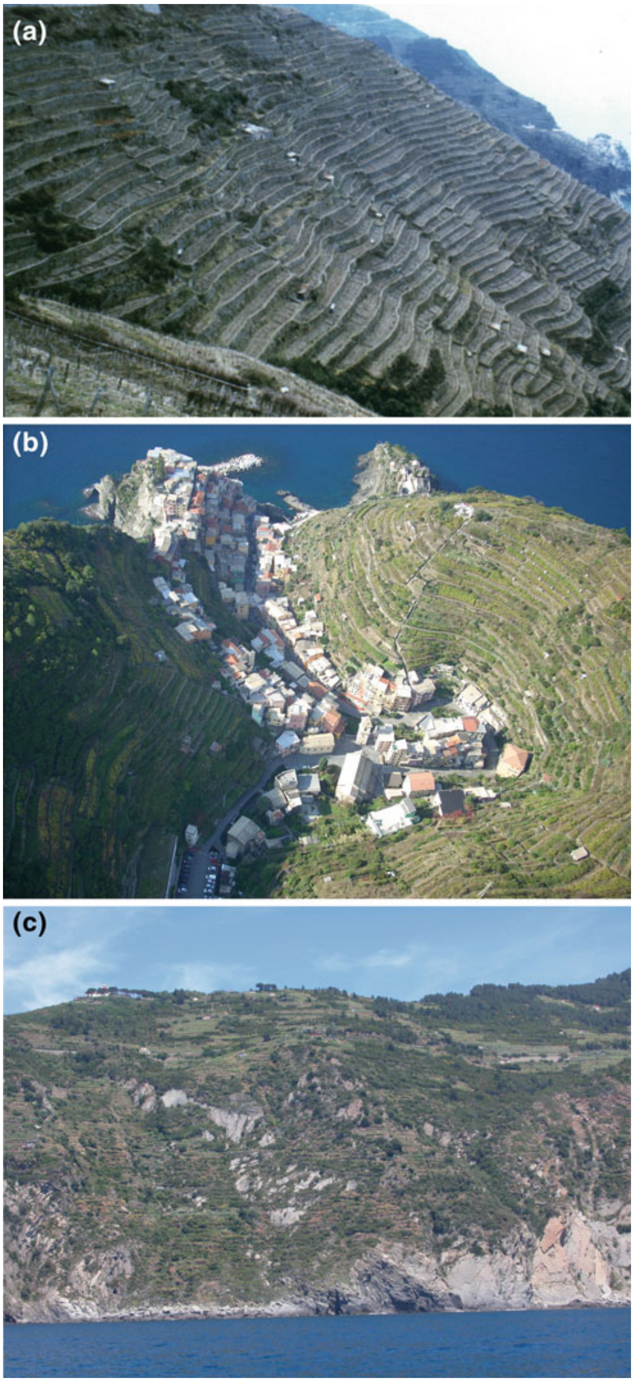

Fig. 20.5 Example of cultivated terraced vineyards in good state of conservation on the slope between Corniglia and Volastra (**a**) (*photo* R. Terranova) and in the lower part of Manarola valley (**b**) (*photo* P. Brandolini); abandoned terracing, built just over the top of sea cliff scarp between Riomaggiore and Monesteroli affected by slope degradation (**c**) (*photo* P. Brandolini)

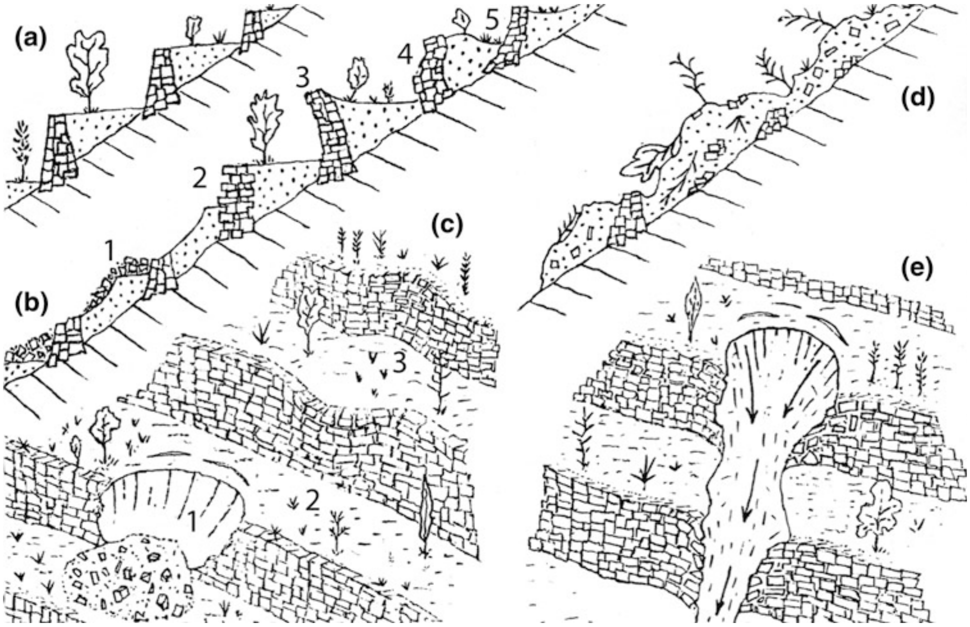

Fig. 20.6 Evolution of slope terracing after farming abandonment: **a** cultivated terraces in good state of conservation; **b** different types of dry stone walls crumbling: fall (*1*), sliding (*2*), topple (*3*), bulging and sliding (*4*, *5*); **c** terrace collapse along a concave surface (*1*), dry stone walls deformations (*2*, *3*). **d** drystone walls completely destroyed. **e** terraced slope affected by shallow landsliding (modified after Terranova 2005)

and limestones with olistolites (Mt. Veri Unit). Significantly, no terraces have been built on quartzose and micaceous-feldspatic sandstones (Gottero Unit) or on cherts, gabbros and serpentinites (Bracco Unit). Cultivation on terraces has also been favoured by the presence of ancient landslide deposits such as those associated with the aforementioned large mass movements of Rodalabia, Guvano and Manarola (Fig. 20.4).

Dry stone wall terracing now covers an area of about 20 km^2, representing 60% of the entire Cinque Terre region. Considering that the width of terraces ranges from 2 to 4 m, the maximum linear extent of dry stone walls can be estimated to total around 6000 km. Furthermore, considering that wall height normally ranges between 1.5 and 2.5 m, depending on slope steepness and terrace width, the total volume of reworked dry stone is likely to exceed 8,000,000 m^3 (Terranova 1984).

This "cyclopean" work of slope terracing is the result of a centuries-old agricultural practice which over time led to the local acquisition of unique dry stone construction skills, adopted in relation to the region's specific geological and geomorphological conditions (lithology, steepness, morphology and hydrology). Moreover, important drainage works have been added, always via the use of dry stone, for running water control and supply. The varied geometric features of terraces and working methods therefore mean they have been integrated almost perfectly within the natural landscape (Figs. 20.2 and 20.5).

Although the terraces are very effective in ensuring both the stability of the debris cover and the shallow infiltration drainage, at the same time they are also fragile because they were built without the use of any cement mortar and therefore require constant maintenance.

Due to the exodus of farmers which began at the end of the 1800s and accelerated after the 1950s, a lack of wall maintenance has resulted in crumbling of many spectacular areas of terraced slopes, which are now widely affected by soil erosion and landsliding (Fig. 20.6). In only a few decades, the upper parts of the abandoned terraces became overgrown with pine trees, and the middle-lower slopes by Mediterranean scrub (Fig. 20.5c).

The result is that more than 80% of terraces are today abandoned; olive groves and vineyards now cover less than 250 ha, with only around 150 ha still devoted to the production of Vermentino and Sciacchetrà wines with a denomination of controlled origin.

In such a complex geological context, with unfavourable tectonic and structural setting and high energy relief, the Cinque Terre are strongly prone to landsliding. The terraces, although fundamental for the preservation of slope stability in the past, due to their almost complete abandonment today are an important factor in the geomorphological risk scenario. The terraced slopes must therefore be considered both an element at risk and simultaneously an element whose degradation could increase the frequency of gravitational phenomena and floods.

In the last 50–70 years, a lack of agricultural management has resulted in many hectares of terraced slopes being completely lost, included in the areas around Volastra, Campi and Fossola. In these locations, the progressive collapse of dry stone walls has been rapidly followed by increasingly extensive erosional processes, shallow

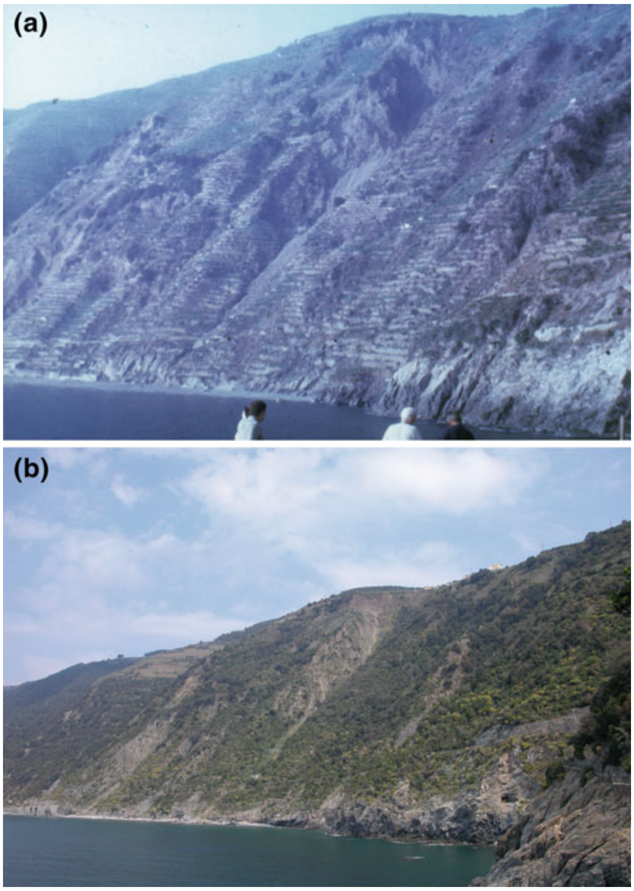

Fig. 20.7 The area around Volastra in 1960 (**a**, *photo* R. Terranova) and in 2011 (**b**, *photo* P. Brandolini)

landslides and debris flows, as illustrated by a comparison of historical photos with the present day situation (Fig. 20.7).

The sensitivity of terraced slopes to intense rainfall, as well as the correlation of the latter with the occurrence of landslides and floods, was dramatically confirmed by the effects of the precipitation event which occurred in Cinque Terre on 25 October 2011, with the rainstorm affecting the Vernazza catchment in particular. A cumulative rainfall total of nearly 400 mm fell in just 6 h, with a peak of around 100 mm in 1 h, causing widespread runoff and erosional processes and triggering hundreds of shallow landslides, ultimately leading to a catastrophic debris flood (Cevasco et al. 2013; Brandolini et al. 2016).

During this event the River Vernazza overflowed its former talweg, creating an alluvial fan in the marina and inundating the main street of the village historic centre, where mud and debris deposits reached an average thickness of around 4 m, flooding the first floors of buildings. The flood resulted in three casualties, with the economic damage to buildings, rail, roads and the tourist trail network estimated at over 130 million euros, without considering the loss of the agricultural terraces (Fig. 20.8).

The rainstorm event also triggered more than 400 shallow landslides within the catchment, mainly slides and flows, with individual affected areas ranging in extent from hundreds to thousands of square metres, covered by 1 or 2 m of debris. These landslides occurred mainly in middle-lower altitude areas of the catchment, on steeper slopes with gradients greater than 30°. A comparison of landslides and land use has revealed that landslide source areas are mostly concentrated near to agricultural terraces, confirming the high landslide susceptibility of abandoned or non-maintained terraced slopes (Cevasco et al. 2014; Galve et al. 2015).

20.5 Conclusions

In the framework of the high risk scenario currently characterising the outstanding coastal landscape of Cinque Terre, the choice of appropriate land management strategies and conservation policies is a very sensitive issue. Any strategy must consider the urgent need to both counteract long-term geomorphological hazards and at the same time preserve the cultural heritage of the man-made terraced landscape.

In fact, the loss of slope terracing not only has a negative impact on the environment in terms of increasing risk conditions, but also implies the disappearance of agricultural and societal practices that have formed the basis of the recognition of the area as a UNESCO World Heritage site and are today the fundamental factor in attracting tourist activity.

Until now, intervention has only been carried out in emergency situations, such as after the rainstorm of 25 October 2011 that affected the Vernazza River catchment. Although only a short-term solution, very expensive local structural works to secure exposed buildings and roads have been primarily undertaken on problematic slopes (flexible shallow landslide barriers, micropiles, dry stone wall reconstruction) and stream segments (enlargement of flow sections, heightening of levees, debris flow barriers).

To drastically reduce the effects of natural disasters and to ensure long-term effective mitigation of geomorphological risk, prevention strategies must be planned on a basin-wide scale, providing widespread restoration of abandoned terraces, recovery of drainage systems and the maintenance and reforestation of wooded areas in the upper parts of the basins (Brandolini and Cevasco 2015). To this end, the National Park of Cinque Terre has recently initiated significant action towards the recovery of terraced vineyards by supplying farmers with vine roots and stone material for wall rebuilding free of charge. However, in order to finance interventions which will successfully mitigate the geo-hydrological risk and safeguard this dramatic coastal landscape, considerably greater economic resources are needed.

Fig. 20.8 The October 25, 2011 rainstorm caused widespread runoff erosional processes and triggered hundreds of shallow landslides which affected the terraced slopes of the Vernazza catchment in particular (*photos* **a** and **b** Corpo Forestale dello Stato Archive). A catastrophic debris flood inundated the main street of the village historic centre (*photo* **c** National Park of Cinque Terre Archive) and resulted in fan accumulation within the marina (*photo* **d** National Park of Cinque Terre Archive)

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Tuscany Hills and Valleys: Uplift, Exhumation, Valley Downcutting and Relict Landforms

21

Mauro Coltorti, Pier Lorenzo Fantozzi, and Pierluigi Pieruccini

Abstract

The Tuscany physical landscape is the result of processes of selective erosion initiated by regional uplift. The overall geomorphological setting is characterized by "highlands" or mountain ridges alternated with "lowlands" or basins filled with Mio-Pliocene continental and marine sediments. A planation surface was shaped over bedrock, including Pliocene marine terrains, and is widely preserved on top of the mountain ridges. As a result of uplift, the sedimentary infillings of the Pliocene synform basins were affected by river incision. Gully and badland erosion dominate the clayey terrains while cuestas, mesas and stepped slopes are found in sandstones and conglomerate terrains. Large karstic depressions are also found. In the past, these hosted palaeo-springs that alimented travertine and calcareous tufa deposition which spread out to occupy large valley sectors.

Keywords

Planation surface • Tectonic depressions • Uplift • Exhumation • Tuscany

21.1 Introduction

The Tuscany landscape is characterized by NNW–SSE trending mountain ridges, where the bedrock crops out, alternating with wide valleys mostly modelled on "soft" unconsolidated or scarcely consolidated Mio-Plio-Pleistocene marine and continental sediments. This landscape is typically found to the west of the highest parts of the Apennine ridge, between the Arno-Chiana valleys and the Tyrrhenian Sea (Fig. 21.1).

The classic model of long-term landscape evolution in the northern Apennines was based on the chronology and facies of the Mio-Plio-Pleistocene sedimentary basins (Elter et al. 1975). Following this model the compressional tectonic phase, which generated the thrust-fold sheets, shifted to the western margin of the Adriatic basin at the end of the Miocene while in Tuscany the extensional tectonics generated a series of horst and grabens that hosted continental and marine sedimentation (Martini and Sagri 1993; Pascucci et al. 2006). Recent research has changed this model and provides a new perspective to the geomorphological setting and evolution of this sector (Coltorti and Pieruccini 1997; Brogi 2011; Finetti et al. 2001).

21.2 Geographical and Geological Setting

To the west of the Arno-Chiana valley, the landscape is characterized by gentle relief with mean elevation of the ridges less than 700 m a.s.l. that contrast with the Apennine ridge to the east where the elevation reaches 1200–1400 m. The steep slopes that mark the separation of these two sectors are associated with NW–SE trending fault system that bounds to the east the Florence basin, the Upper Valdarno and Valdichiana basins (Fig. 21.1). The continuity of these basins, filled with Plio-Pleistocene marine and continental sediments, are interrupted along their length by NE–SW trending thresholds due to the rise of the harder pre-Pliocene bedrock. To the west, these basins are bordered by the Outer Tuscany Ridge, also known as Cetona-Rapolano-Chianti-Mt.

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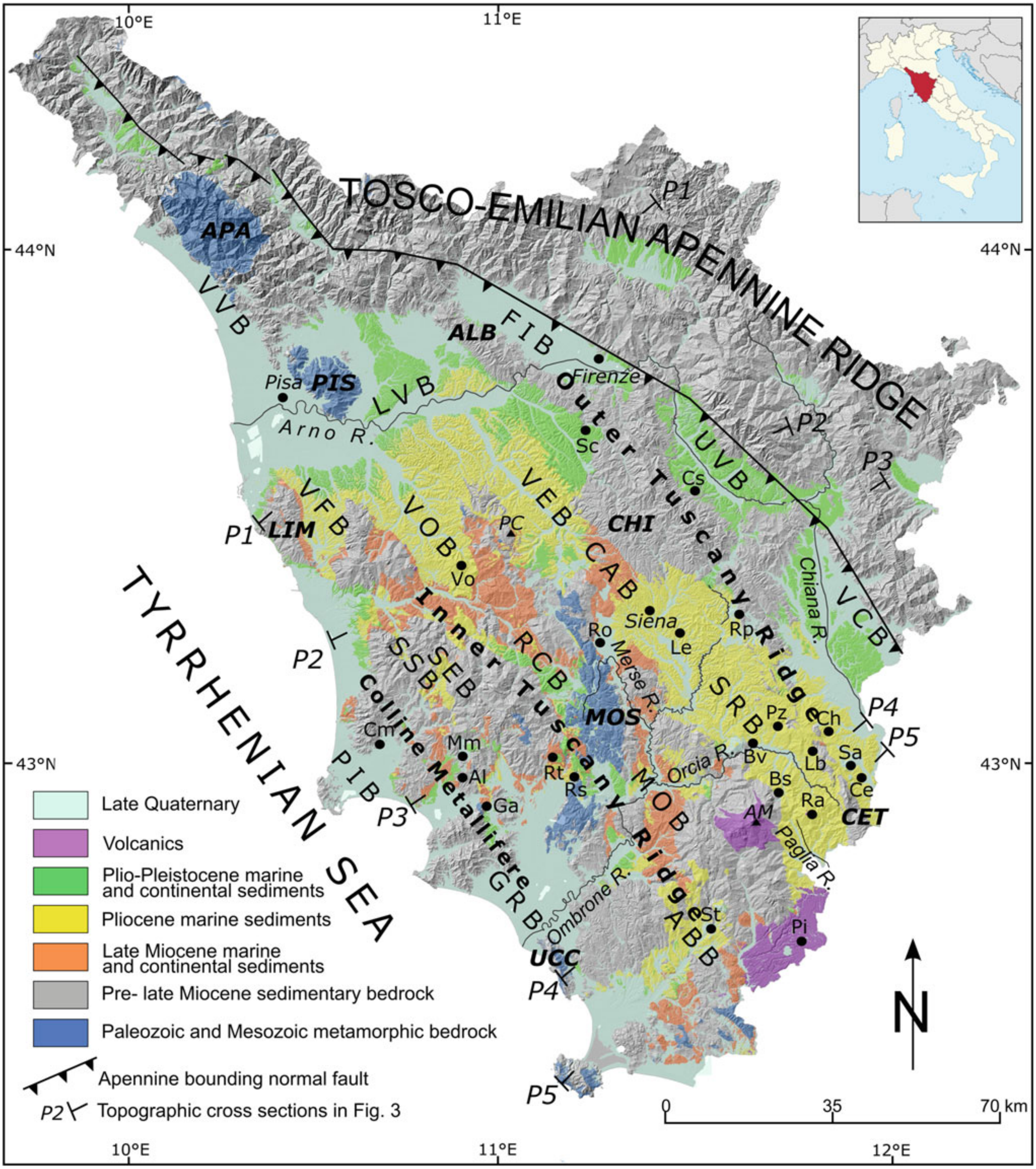

Fig. 21.1 Sketch map of the Tuscany hills and valleys landscape. *Mountain Ridges*: Apuane Alps (*APA*); Pisani Mts. (*PIS*); Mt. Albano ridge (*ALB*); Chianti ridge (*CHI*); Cetona ridge (*CET*); Livornesi Mts. (*LIM*); Montagnola Senese (*MOS*); Uccellina Mts. (*UCC*). *Reliefs*: Mt. Amiata (*AM*); Poggio del Comune (*PC*). *Basins*: Versilia basin (*VVB*); Casino basin (*CAB*); Lower Valdarno basin (*LVB*); Florence basin (*FIB*); Upper Valdarno basin (*UVB*); Valdichiana basin (*VCB*); Valdelsa basin (*VEB*); Siena-Radicofani basin (*SRB*); Volterra basin (*VOB*); Radicondoli-Chiusdino basin (*RCB*); Middle Ombrone basin (*MOB*); Albegna basin (*ABB*); Val di Fine—Val di Cecina basin (*VFB*); Sassa basin (*SSB*); Serrazzano basin (*SEB*); Piombino basin (*PIB*); Grosseto basin (*GRB*). *Localities*: Campiglia Marittima (*Cm*); Radicofani (*Ra*); Chianciano Terme (*Ch*); Sarteano (*Sa*); Cetona (*Ce*); Pienza (*Pz*); San Casciano Val di Pesa (*Sc*); Bagni San Filippo (*Bs*); Bagno Vignone (*Bv*); Rapolano (*Rp*); Rosia (*Ro*); Massa Marittima (*Mm*); Saturnia (*St*); Castelnuovo dei Sabbioni (*Cs*); Roccatederighi (*Rt*); Roccastrada (*Rs*); Volterra (*Vo*); Accesa Lake (*Al*); Lucciola Bella (*Lb*); Camposodo/Leonina (*Le*); Gavorrano (*Ga*), Pitigliano (*Pi*)

Albano ridge. To the west, the ridge bounds the Mio-Plio-Pleistocene Valdelsa, Lower Valdarno, Casino and Siena-Radicofani basins. Further to the west, the latter basins are bounded by the Inner Tuscany Ridge that is a complex system of NW–SE trending ridges extending to the coast. The ridges can be continuous over long distances (Montagnola Senese—Poggio del Comune, Colline Metallifere) or shorter (Livornesi Mts., Campiglia Marittima, Uccellina Mts.) and interrupted by Mio-Plio-Pleistocene basins (Volterra, Radicondoli-Chiusdino, Val di Fine—Val di Cecina), Sassa, Serrazzano, Middle Ombrone, Piombino and Grosseto).

Bedrock (Figs. 21.1 and 21.2) is made of a series of tectono-sedimentary units containing metamorphic and sedimentary Palaeozoic to Miocene rock (i.e. limestones, sandstones, marbles, marly limestones, marls, etc.) tectonically transported for hundreds of kilometres from west to east along low-angle fault planes. During the tectonic transport they were severely thinned (reduced succession) and locally deformed to generate a chaotic melange (allochthonous units, Carmignani et al. 2001) (Figs. 21.1 and 21.2). The oldest units, made of Palaeozoic-Oligocene metamorphic complexes, crop out discontinuously between the Uccellina Mts. and the Montagnola Senese to the south, and in the Pisani Mts. and Apuane Alps to the north. The Palaeozoic basement is overlain by the metamorphic Mesozoic-Tertiary Tuscany Units (Fig. 21.2). Non-metamorphic Tuscany Units are tectonically superimposed on the metamorphic complex and, in turn, covered by the so-called “Allochtonous” Ligurian Complex, also made of Mesozoic-Tertiary sedimentary units that include ocean floor basalts and ophiolites (Fig. 21.2). The first evidence of emerged land is shallow marine and continental sediments late Miocene in age (autochtonous units, Fig. 21.2, i.e. Casino and Volterra basins). The variation in thickness of these deposits suggests the presence of an articulated topography and the occurrence of unconformities. In fact, these sediments are unconformably overlain by Early-Middle Pliocene and Early Pleistocene marine sediments made of clays, sands and gravels of neritic to coastal environments. Unconformities are associated with transgressive-regressive cycles. Progressive unconformities separate major cycles affected by syn-sedimentary folding (Coltorti and Pieruccini 1997; Pascucci et al. 2006; Coltorti et al. 2007; Brogi 2011). The sedimentary sequences are preserved in the basins and rarely on the ridges that usually record only the last erosional phase. Therefore, Pliocene and, to a greater extent, Miocene palaeogeography is not consistent with the present day geomorphological setting. Geotechnical analysis carried out in the Siena-Radicofani basin on the degree of consolidation of the Pliocene marine clays revealed that almost 2000 m of sediments were removed after their deposition (Disperati and Liotta 1998). Therefore, the tectonic style once associated with horst and graben delimited by high-angle extensional faults (Elter et al. 1975; Martini and Sagri 1993; Pascucci et al. 2006) is now associated with synform (Coltorti and Pieruccini 1997), perched, piggy back or bowl-shaped basins (Finetti et al. 2001; Brogi 2011). Finetti et al. (2001) claimed that the deformation occurred in a compressional regime whereas according to Coltorti and Pieruccini (1997) and Brogi (2011) the basins were formed due to surface deformation related to the activity at depth of east dipping low-angle normal faults. The only important system of high-angle normal faults is the one bounding to the east the Florence-Valdarno-Valdichiana basins, activated during the Early Pleistocene. Minor and rare high-angle normal faults have been described but they do not have lateral continuity.

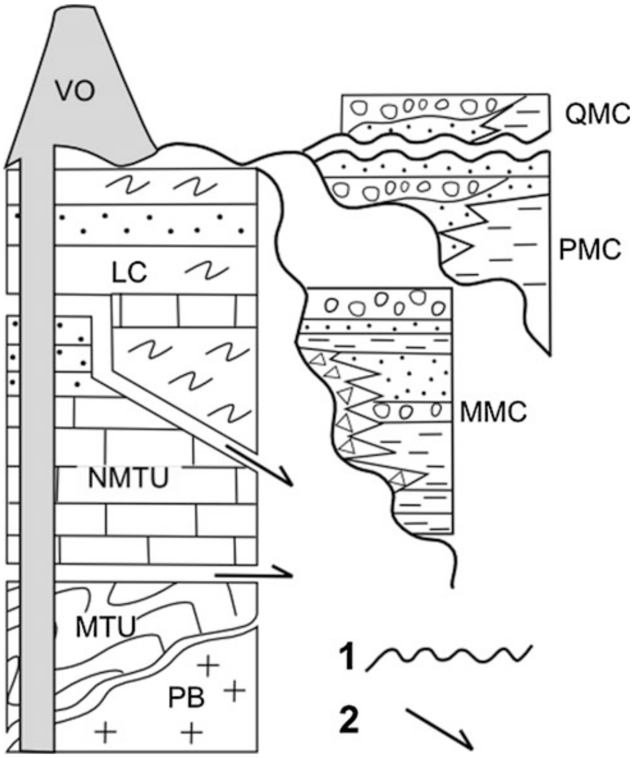

Fig. 21.2 Stratigraphic scheme of the tectono-sedimentary units cropping out in Tuscany. *Legend VO* volcanic; *QMC* Quaternary marine and continental deposits; *PMC* Pliocene marine and continental deposits; *MMC* Late Miocene marine and continental deposits; *LC* Ligurian Complex; *NMTU* non-metamorphic Tuscan Units; *MTU* metamorphic Tuscan Units; *PB* Palaeozoic Basement; (*1*) main sedimentary unconformity; (*2*) main tectonic unconformity (modified after Coltorti et al. 2012)

21.3 Landforms and Landscapes

Coastal Pliocene sediments are locally preserved on top of the mountain ridges and within sedimentary basins. At depth, inside the basins, sediments testify to a slightly deeper depositional environment. On top of the ridges, these sediments have locally a very limited thickness and most probably in the past they covered a larger area. Marine conditions characterized the area until the Middle Pliocene. No faults displace the planation surface along the margins of the basins, clearly indicating that the depressions are the result of selective erosion (Coltorti et al. 2012). After the emersion of the area, the hydrographic network easily deepened through the basins due to the presence of the erodible Mio-Plio-Pleistocene sediments (Fig. 21.3). Only the Florence—Upper Valdarno—Valdichiana basins are fault-angle valleys and the river flows parallel to the normal fault system located to the west of the Tosco-Emilian Apennine ridge. In the Florence basin, the Arno River abruptly changes direction to the WSW cutting the Mt. Albano ridge and flowing straight to the sea. The Chiana River runs for a short distance parallel to the same fault system, but it mostly crosses slantwise the Valdichiana basin before joining the Tiber River. Also the upper valley of the Ombrone River deepens in correspondence with the softer terrains of the Siena-Radicofani basin before turning abruptly to SW to cut the Inner Tuscany Ridges down to the coast. All the major

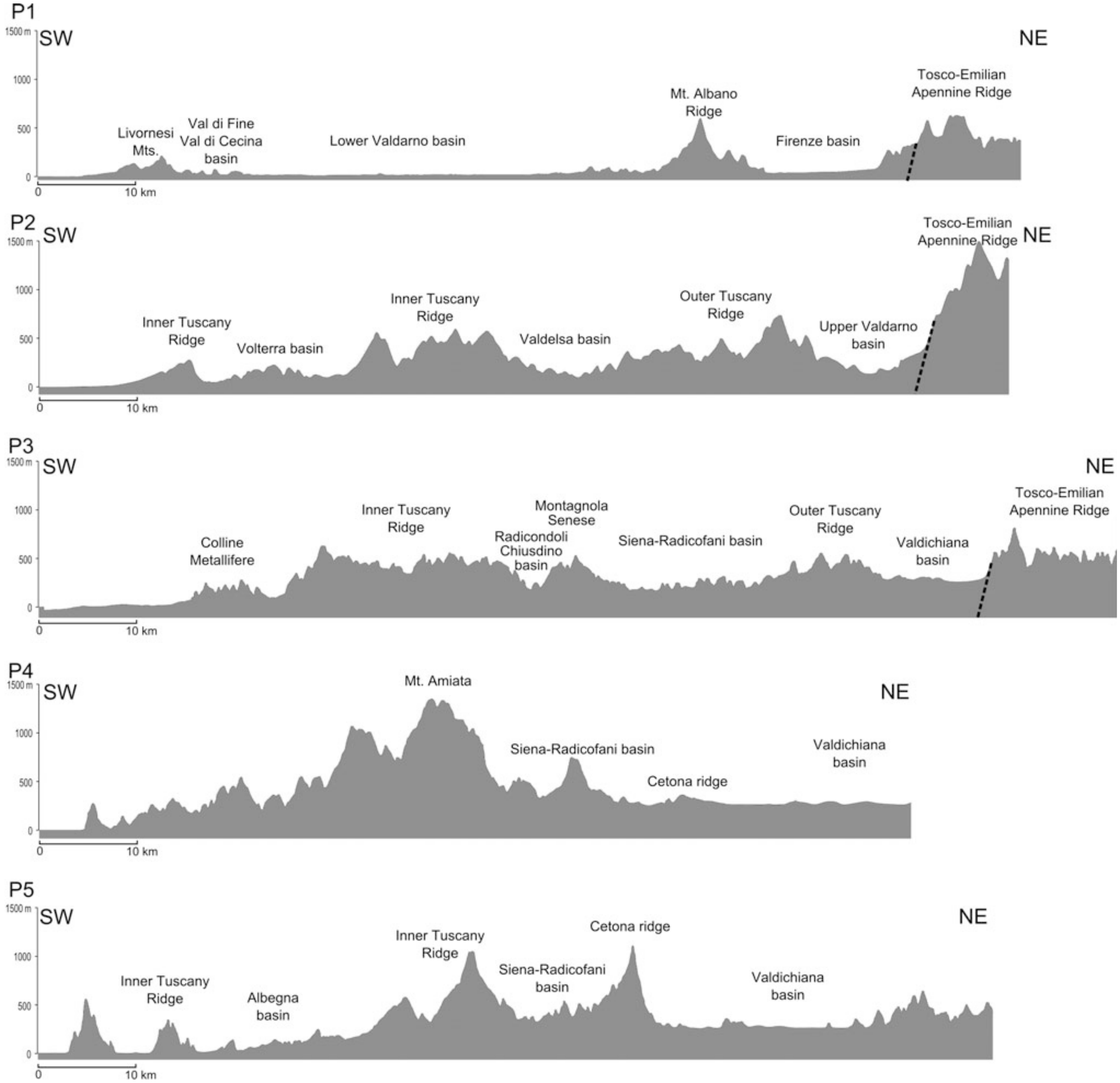

Fig. 21.3 Topographic cross sections across central-southern Tuscany showing the main basins and ridges. Location of profiles in Fig. 21.1. In Sections 1–3 the master, west dipping normal fault bounding to the west the Tosco-Emilian Apennines, is shown

Fig. 21.4 The western border of the Valdarno at the contact with the Chianti Mts. The main escarpment is found in the upper part of the slope while a series of long and deep trenches characterize the middle part (*photo* M. Coltorti)

rivers deepen within the Mio-Pliocene sediments. However, some anomalies in the river pathways are recognizable across the area. In fact, in the inner western reaches many rivers (i.e. Merse River) flow to the east and make a long turn before going west towards the Tyrrhenian Sea.

21.3.1 The Apennine Western Foothill: The Upper Valdarno, Valdichiana and Florence Basins

The eastern side of the Upper Valdarno and the Florence basin is characterized by spectacular triangular and trapezoidal facets associated with the main fault system. The displacement of this fault is 500–600 m, inferred from the elevation of the planation surface preserved on both blocks. Coalescent alluvial fans, mainly deposited during the cold phases of the Middle and Late Pleistocene, seal the footslope. The alluvial fans grade to alluvial terraces that are up to 110 m high above the river bed (Coltorti et al. 2007). These sediments unconformably overlie Early Pleistocene alluvial sands and gravels associated with the cooling phases of the Early Pleistocene (*ca*. 2.5–2.2 Ma) and Middle or Early Pliocene deposits with lignites (Brogi et al. 2013). Along the western side of the valley, an unconformity tilted up to 60° eastward marks the contact with bedrock. The re-exhumation of this unconformity generates flatirons but no faults have been recognized.

In the rest of the Upper Valdarno basin, the deep incision generated steep slopes in gravels and gentle slopes in silts and clays. Runoff processes generated a typical badland landscape (locally “Balze” or “Motte”) and earth pyramids. Gravitational movements, mainly mud, earth and debris flows, are frequent although larger slides are found at the contact between the Pliocene clays and gravels.

Deep-seated gravitational slope deformations (DGSDs) more than 6 km in length (Fig. 21.4) have been recognized along the western slope (Coltorti et al. 2009). However, despite a series of trenches that characterize the base of the main scarp, the front has not collapsed. This was attributed to stream erosion that drained the landslide body. However, large landslides were activated from these DGSDs and one of them led to the abandonment of the historical village of Castelnuovo dei Sabbioni, to the east of the Chianti Ridge.

The Upper Valdarno is connected with the Florence basin to the north by narrow valleys that at higher elevation dissect the remnants of large concave valley modelled in bedrock. To the south the connection with the Chiana valley is marked by the occurrence of fluvial terraces. On the contrary, in both Florence and Valdichiana basins alluvial terraces are almost absent and very restricted in size. The Valdichiana basin was probably overfilled during the Late Pleistocene and not affected by headward erosion. It was a swampy area and a series of reclamation works was carried out since the sixteenth century and definitively reclaimed after the nineteenth century with artificial channels and sedimentary traps. Valdichiana is characterized by intensively cultivated gentle hills modelled on Pliocene marine and coastal clays and sands. Along the western slopes (Cetona ridge), these sediments are tilted eastward to generate typical cuestas whereas in the central part of the basin, mostly undeformed, mesas and step-like slopes dominate (Boscato et al. 2008). Again along the western slope (Chianciano Terme, Sarteano, Cetona, etc.) thermal and normal springs formed travertines and calcareous tufa systems of ponds preserved in the form of flat terraces (palaeo-ponds) alternating with steep escarpments in correspondence with palaeo-water falls. Karstic processes locally generated caves containing Pre- and Proto-historic artefacts and bones (i.e. Cetona). The Florence basin has also been overfilled and

Fig. 21.5 The late Middle Pliocene planation surface (*dashed line*) along the Eastern Tuscany Ridge to the north of Mt. Cetona (*photo* M. Coltorti)

apparently only slightly dissected during the Holocene. Flat alluvial fans are found at the foot of the eastern slope. The Arno River cuts deep gorges in the areas between basins, but it enlarges its valley in the Pliocene sediments and generates a large alluvial plain where the thalweg is confined within artificial levees in order to mitigate the hazards and risks. However, these structures did not prevent Florence to be devastated by the 1966 flood.

21.3.2 The Outer Tuscany Ridge: From Mt. Cetona to Mt. Albano

Planation surface remnants are one of the typical landscape of the Outer Tuscany Ridge where they cut coastal Pliocene sands and gravels as well as the bedrock up to *ca*. 730 m a.s.l (i.e. north of Cetona ridge; Fig. 21.5) (Coltorti and Pieruccini 2000; Boscato et al. 2008; Coltorti et al. 2012). It is possible that in some places two planation surfaces merge in a single one or that, after removal of the sedimentary cover, only the older one is preserved. Mt. Cetona (1148 m), the highest peak of the ridge, was an island emerging from the coastal sediments during the Middle Pliocene (Boscato et al. 2008). To the north the planation surface lowers down up to the Chianti Mts. where it is entirely modelled over bedrock. This variation of the mean elevation of the planation surface indicates post-Pliocene deformation during uplift. The planation surface was dissected by V-shaped valleys and gorges but it is well preserved on more resistant limestone terrains while is almost obliterated on sandstones and marls of the Chianti Mts.

21.3.3 The Siena-Radicofani and Valdelsa Basins

The famous hilly Tuscany landscape is mostly modelled on marine and coastal Pliocene sediments where clays and sands dominate the lower part of the succession and sands and gravels are present in the upper part. The southern part of the Siena-Radicofani basin, dominated by clay outcrops, is the Val d'Orcia UNESCO World Heritage Site. The landscape is characterized by gently undulating arable slopes. The most striking features are the badlands, made of "*calanchi*" (Fig. 21.6) and "*biancane*" (Fig. 21.7), both landforms generated by runoff processes and gravitational movements. The calanchi mainly develop as consequence of gully erosion, sometimes on slopes with coarser grained sediments on top of clays. The biancane are dome-shaped features usually less than 20 m high modelled on clays. Their formation has been related to the retreat of the crest of the gullies, and to the accelerated erosion along reticulated systems of fracture (Alexander 1982; Del Monte 2017). The whitish colour is due to salt precipitation, especially during the summer season. The formation of this landscape is related to soil erosion induced by deforestation and overgrazing since pre-historical times. After the Second World War, the abandonment of agriculture and farming induced progressive stabilization of the slopes. The extensive mechanization led to the flattening of most of the rugged topography although today, due to their geotouristic value, some of these badlands are protected.

In the southern part of the basin, an Early Pleistocene residual volcanic neck (896 m), emplaced between 1.3 and 0.9 Ma, crops out at Radicofani. In this sector, along the eastern side of the basin, at the contact with the Cetona ridge, there is a long escarpment that has been associated with a Pliocene extensional fault, probably the best example in the region. Mussel borings have been found along the escarpment (Disperati and Liotta 1998) suggesting its Pliocene activity that, however, did not extend through the Quaternary. The escarpment, and therefore the supposed fault is *ca*. 6 km long. To the north and to the south of the escarpment, Pliocene clays rest unconformably over the pre-Pliocene rocks. Moreover, the basin filling is characterized by progressive unconformities and it is possible that what has been considered a Pliocene fault escarpment might

Fig. 21.6 Badland morphology (calanchi) to the south east of the Siena Basin (Monte Oliveto Maggiore) (*photo* P. Pieruccini)

Fig. 21.7 Badland morphology (biancane) to the south of Siena (Torre a Castello) is dominated by selective erosion of fractured clays and slope wash processes (*photo* P. Pieruccini)

represent the scar of a giant Pliocene gravitational movement. A modern analogue of this feature can be observed on the western side of the same basin where, along the eastern flank of the Amiata volcano, a DGSD more than 6 km long has been described (Coltorti et al. 2010).

To the north of Radicofani, the Pliocene clays at the base of the succession are buried under marine sands and conglomerates generating step-like slopes and bevelled cuestas on which lie many historical villages and towns including Siena and Pienza (Fig. 21.8).

Fig. 21.8 Bevelled cuesta at Pienza, modelled over Middle Pliocene sandstones. The Eastern Tuscany ridge is in the *background* (*photo* P. Pieruccini)

The Valdelsa basin to the north is separated from the Siena-Radicofani basin by a low threshold modelled on continental Miocene sediments. During the Pliocene, the two basins were continuous as indicated by similar stratigraphy and facies. The threshold is located in correspondence of a periclinal deformation of the synform basins since no transverse faults can be identified. To the north, on the eastern side of the Valdelsa basin (San Casciano Val di Pesa) the sediments belonging to a Plio-Pleistocene palaeo-Arno fan delta are interfingered with marine deposits of the Lower Valdarno basin. This interlayering gives rise to mesas and step-like slopes, dominated by large planar or rotational slides.

Travertines and calcareous tufa of late Pleistocene and Holocene age are found along the margins of the basins. Active hydrothermal springs are present at Bagni San Filippo, Bagno Vignone and Rapolano. To the north of Siena along the southern sector of the Valdelsa basin calcareous tufa and travertines form flat surfaces several kilometres wide at different elevations. Travertine ridges along the sides of these basins have been used to infer the presence of active faults (Brogi et al. 2014), although other geological and geomorphological evidence of faulting are missing.

Holocene and Late Pleistocene fluvial terrace staircases have been recognized elsewhere and are usually better preserved close to the confluences. Middle Pleistocene terraces are less preserved.

21.3.4 The Inner Tuscany Ridge and Related Basins

The Inner Tuscany Ridge is wider and more complex than the Outer Tuscany Ridge because it includes shorter minor ridges and basins almost parallel to each other. The relief is deeply incised by the rivers, although remnants of the planation surface are well preserved everywhere. Higher relief exceeding 1000 m is found in the southern sector, to the south of Mt. Amiata, where the planation surface is recognizable only as peaks of equal heights. Mt. Amiata (1738 m) is a shield volcano that experienced activity between 300 and 190 ka with lava flows that filled valleys in an already dissected landscape. To the south of Mt. Amiata the mean elevation drops along an alignment that is transversal to the ridge. This is the Pitigliano area, in the northern flank of the Bolsena volcano, located to the southwest in the Latium Region, that was active during the Middle and the very early Late Pleistocene with a series of ignimbrites, the latter of which dates to the Last Interglacial. To the northwest of Mt. Amiata, along the ridge there are very limited remnants of other effusive lavas at Roccatederighi and Roccastrada, to the east of Siena. In this sector, the mean elevation decreases and remnants of the planation surface are better preserved such as those around the Montagnola Senese, where thick deposits of calcareous tectonic breccias overlie metamorphic rocks. Slightly to the north, on the ridge Pliocene coastal biocalcarenites and conglomerates crop out again unconformably lying on bedrock before it dips under the Mio-Pliocene sediments of the Lower Valdarno basin.

On bedrock made by severely deformed terrains the downcutting of the valleys activated widespread rock slides and rock flows, locally affecting also small towns. The continuity of the ridge is interrupted by a series of basins sometimes interconnected such as the Radicondoli-Chiusdino and Versilia, that split in the eastern long and wide Volterra basin, and a western Val di Fine—Val di Cecina basin filled with Mio-Pliocene continental deposits. The connection of the two latter basins is suggested by the remnant of Pliocene terrains

Fig. 21.9 Stepped morphology at Montespertoli: the steeper slopes are modelled in Early Pleistocene sands while the gentle slopes truncate interlayered clays. Rotational slides and rock flows also affect the slopes (*photo* M. Coltorti)

in the small Sassa and Serrazzano basins (Riforgiato et al. 2005). To the southwest Mio-Pliocene terrains are preserved in the Grosseto basin, close to the coastline and in the Middle Ombrone and Albegna basins slightly to the east. An abrupt contact with the pre-Miocene bedrock usually corresponds to tilted unconformities although we cannot exclude the presence of palaeo-valleys filled with continental deposits.

The morphology of the basins is strongly influenced by the intensity of the river downcutting. Large valleys are found in the larger basins especially where clay formations crop out. These basins are the site of intense gully erosion, badland formation with widespread earth and mud flows, as well as large rock flows and rock slides on the consolidated terrains. In correspondence with alternations of sands/sandstones and clay/marls in Miocene and Plio-Pleistocene terrains step-like slopes (Fig. 21.9), mesas and sometimes cuestas were formed. One of the best examples is the famous Volterra “balze” (cliff) modelled on sandstones overlying clays deeply affected by badland formation.

In limestones, karstic processes have led to the origin of wide depressions aligned NW–SE along the eastern side of the Montagnola Senese ridge but also to the west near the town of Massa Marittima. These depressions originally hosted springs and were later filled with palustrine and fluvial sediments and incorporated within the drainage network. A contemporary example is the Accesa Lake, to the southwest of Massa Marittima (Fig. 21.1), hosting a Late Pleistocene–Holocene record of climatic and vegetation changes including human impact (Magny et al. 2007). Locally thick deposits of travertines and calcareous tufa originated from these old springs, whilst locally they are still forming today (i.e. Saturnia). Calcareous tufa almost on top of the local relief (i.e. Massa Marittima) suggests that karstic springs were an important component of landscape evolution since the beginning of the uplift. To the southwest of Rosia, marine Pliocene sands fill a doline indicating that locally these features have been inherited from Pliocene karstic processes.

21.4 Conclusions

The landforms of western Tuscany reflect an interaction between regional uplift and valley downcutting. A planation surface interpreted as a plain of marine erosion was modelled over the entire sector and was later uplifted. The planated coastal sediments allow to establish a mean uplift rate of *ca*. 0.2 mm/year (*ca*. 700 m in *ca*. 3.5 Ma). The uplift was not perfectly uniform and mild deformations have been observed. The uplifted area is bordered to the east by an important fault system (Florence basin—Valdarno—Val di Chiana), the footwall of which was even more uplifted. However, to the west of this alignment, there are no horst and grabens but synform basins alternating with antiform ridges that were generated by large-scale Pliocene tectonic deformation. A buried palaeo-landscape dominated by karstic and fluvial landforms has been recognized in places. Extensional tectonics did not play a role in the evolution of the present day landscape that is mainly the result of river downcutting and gravitational processes that were more intense in softer Mio-Plio-Pleistocene sediments. Along the western side of Mt. Cetona erosion re-exhumed what has been considered one of the few high-angle extensional Pliocene faults. To the north and south of this 6 km long fault-generated escarpment an onlap of Pliocene sediments has been observed. We suggest that this evidence could be associated with large-scale Pliocene gravitational phenomena.

Exhumation processes almost erased the evidence of the planation surface across the top of the Pliocene deposits inside the basins although it is still locally recognizable. It is very well preserved on top of the ridges, especially on the more conservative limestone terrains, and it represents one of the largest relict landscapes in the Italian peninsula. During the deepening phase of the drainage network the most photographed and famous features of the Tuscany landscape such as the cuestas, mesas and badlands on clay and marly terrains were modelled.

The area hosts many National Parks and Protected areas where several geomorphological features can be observed and a large number of geosites has been identified. The above-mentioned "*calanchi*" and "*biancane*" are well exposed in the protected areas of Lucciola Bella and Camposodo/Leonina in the Orcia Valley. From these areas, it is also possible to have splendid views of Radicofani volcanic neck, Mt. Amiata volcano as well as the planation surface that affected the Inner and Outer Tuscan Ridge. A nice location where to walk across the almost unspoiled valleys and gorges that cut the Inner Tuscany Ridge is the Upper Merse Natural Reserve. The Natural Park of Mt. Amiata allows to visit across more or less dissected lava flows and DGSDs that have been recognized along its eastern flank. To the west of the Accesa Lake, in the Natural Park of Gavorrano, is one of the best preserved karst spring in the region.

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Landscapes and Landforms of the Duchy of Urbino in Italian Renaissance Paintings

22

Olivia Nesci and Rosetta Borchia

Abstract

The territory of the Duchy of Urbino (Adriatic Central Italy) is characterized by the presence of a natural heritage that is associated with attractive vistas and exclusive scientific, historical, archaeological and architectural assets. The great Renaissance artists who used to travel across these areas were aware of this. Among them, Piero della Francesca, Raphael and Leonardo were particularly fascinated by these landscapes and reproduced them in their most celebrated works of art. Both the Dyptic of the Dukes by Piero della Francesca and Gioconda by Leonardo bear the land of the Duchy in their background. Alluvial plains, lakes and landslides are the geomorphic features that can be best recognized in those landscapes.

Keywords

Cultural geomorphology • Renaissance art • Duchy of Urbino • Montefeltro

22.1 Introduction

Until recently, the landscape backgrounds of Italian paintings from the Renaissance have been generally assumed to be vivid but generalized creations of the painters' imagination, although some art historians have guessed that they were representative of a number of locations. Our work demonstrates that for several Renaissance painters these landscapes were actually realistic portrayals of vistas of the past. Previously, no one superimposed those panoramas on the present-day landscapes. Recent studies (Borchia and Nesci 2012a, b) have documented that the landscapes seen in the backgrounds of the most famous paintings of the Italian Renaissance, e.g. the Diptych of the Dukes of Urbino by Piero della Francesca and La Gioconda by Leonardo da Vinci, are real and belonged to the territories of the former Duchy of Urbino (Central Italy, Fig. 22.1). As these artists can be regarded as real "photographers" of the landscapes they saw, and because their paintings are the sole testament to the past morphology of these territories, this kind of research is relevant to both art historians and geologists. A careful examination of the painted landscape backgrounds of the Renaissance is of great importance to the study of the changes that occur in a territory.

Our focus is on an area formerly known as the Duchy of Urbino, which historically includes parts of the Marche, Romagna, Tuscany and Umbria regions (Fig. 22.1). These territories consist of a remarkable variety of landscapes and are fascinating because of both its intrinsic beauty and breathtaking geomorphodiversity (*sensu* Panizza 2009). Indeed, we are not surprised that these scenes kindled the sensitivities of the artists who once travelled across this land, especially during the Renaissance.

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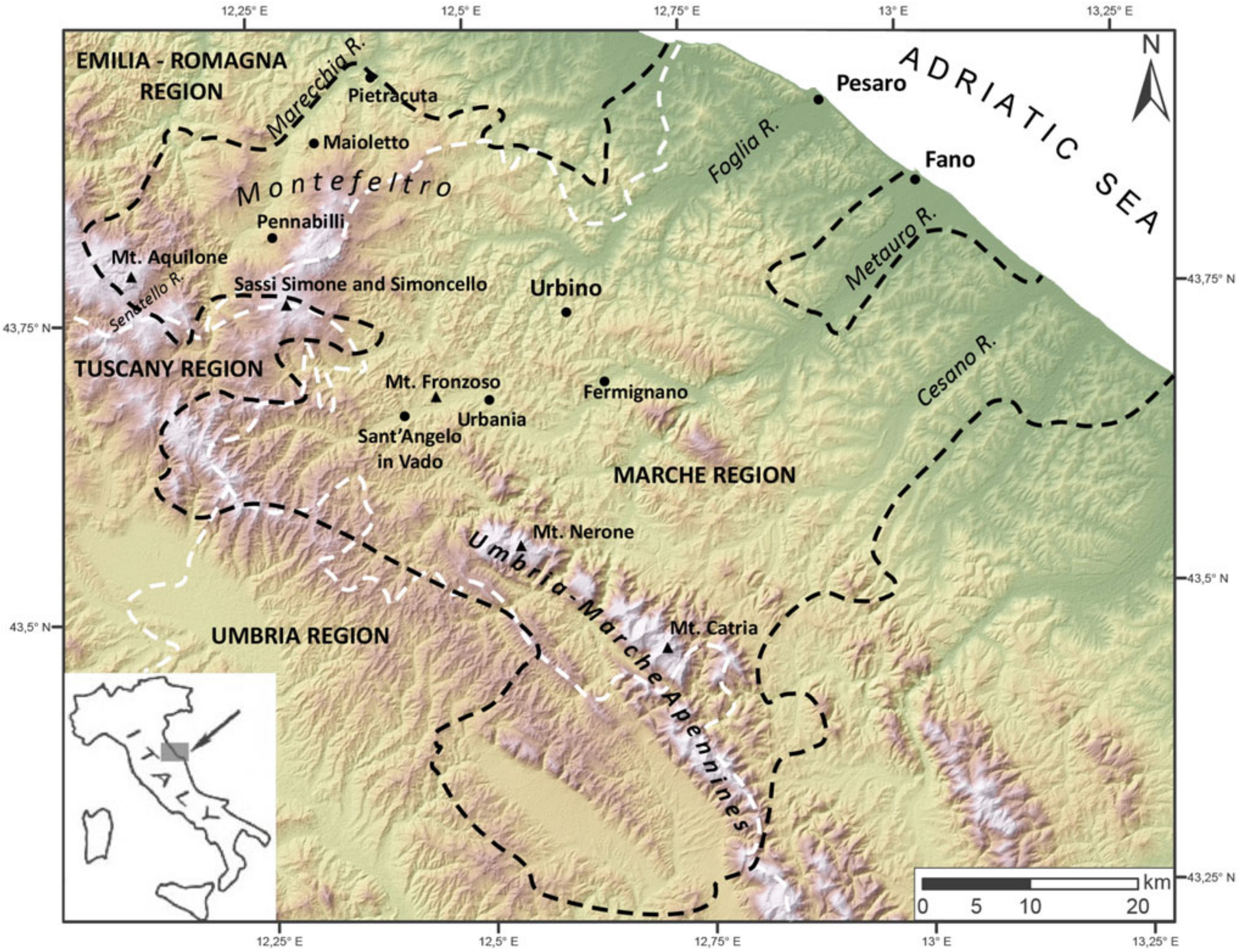

Fig. 22.1 Location map of the Adriatic Central Italy. The *black dashed line* indicates the extension of the ancient Dukedom of Urbino. The *white dashed line* refers to the present regional boundaries

22.2 Geological and Geomorphological Setting

The geological and geomorphological setting of this section of the Apennines has left a unique mark on the landscape due to the variability of its rocks and geological structures. The geological record indicates environments from deep marine to continental. The Umbrian-Marchean succession is an uninterrupted series of strata recording a nearly continuous time interval from the Late Triassic to the Pleistocene (Passeri 1994). The territory began to resemble its modern geomorphological structure during the second half of the Miocene (about 13 to 5 million years ago) when the Apennine ridge took shape and the entire area began to emerge (Mayer et al. 2003). The uplift and emergence of the region took place with a shift from the southwest to the northeast, in the direction of the Adriatic Sea, through an intense corrugation of the earth's crust characterized by the formation of a broad fold and thrust belt. Tectonic deformation was more intense in the inland areas, where it caused greater uplift and, as a consequence, a more accentuated relief of the valleys, as well as the moulding of mountain landscapes that are at times rugged and bare (Fig. 22.2a). A gentler deformation, less abrupt rise in the eastern valleys and along the coast, and less resistant rocks have contributed to the origin of a soft hilly landscape up to the sea, save for small local ridges (Mayer et al. 2003).

Most of the western territory (upper valleys of the Metauro, Foglia and Marecchia rivers) shows a monotonous sequence of marly-arenaceous strata dating back to the Miocene (Passeri 1994) that forms a landscape characterized by cuestas, hogbacks and flatirons. The Umbria-Marche Apennines are bounded to the north by the Valmarecchia Sheet, which is embedded in lower Pliocene clays, thus

Fig. 22.2 The most representative geomorphological landscapes in the study area. The Mt. Catria–Mt. Nerone anticline ridge (**a**), Sassi Simone and Simoncello (**b**), Upper Pleistocene terraced alluvial plain of the Metauro River valley (**c**)

dating the Sheet emplacement. The Sheet is formed by Ligurian Units overlain by Epi-Ligurian ones (Perrone et al. 2014). The sharp lithological and erodibility contrast between the Ligurian substrate, which is mostly clayey, and the more rigid Epi-Ligurian "rafts" has contributed to the formation of a unique landscape in the Apennines. The present vista of Montefeltro is the result of this geological and geomorphic evolution that lasted for about 12 million years. Larger relief zones that experienced both great climatic and tectonic forces shattered into smaller pieces, and landslides reduced their relief. Only a few vestiges of the primary morphology are left in the form of blocks, spires and towers that can be seen here and there among the clay slopes. The shape of several single cliffs depends on the orientation of the strata, as can be observed in the Sassi Simone and Simoncello Natural Park (Fig. 22.2b). The present geomorphic arrangement, that is the existence of broad fluvial valleys sloping gently down from the Apennine watershed to the Adriatic Sea, was initiated quite recently, about 700,000 years ago, during the Middle Pleistocene, when the area experienced the effects of global climate changes (Guerra and Nesci 1999). The landscape was thus moulded by erosion and accumulation processes, as glacial periods alternated with subtropical climates. In particular, erosion at higher elevations and the accumulation of debris on the valley floors peaked during the cold ages, when the physical process of rock degradation was more intense and the rocks themselves were covered with scarce or no vegetation. It was during these periods that broad alluvial plains took shape, which now occur in strips alongside riverbeds; these are alluvial terraces and a record of the power of widespread fluvial sedimentation (Fig. 22.2c).

Warm and cold periods also followed on from one another in the Holocene, although they were not as long and intense as the previous Pleistocene events. Nevertheless, they have also left a mark on the landscape, slopes and fluvial plains in the form of remarkable geomorphological features and processes such as erosive escarpments, fluvial floods, major landslides and badlands (Nesci et al. 2012).

The Little Ice Age (LIA) began in the 1500s, and was marked in the northern hemisphere by colder temperatures and abundant heavy rainfall, which lasted through most of the nineteenth century (Mann 2002). In the Northern Apennines, and in particular in the Romagna-Marche region, there were many phases of climatic deterioration and consequent hydrogeological instability. It is difficult to establish to what extent human beings might have been responsible for the changes in the landscape in comparison with climatic effects. Since Roman times there has been clear evidence that riverbeds were modified, diverted and dammed to produce water reservoirs and mechanical energy, as well as to create fords and for agricultural purposes. Deforestation itself may have been partly caused by human factors as, especially during the cold periods, it was common practice to regularly cut down trees for firewood (Surian et al. 2009).

22.3 Landscapes and Landforms in Paintings

The project "The Invisible Landscape: The Real Landscapes of Piero della Francesca" was born in October 2007 with the recognition of the landscape as a backdrop to the portrait of Federico da Montefeltro in the famous Diptych of the Dukes of Urbino by Piero della Francesca (Borchia and Nesci 2012a). The methodology used for the detection and reconstruction of landscapes is the image analysis process that works on both the picture and the present landscape. Thanks to software graphics, it was possible to accurately investigate every aspect of the area, enabling differences in colour and morphology and the focus of the details of the paintings to be brought out. As a result, landforms and topographic profiles that in some cases even overlap have been identified, highlighting any subsequent changes over the centuries.

Digital elevation models were used to visualize landforms from various altitudes and angles. The geomorphological analysis was useful for understanding the evolution of the landscape and explaining the present-day absence of particular elements that were present in the painting (e.g. lakes, landslides). Slope and river erosion processes were considered, because they may have significantly altered the landscape, particularly extreme formative events which often led to sudden changes (Persi et al. 1993).

22.3.1 The Diptych of the Dukes of Urbino

The dual portrait of the Dukes of Urbino (Piero della Francesca, Galleria degli Uffizi, Florence, Italy) which was painted in oil (47 × 33 cm) in about 1465, is regarded as an absolute masterpiece of Piero's maturity in the Court of Urbino. The diptych is painted on both the front and back: on the front, Duchess Battista Sforza (Fig. 22.3a) and Duke Federico da Montefeltro (Fig. 22.3b) are portrayed in half-length and seen in profile, one opposite the other, whereas on the back the two characters are sitting on triumphal chariots and seem to be moving towards one another.

There is general agreement among scholars that geographical regions, but not precise locations, can be recognized in the backgrounds of Piero's paintings. These vistas have been identified as being anything from a generic view of the domains of Federico da Montefeltro to the Metauro valley, while other authors have recognized different locations (Brizzi 1991 and references therein).

The first morphological element that we recognized in the diptych was the small hill located in the background of the painting in which Federico da Montefeltro is portrayed (Fig. 22.4). This is Mt. Fronzoso, a small pyramid-shaped hill marking the boundaries of the Metauro alluvial plain between Urbania and Sant'Angelo in Vado (Fig. 22.1). In today's landscape, the elements with the same patterns as in the painting correspond to the woody mantle, the growth of which is favoured by the presence of a calcareous-marly

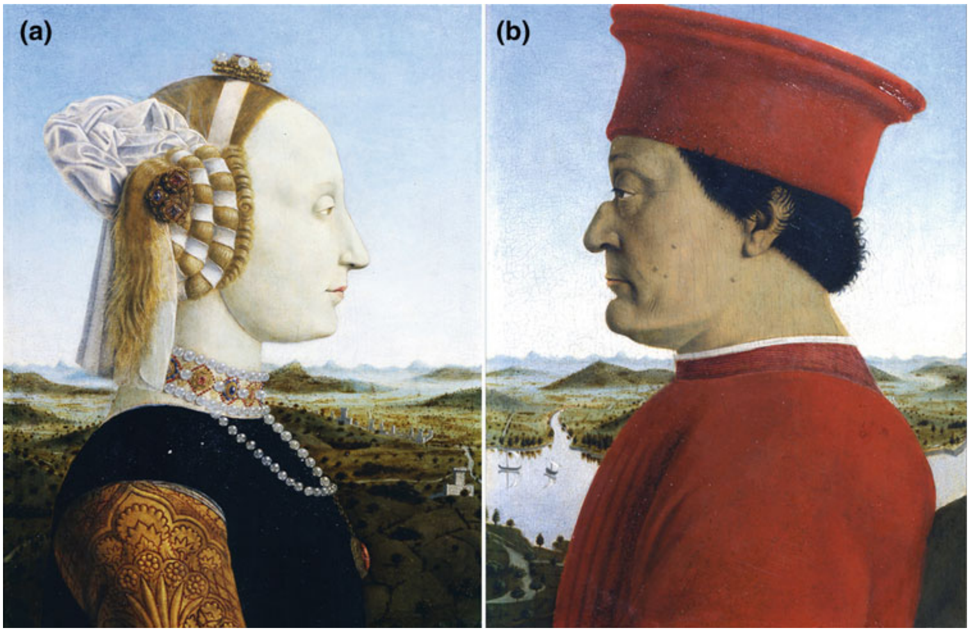

Fig. 22.3 Piero della Francesca (1415/20–1492): Portrait of the Dukes of Urbino. Florence, Uffizi Gallery. © 2015. Photo Scala, Florence—concession Italian Ministry of Heritage and Culture

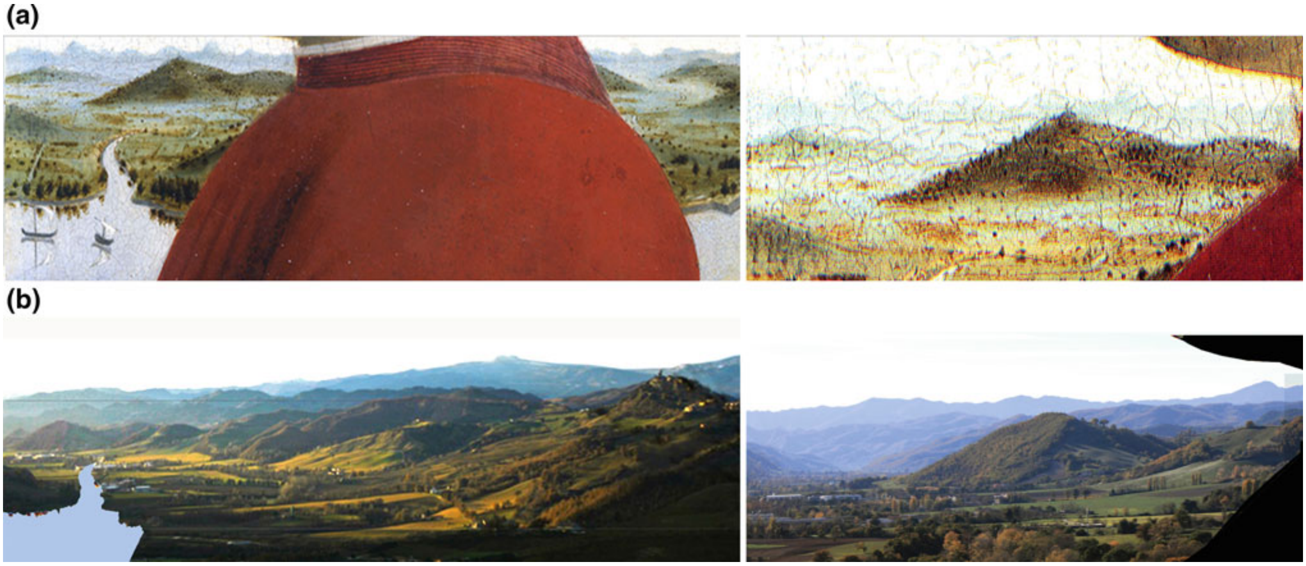

Fig. 22.4 The Diptych of the Dukes. Comparison of the landscape behind the profile of the Duke (**a**) with the present landscape of the middle valley of the Metauro River (**b**). The lake is no longer present, but is included to aid understanding. On the *right*, the detail of Mt. Fronzoso

substrate, and the meadows where we can find more marly rock units that do not enable arboreal plants to take root, respectively (Fig. 22.4). The granular texture and dark colours on the side next to the river are quite different from the light hues of the opposite slope. All of the details of the painting have been recognized (cf. Borchia and Nesci 2012a). The only apparently incongruous natural element in the landscape in the Duke's portrait is the wide meandering river that flows into a broad lake basin that is clearly visible in the foreground. However, the lake has been replaced by a broad alluvial plain. The paleolake formed because of a weir that the Duke himself ordered to be built at the Riscatto Bridge near Urbania (Fig. 22.5a). Some reliable reconstructions of the historical built-up area of Urbania have been found, in which the traces of the weir can be observed (Fig. 22.5b). Local folklore has widely confirmed the

Fig. 22.5 The town of Urbania with the Riscatto Bridge in a drawing by Mingucci (1626) (**a**). In detail (**b**), the groove present in the bridge arches, indicative of the presence of a structure that closed the bridge, is highlighted. The current bridge and the Ducal Palace behind it (**c**). © [2015] Biblioteca Apostolica Vaticana

existence of this hydraulic device that allowed the Duke to come by boat to his game reserve known as “Il Barco”. Relying on morphostratigraphy and topography, we have tried to prove the possible existence of a kind of river-lake by means of a detailed geomorphological survey and a thorough examination of the stratigraphy resulting from drilling (Borchia and Nesci 2012a). This allowed us to be certain that the location of the lake, even if it was not directly surveyed due to the lack of surface water, might be reasonably compatible with the heights of the countryside from 500 years ago. Due to the LIA, the entire area underwent intense colluviation originating from both the slopes and widespread sedimentation in the minor watercourses. Disastrous floods, which are widely described in many historical papers (Persi et al. 1993), may have compelled the Duke’s engineers to open the weir to prevent a dangerous overflow. Coinciding with this, the river recovered its erosive power and formed the remarkable incision of the river channel that is still visible today. Curiously, 40 years later, the same landscape was depicted in a painting by Raphael (Small Cowper Madonna, National Gallery of Art of Washington). The pictorial technique in this work is, of course, different, and yet we are able to recognize the same details, such as the lake basin, the convent and Mt. Fronzoso (Borchia and Nesci 2012a).

The landscape in the background of the pictures with the Dukes on their triumphal chariots (Fig. 22.6a) has its actual counterpart in the large plain where the Metauro River flows

Fig. 22.6 The Triumphs of the Diptych of the Dukes (**a**). The broad plain of River Metauro identified as the background of the painting (**b**). Comparison of the hills of San Lorenzo and Farneta (**c**) and San Pietro (**d**) with the landscapes on the painting

(Fig. 22.6b). This is a broad valley with a lake at its centre where we can see some sailing boats and a small island. Piero della Francesca reproduced both the outlines and the details with great accuracy in his Triumphs to such an extent that it is quite easy to detect almost all of the elements of the landscape. The valley in the Triumphs is the wide plain crossed by the Metauro River between Urbania and Fermignano (Fig. 22.1). The hill in the foreground (Fig. 22.6c) corresponds to San Lorenzo, whereas the third hill is the Farneta, which is slightly visible behind the Duchess. The hill on the left, behind the Duke’s chariot is San Pietro (Fig. 22.6d). There is also an element in the Triumphs that we can no longer identify, namely the lake in the middle and the small island within it. It is, however, much easier to understand and explain how the lake formed in this section of the plain. The slopes along this part of the valley are remarkably lower than those of the former valley, while the valley floor itself reveals the old morphology in some of its parts. A digital model of the ground highlights the hollow areas as well as the disclosed stretch, which is the dry land at the centre of the lake (see Fig. 23 in Borchia and Nesci 2012a). On the left side, the lake depression is buried beneath the conspicuous colluviation that occurred due to cooling climate of the next century.

Another landscape, seen in the background of the portrait of Battista Sforza (Fig. 22.7), is located in the middle of

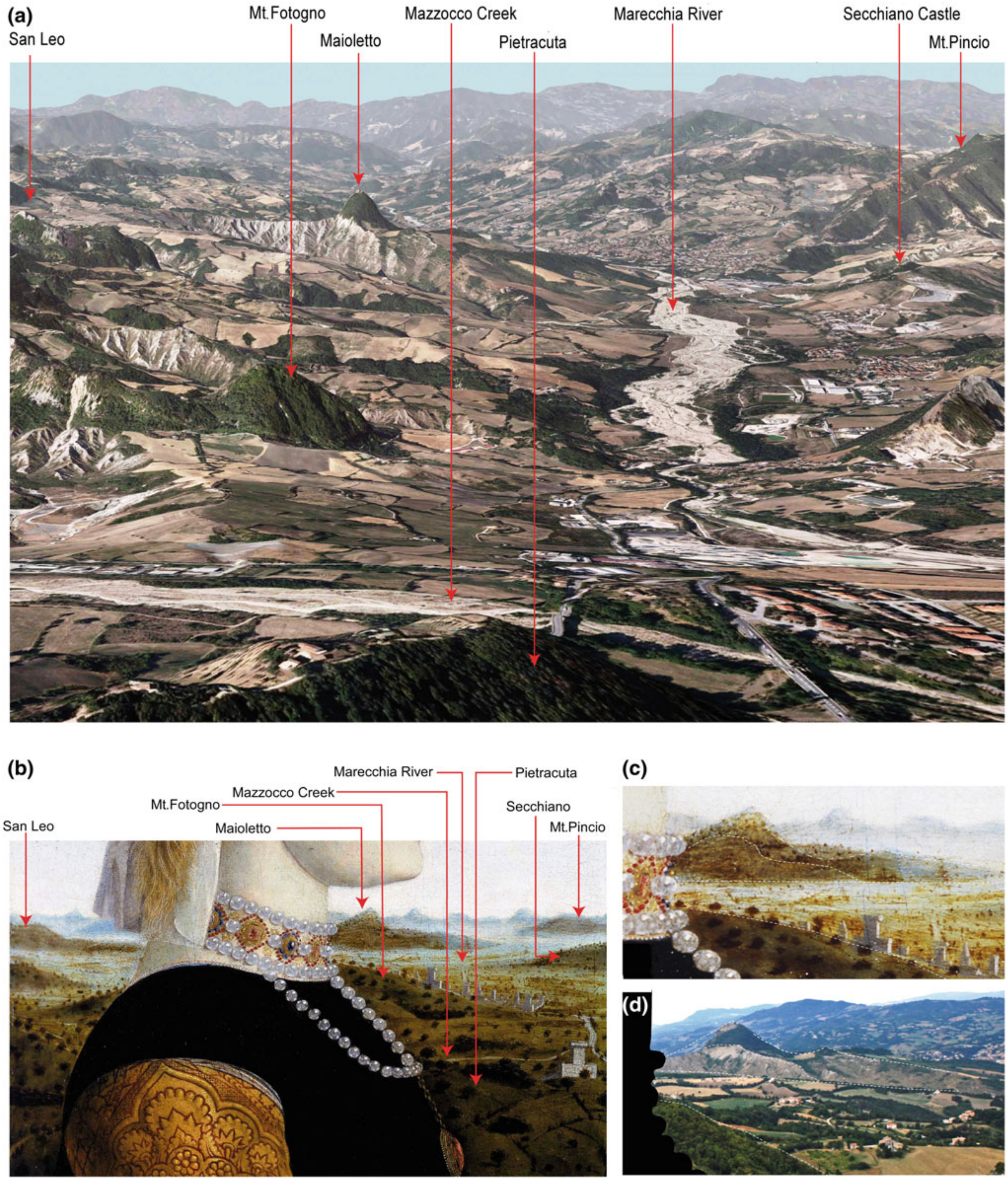

Fig. 22.7 Comparison of the mid Marecchia River valley (**a**) with the backdrop of the portrait of Battista Sforza (**b**). Particulars of relief located under the chin of the Duchess (**c**) and the comparison with the Rocca di Maioletto (**d**)

Valmarecchia, and the rugged hill is the cliff of Maioletto with the vestiges of the homonymous castle. The viewpoint from which Piero della Francesca painted the entire territory is located on the cliff of Pietracuta (Fig. 22.1); the perspective is a bird's-eye view, which is a very useful pictorial tool with which to take in the complete landscape (Fig. 22.7a). This kind of viewpoint flattens the scenery, but many landforms are still easily recognizable. The small asymmetric hill that is visible under the chin of Duchess Battista Sforza appears to be modified. The cliff of Maioletto has been devastated by several landslides since ancient times, the most ruinous of which occurred on 29th May 1700 and forced the locals to abandon once and for all the castle of Maioletto that had been built at the top of the cliff. The ruins of the ancient walls, along with some fragments of brick, are still witnessing the existence of this thriving medieval castle. It seems that this major landslide may have been due to severe climate conditions, since it took place between 1690 and 1700 during the acme of the LIA. Long and extremely cold winters were followed by rainy middle seasons and very short summers with frequent downpours. On 28th May 1700 a violent deluge hit Maiolo, and it rained non-stop for 40 h (cf. Persi et al. 1993). On the night of the 29th, while it was still raining, a large rock fall moved down the valley, causing a portion of the developed area to crumble away (Nesci et al. 2005). It is significant that Piero della Francesca did not paint the badlands; indeed, there are no patterns demonstrating these peculiar forms of erosion. This can be explained by the fact that badland morphogenesis is often associated with intense rainfall events, and changes in land use occurred later, around the second half of the nineteenth century (cf. Torri et al. 2000). Piero della Francesca thus lived when the badlands had probably not yet developed.

22.3.2 La Gioconda

La Gioconda (Leonardo da Vinci, Louvre, Paris, France) is the most famous painting in the world and is also known as the Mona Lisa. We could not ignore a landscape that was so similar, and suggest that the background vistas of the painting encompass the entire Duchy of Urbino seen from the heights of Valmarecchia (Borchia and Nesci 2012b). In order to allow complete visibility, the landscape was represented from a bird's-eye view and from a considerable altitude of more than 1000 m. The portrait of the Gioconda interrupts, but does not conceal, any part of the landscape. The details of the landscape in the painting have an exact spatial location and therefore a precise counterpart in the actual physical landscape (Fig. 22.8).

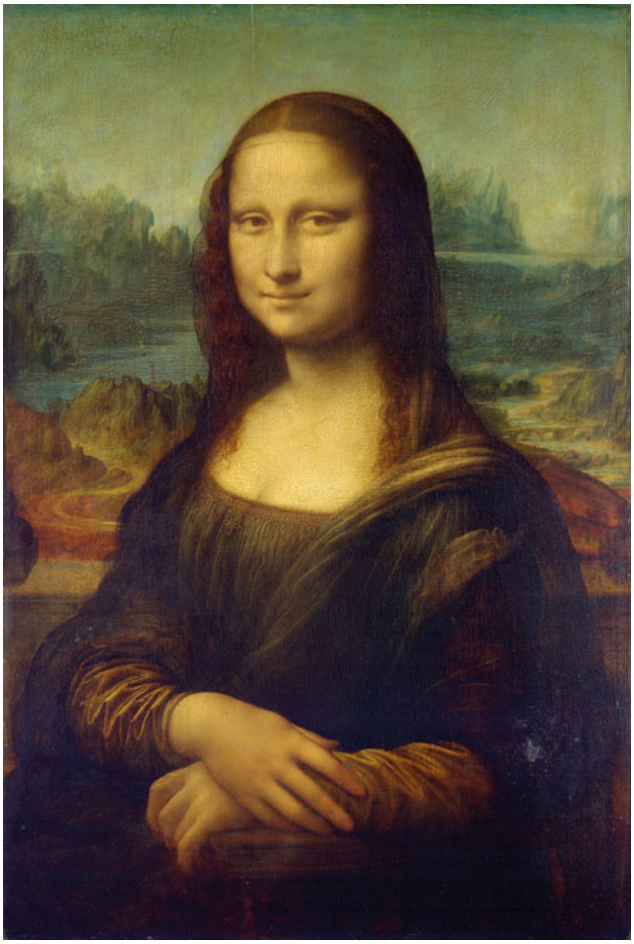

Fig. 22.8 Leonardo da Vinci (1452–1519): La Gioconda, 1503-6. Paris, Louvre. Oil on poplar board, cm 77 × 53. © 2015 Photo Scala, Florence

It is important to be familiar with two key expressions to fully understand the complexity of Leonardo's landscape: an aerial bifocal perspective and compression (cf. Borchia and Nesci 2012b). These methods of mapping are accurate rules that Leonardo himself documented and published in his "Treatise on Painting", which is also known as the "Urbino Code". The first detected landscape is at the bottom right of the woman in the picture (Fig. 22.9). The comparison of the painted cliff with the real landscape is immediate and easily recognizable and both natural and human elements have been identified within this part of the landscape. The only aspect that can no longer be found is the famous bridge with at least four arches that rest on large boulders (Fig. 22.9a). This part of the valley is, at its narrowest point, an ideal spot to build a bridge or a road, and is characterized by the presence of a floodplain with large calcareous boulders which rolled down from the overlying periglacial pediment.

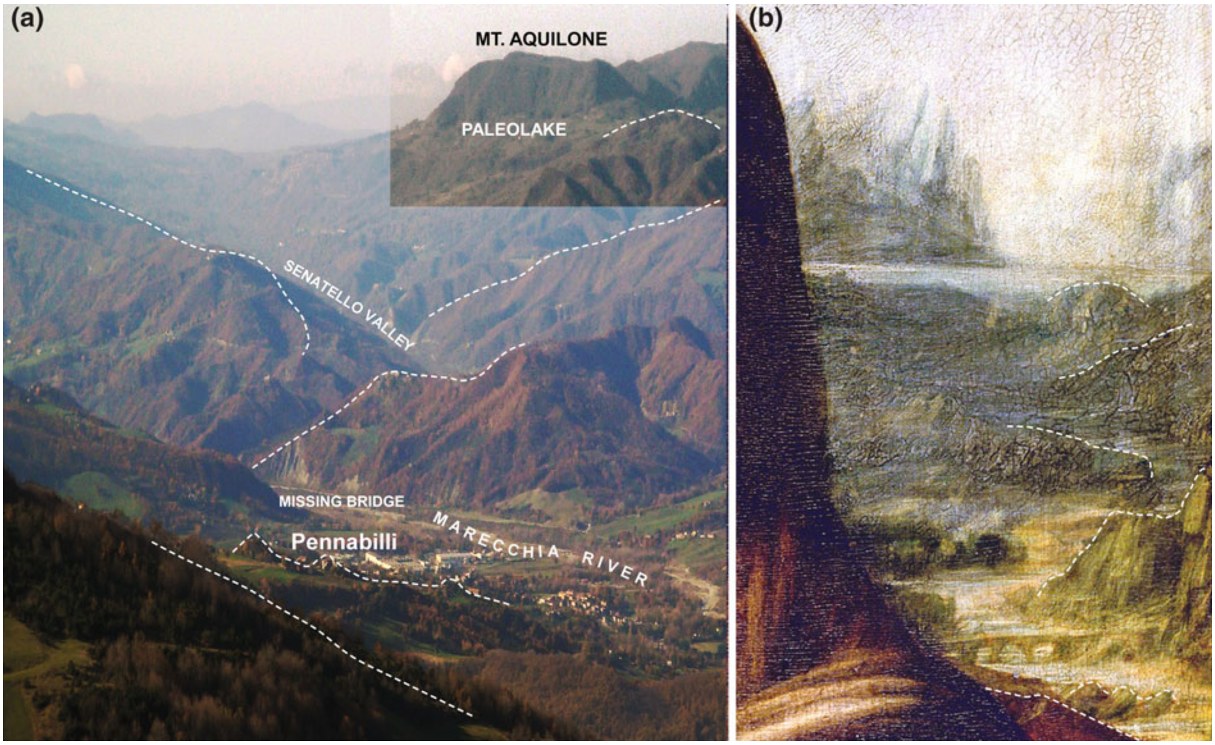

Fig. 22.9 The landscape identified in the high Valmarecchia (**a**) compared with the right side of La Gioconda (**b**). The *dashed white lines* help us to understand the accuracy of the profiles

Beyond the visual correspondences, further evidence comes from a study of the ancient roads conducted by Sacco (2012), which has shown that a road crossed the river at that point. There are many historical documents suggesting the presence of numerous bridges over the Marecchia River that were later destroyed by floods (Persi et al. 1993). The rugged relief that appears in the background of the painting has been recognized as Mt. Aquilone (Fig. 22.9a). Leonardo painted a large lake, lapping the reliefs. The presence of lakes and ponds has been known about since historical times (Gambi 1948), and the place names indicate the presence of water everywhere. The morphology of the site, however, does not exclude the presence, in the past, of a natural reservoir of larger dimensions, which is unfortunately not chronologically identified. At the base of the relief, there is actually a great depression that was probably created by major gravitational deformations that have produced counter-slopes upon which water run-off and the numerous sources could collect. These processes may have formed the great lake that Leonardo painted at the base of Mt. Aquilone. The subsequent mobilization of landslides could have drained the lake and determined its final infilling, leaving only a few small depressions. The recognition of some locations in the painting was helped by some of Leonardo's drawings. In one drawing (Fig. 22.10) he emphasized both the flatirons that are typical landforms in a landscape with stratified rocks, such as the Umbrian-Marchean Ridge, and the allochthonous Valmarecchia Sheet.

We recognized other landscapes thanks to numerous old prints (Fig. 22.11). The two cliffs, named Sassi Simone and Simoncello (Figs. 22.2 and 22.11a), are part of a popular resort in Montefeltro, and now belong to a famous nature reserve that is also an important geological site in the Marche region. There are plenty of maps and drawings of this area because Cosimo de' Medici founded a new town on the flat top of Sasso Simone, which he named Town of the Sun. This survived for only a century, and was abandoned because of harsh conditions during the LIA (Allegretti 1992). We see a remarkable resemblance between the sets of fractures in the crest of Sasso Simoncello shown in Fig. 22.11b, c.

In parallel with our research, an Italian historian, Zapperi (2010), has demonstrated that the painting does not represent Lisa Gherardini, the wife of Francesco del Giocondo, a merchant of Florence. Instead, it would depict Pacifica

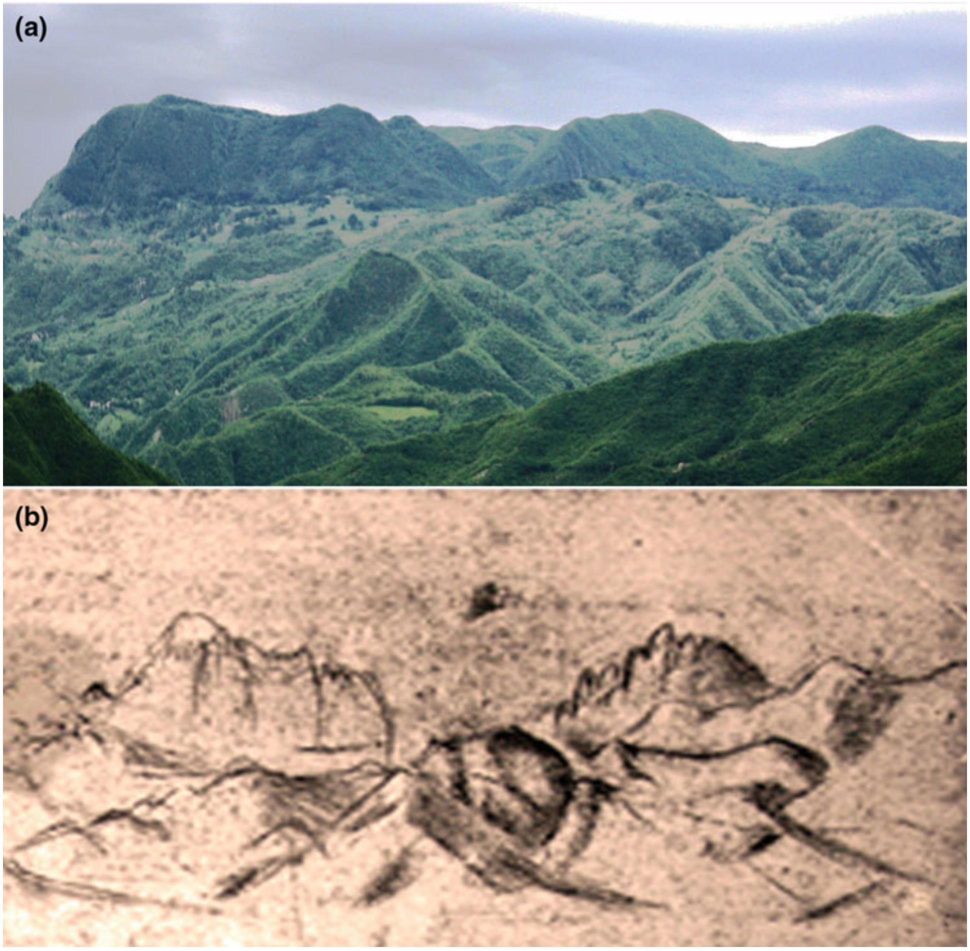

Fig. 22.10 Mt. Aquilone present landscape (**a**) compared with Leonardo's drawing (**b**) (Mountain Range RL 12414. Windsor, Royal Borough Museum Collection. © 2015. DeAgostini Picture Library/Scala, Firenze)

Brandani from Urbino, who was the lover of Giuliano de' Medici and the mother of his only male child. This supports the hypothesis that the landscape has a close relationship with the portrait in the foreground (Perrig 1980).

22.4 Geomorphology and Geoheritage

The landscapes that form the backdrop to Renaissance paintings are real places that identify with the characters portrayed in the foreground. Aromatico (2012), in his interesting essay on the Flagellation by Piero della Francesca, argues that painters could not always express their creativity, especially in portraiture where they were submissive to the will of their clients, who often decided what to include in a painting. Piero had Duke Federico da Montefeltro as a client, and he designed the work that the artist produced as a good "labourer". Taken together, the three landscapes of the Diptych constitute the entire territory of the Duchy of Urbino (Fig. 22.1). In this way, the Duke wanted to immortalize his domain and good governance. In the case of the Gioconda, the landscapes would be the homeland of Pacifica Brandani and her son Ippolito, combined with the Tuscan territories of her lover, Giuliano de' Medici, the boy's father (Zapperi 2010). It is fascinating that the historical memory of our land can be better understood through a new visual approach to the most famous Renaissance works of art. Indeed, many art scholars have followed this kind of research for over 500 years, but it is now possible to approach the problem using modern scientific methods that can undoubtedly support and enrich traditional investigations. The Duchy of Urbino area, which is world famous for its natural landscapes of great beauty and charm and its particular geological evolution, not only becomes a new horizon of knowledge as “landscape art”, but an unexpected cultural resource to share, transmit and promote. The goal is to create an open-air museum with viewpoints that will lead the visitor through the extraordinary experience of being part of a work of art.

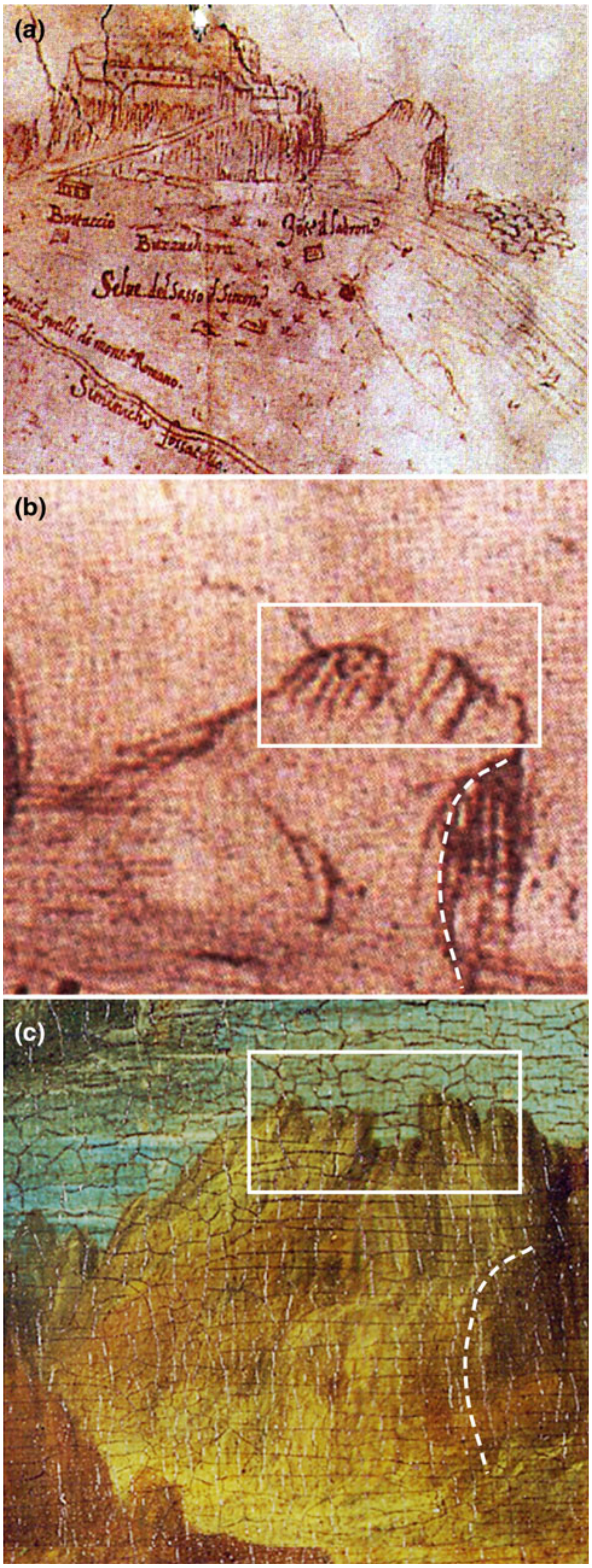

Fig. 22.11 Ideographic drawing of Sasso Simoncello in the late sixteenth century, Carpegna, municipal archives (**a**). Detail of Sasso Simoncello (**b**) compared with that of the Gioconda (**c**). The *white dashed lines* show similar morphological features

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Rocky Cliffs Joining Velvet Beaches: The Northern Marche Coast

23

Daniele Savelli, Francesco Troiani, Paolo Cavitolo, and Olivia Nesci

Abstract

The northern Marche coastal area epitomizes many of the elements forming the rich natural, historical and cultural tissue of the Adriatic seaside of central Italy. The natural heritage, partly protected in natural reserves, also amalgamates with tourist facilities that exploit several renowned beach resorts. The northern Marche coastal area, consisting of a coastal plain interposed between two rocky shore sectors, forms a peculiar blend of different geomorphological units with distinctive landforms. The coastal plain joins landwards fossil cliffs and includes the major river mouths. The rapidly recessing rocky shores develop structural landforms, sea-stacks and benches. Both active and relict cliff retreat induces extensive landsliding in the whole sea-facing hillslopes.

Keywords

Coastal geomorphology • Rocky cliffs • Beaches • Northern Marche

23.1 Introduction

The central Adriatic Sea joins the forehills of the Apennines along a roughly rectilinear coast (Fig. 23.1) where rocky cliffs alternate with famed beaches. This side of the Apennines is internationally acknowledged for its remarkable geological heritage embracing several classical localities where, since the nineteenth century, influential geological and geomorphological researches have been accomplished. Here, in long celebrated sceneries of gentle hills and valley flats joining crags and stunning gorges, praised by poets and Renaissance painters, the physical landscape merges with an extraordinary heritage of Roman vestiges, ancient towns, castles and abbeys. Thus, besides being a renowned place for summer tourism, the coastal area is also a major historical and cultural attraction. It is also well known as an eminent place for nature-based tourism in the development of which the local geological-geomorphological heritage plays a pivotal role. Furthermore, accessible geo-paleontological sites on the sea-cliffs complement peculiar costal landforms, making this area a must for Earth scientists and scholars (Passeri 1995; Ciarapica and Passeri 2001).

23.2 Geographical Setting

The northern Marche coast (Fig. 23.1) strikes NW–SE for about 100 km, between the seaside towns of Gabicce (NW) and Sirolo (SE). The whole coastal area belongs to the Marche Region, provinces of Pesaro-Urbino and Ancona. The coastal zone as a whole displays rounded hills declining towards the northeast. Except for Mt. Conero (572 m a.s.l.), summit elevations do not exceed 200 m close to the coastline and 500 m a little more inland. The coast consists of about 60 km of sandy-gravel beaches which at both ends join rocky shores that then extend roughly 15 km to the northwest (Mt. San Bartolo sector) and 25 km to the southeast (Mt. Conero sector). The first sector culminates with Mt. San Bartolo (221 m) and follows an overall

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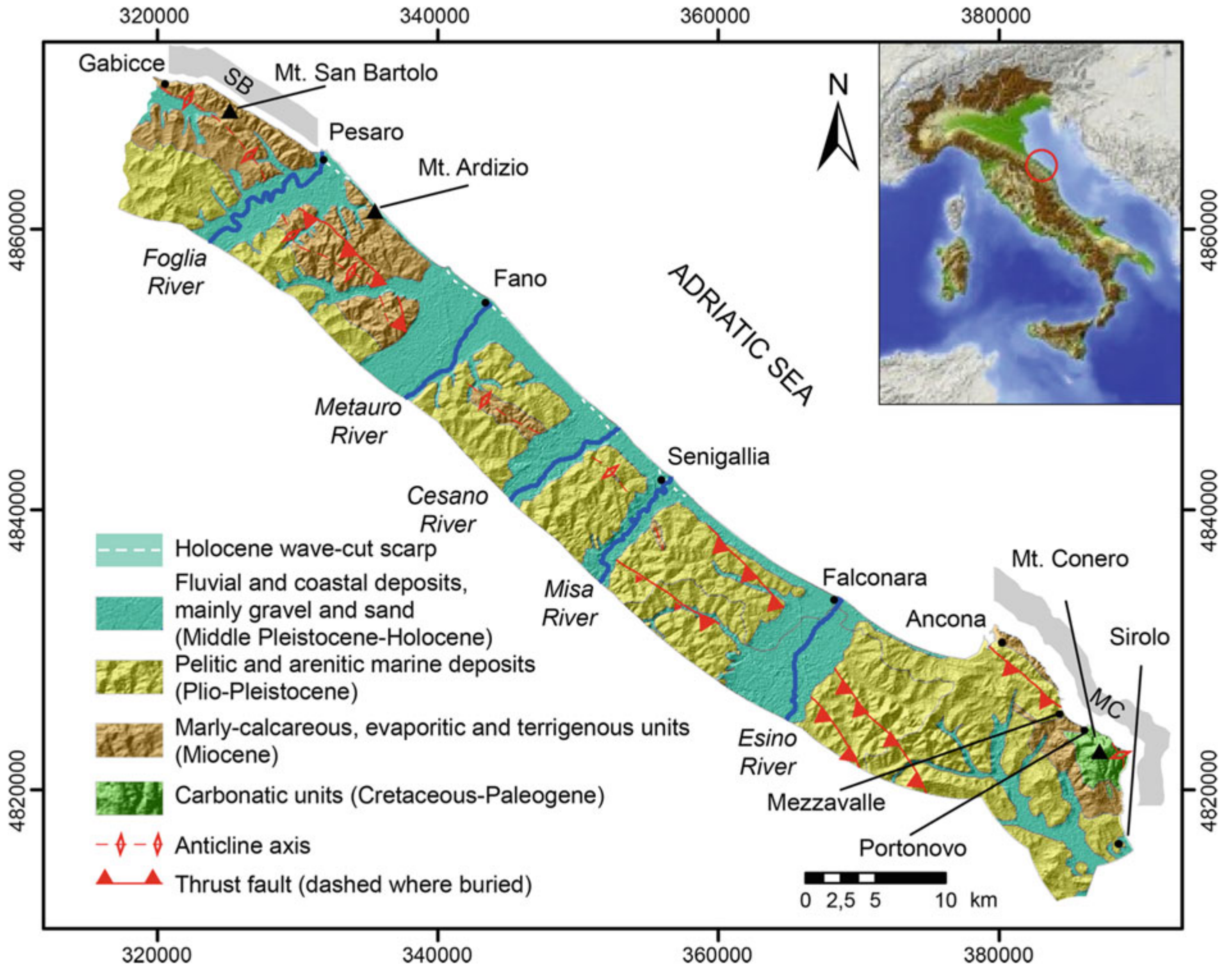

Fig. 23.1 Location map and geological sketch of the northern Marche coastal area. The *grey* bands SB and MC designate the Mt. San Bartolo and Mt. Conero rocky shore sectors respectively, both described in the text

rectilinear coastal trend. Conversely, the latter sector, where the highest cliffs (up to 300 m) of the Italian Adriatic coast occur, is a promontory protruding seaward for 3.5 km and culminating with Mt. Conero. The major northern Marche rivers cross-cut the coastal stripe directly flowing into the Adriatic Sea (Fig. 23.1).

Along the coast many seaside resorts, renowned for the fine sands of their beaches, have been repeatedly awarded for water quality and for the safeguarding of marine environments. Almost the whole coast is accessible by motor roads or by footpaths, with the exceptions of the steepest sectors of the cliff areas, accessible only by sailing.

The climate of the coastal zone is warm-temperate of the Mediterranean type. Mean annual precipitation averages 780–790 mm and mean annual temperature ranges between 14 and 15 °C. Summers are hot and relatively dry, whilst a pronounced variability mainly depending on the Atlantic cyclogenesis characterizes winters.

Since the westerly winds are hindered by the Apennines, the dominant storms are from the NNE (Bora, speeds sometimes >100 km/h) and from the SE (Scirocco). The southwesterly winds (Maestrale) are also effective, able to generate winter storms, particularly in the Mt. San Bartolo sector, where the effects of winds from the N (Tramontana) and from the NE (Grecale) also increase. As a result, the prevailing yearly direction of wave motion is from the N, NE and SE.

23.3 Geological and Geomorphological Setting

The Marche Apennines form part of the northern Apennines orogenic belt, an east- to northeast-vergent fold and thrust belt joining to the northeast with the Adriatic Sea—Po Plain, this latter being the present-day remnant of the foredeep (Coward et al. 1999). The Marche Apennines display an overall arc-shape with a marked north-eastward convexity that culminates in latitudinal alignment with the Mt. Conero. The central-northern Adriatic Sea is an epicontinental sea with depths not exceeding 70 m. Owing to its physiography, this sector of the Adriatic basin experienced repeated emersions in the late Quaternary, driven by glacial stages, becoming a prolongation of the Po Plain (Trincardi et al. 1994)—the largest alluvial plain in Italy—to which the northern Marche rivers extended. At first, the sea-level fall forced the rivers to entrench in the mid-Adriatic shelf, but in subsequent pleniglacials the formerly incised valleys were subject to aggradation (Nesci et al. 2012). The post-glacial sea-level rise brought the Holocene shoreline to break into the Apennines foothills (Lambeck et al. 2004). As a result, the modern coastline at the regional scale displays an overall north-eastward convex shape, that is roughly parallel to the external margin of the oroclinal bending of the belt.

The northern Marche coastal zone, covered by this chapter, consists of relatively soft Plio-Pleistocene pelitic and arenitic marine deposits overlying Upper Miocene marly, siliciclastic and evaporitic formations and, at Mt. Conero, Cretaceous-Paleogene resistant stratified calcareous and marly calcareous units (Fig. 23.1). The onshore undergoes tectonic uplift with long-term rates gradually decreasing from the 0.3 to 0.5 mm/a over the last 1 Ma of the inner sectors (D'Agostino et al. 2001) to the 0.01–0.15 mm/a extrapolated on the coastal area (Antonioli et al. 2009; Calderoni et al. 2010).

Both geology and the position of trunk-valleys exert a key control on the evolution and physiography of the coastal area. In the rocky shore sectors, active and relict cliffs break through coastal relief, which usually match thrusted anticlines cored by relatively resistant rocks (Fig. 23.1). In both sectors, excellent outcrops along the shore expose stratigraphic sections, markers and boundaries, and highlight the tectonic structure. Conversely, an up to 1.2 km-wide depositional plain fringes the whole central part of the coastal area (Figs. 23.1 and 23.2), joining seaward sandy-gravel beaches. The plain as a whole has undergone a rather complex morphoevolution, with both local and generalized advancement and retreat episodes starting at least in late mid-Pleistocene times. Nevertheless, the most part of the plain formed after the Holocene maximum marine ingression (Nesci et al. 2012). Quite different is the situation of the rocky shores, rapidly retreating during the highstand stages, with rates that, for the Mt. San Bartolo sector, have been estimated as high as 300–1000 m in the last 6000 years (Colantoni et al. 2004).

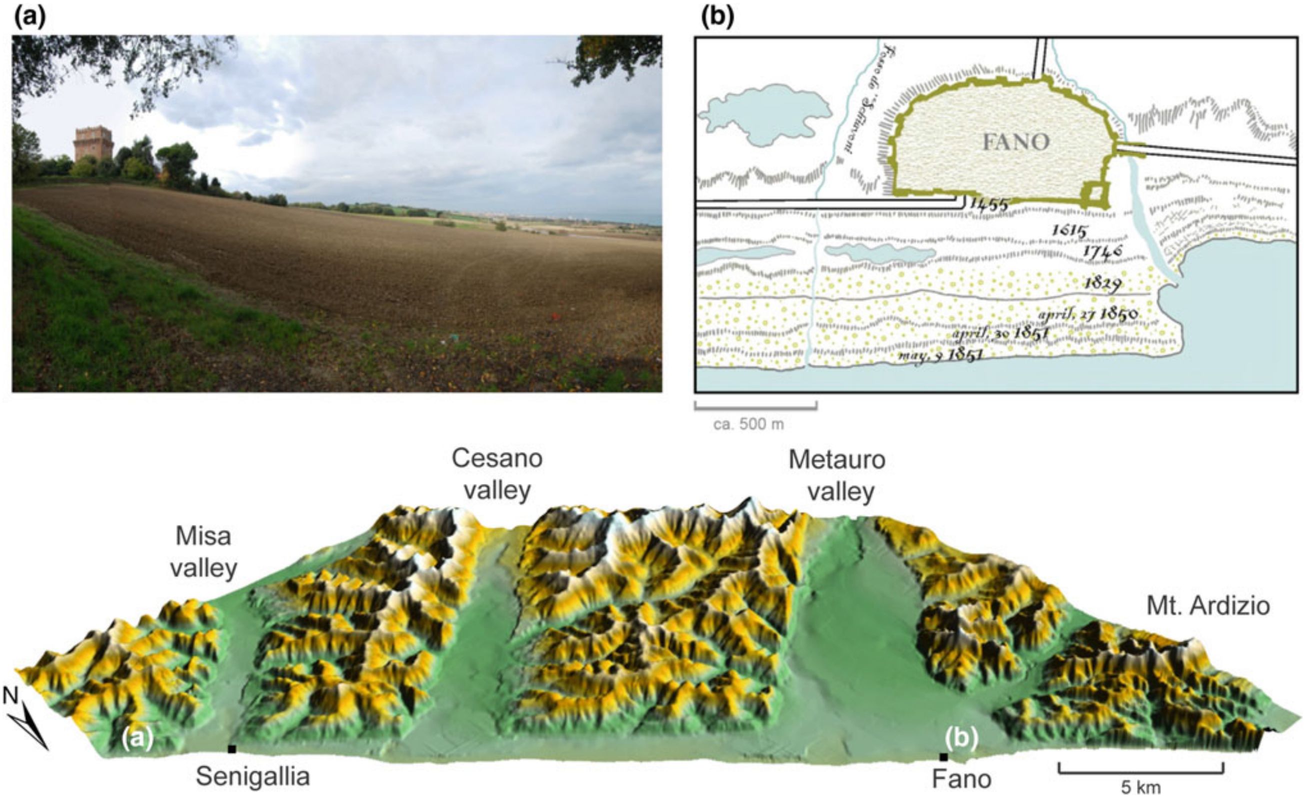

Fig. 23.2 Three-dimensional view of the central sector of the coastal area. A relict, strongly remoulded cliff (**a**) joins the plain; the recent development of the coastal plain is exemplified by historical maps, such as that of Fano (**b**), redrawn after De Cuppis (1866)

23.4 Landforms

The proximity to the foothills, the variability of rock types and the presence of river mouths bring into light a wide range of active and relict landforms of scientific interest and, in many cases, with an intrinsic scenic beauty. Besides common landforms produced by wave action, peculiar geomorphological features can also be observed, such as landslides (some of which of historical importance) and structural landforms.

Taking into account the physiographic domains along the northern Marche coastal area, this section describes representative landforms and key evolutionary mechanisms.

23.4.1 Coastal Plain

23.4.1.1 Beaches

The sandy-gravel beaches (Fig. 23.3) achieved their present position in the nineteenth century, following the accretion of the plain which, in the previous four centuries, moved the beaches more and more seaward (Fig. 23.2b). In the last century, the advance has been replaced by a renewed tendency to erosional recession, peaking in the 1960s–1970s and primarily attributed to anthropic actions within the drainage basins and along the shore zone. Human intervention in the first case brought about an overall reduction in river bedload supply, whilst in the latter case caused modifications of the longshore redistribution of sediments (Coltorti 1997; Colantoni et al. 2004).

At present, beach sand and gravel form a 15–20 m-thick depositional body extending seaward to water depths not exceeding 7 m, consisting primarily of river bedload redistributed longshore by wave-generated currents. Due to the prevailing north-westward direction of the longshore drift, beaches located close to the river mouths and slightly to the north of them are usually gravel-dominated. A well-known example is the Sassonia Beach at Fano. Moving away from the river mouths, the grain size decreases and sandy beaches predominate: examples are the celebrated "velvet beaches" of Senigallia and the beaches between Fano and Pesaro.

In the last decades, in order to prevent beach recession, breakwaters began to be placed systematically (see Fig. 23.3) and artificial nourishment of several beaches was also implemented (Colantoni et al. 2004). At the same time, most of the landward beach ridges have become occupied by railroad and roads, buildings and tourist facilities. Human modification of the coastal area strongly involved the backshore sectors too, where land reclamation brought about the disappearance of distinctive landforms such as coastal bars, ponds bounded by coastal dunes, littoral swamps and salt marshes (Senigallia). Thus, at present, such landforms are completely vanished, staying only as historical evidence in archives and maps of the seventeenth–nineteeth centuries (see Fig. 23.2b), without major geomorphological signatures in the field.

23.4.1.2 River Mouths and Retreated Cliffs

The major river mouths consist of narrow estuary-type outlets closed by mobile spit-bars (Fig. 23.4) which are destroyed and rebuilt seasonally, if heavy storms and/or floods impact the shore. Given the shallowness of their outlets, the gravel-bedded Metauro, Cesano and Esino river mouths were never used as harbours. Thus, although

Fig. 23.3 Gravel-sandy beach northwest of the Esino River mouth

Fig. 23.4 The Metauro River mouth (December 2005)

modified by human action, they underwent minor interventions. Conversely, the relatively poor in gravel, hence deeper Foglia and Misa outlets have played since long the role of ports and have been transformed into artificial inlets.

From Fano to Falconara, the coastal plain connects on the landward side with rectilinear, strongly remoulded scarps carved out in the Plio-Pleistocene soft sedimentary formations, which form the seaward hillslopes (Fig. 23.2a). The scarps reveal poly-phase evolution by wave undercutting at the hilly footslopes, effective during highstand stages, most likely since the middle Pleistocene (Nesci et al. 2012). Conversely, both to the southeast and to the northwest the plain narrows to a less than 50 m-thin ribbon fringing the relict cliff of Mt. Ardizio, abandoned in very recent times, and the Ancona-Falconara sea-facing hillslopes, respectively.

What at a first glance is a simple, regular depositional flat joining the modern beach to the hillslopes, is actually a series of low scarps, flexures and gravel ridges, which stress the complex evolution of the plain over the latest Quaternary times. Notably, the upper Pleistocene-early Holocene fluvial plains terminate 300–500 m inland, against 1–8 m-high retreated cliffs (Fig. 23.1), which strike parallel to the modern coastline. The cliffs are sharp and well developed close to the Metauro and Cesano river mouths, whereas in the Foglia and Misa valleys they are smoothed and partly concealed by urbanization. According to the exhaustive evolution model proposed by Nesci et al. (2012), these scarps were carved out by wave erosion of coastal-fans formed in the uppermost Pleistocene—early Holocene and today preserved only in their apex sectors.

About at the mid-Holocene these retreated cliffs achieved a position that, apart from lesser shoreline fluctuations, was maintained up to the Roman times. Such appraisal, substantiated by archaeological evidence of fluvial harbours and other remains, is the reason why this scarp is often referred to as the best evidence of the shoreline in Roman times (Elmi et al. 2001). After Roman times—early Middle Ages, alternating episodes of advance and recession to the “Roman position” of the shoreline took place, until an ultimate sedimentary regressive tendency was established from the fifteenth–sixteenth century up to the end of the nineteenth century (Fig. 23.2b), roughly coinciding with the Little Ice Age. This latter advance resulted in the construction of the entire 300–500 m-wide sector of the coastal plain facing the wave-cut scarps, thus originating the present coastal plain-beach system (Figs. 23.2 and 23.3). It is towards the end of this phase that the arenaceous cliff of Mt. Ardizio was deactivated, thus allowing the construction of the railroad which, sealing definitively the cliff seaward, impeded any further reactivation.

23.4.2 Rocky Shores

23.4.2.1 Controls on Marine Erosion

The Mt. San Bartolo and Mt. Conero sectors consist of smooth relief that becomes abruptly steeper seaward as the gentle land surfaces plunge down in retreating cliffs undermined by rapid foreshore erosion (Fig. 23.5). The evolution models proposed by Bird (2004) in his comprehensive overview, and by Colantoni et al. (2004) in the local frame of the Mt. San Bartolo rocky shore, describe well what may be observed in both sectors. Specifically, the cliff faces consist of well-stratified, at places seaward dipping, highly fissured calcareous, marly and arenaceous rocks. Erosional contrasts of different lithologies, bedding and rock mass fracturing, besides promoting the development of structural landforms (Fig. 23.6), facilitate both marine and subaerial erosion, favouring bedrock instability. The base of the cliffs

Fig. 23.5 Panoramic views of the active cliffs of Mt. Conero (**a**) and Mt. San Bartolo (**b**)

joins rocky benches and narrow, discontinuous gravel beaches (see Figs. 23.6 and 23.7). Debris storage at the foot of the cliffs, consisting of local landslide accumulations and sediment bars (Colantoni et al. 2004), temporarily protect the cliffs from basal erosion. The removal by wave erosion of such natural defences resumes undercutting, thus restarting cliff retreat. With some localized exceptions (Fig. 23.8), nearly the entire cliff undergoes erosional recession at present. The exceptions consist of effectively protected sectors that can be noticed both on straight reaches (e.g. close to Gabicce) and within coves (e.g. Mezzavalle). Here beaches can reach dimensions broad enough to allow only the largest waves to break against the footslope, thus preserving the cliff behind from the "ordinary" storm-wave action and favouring its vegetation and decline by subaerial processes. Notably, in such poly-phase evolution frame, the combination of cliff recession with subaerial remoulding of the sea-facing slopes produces the erosional truncation of gullies and landslide hollows. The result is the formation of characteristic triangular and trapezoidal facets, which are outstandingly developed in the Mt. San Bartolo sector (Fig. 23.7), where a net of subparallel, closely spaced gullies truncated by foreshore erosion hang above the shore (Colantoni et al. 2004).

23.4.2.2 Cliffs and Adjacent Benches

The ongoing shoreline recession is everywhere marked by a quite continuous, locally overhanging bare scarp varying in height from 1 m up to a few tens of metres. Constrained by fault-fracture systems and/or by resistant layers, morphoselection generates headlands and spurs, sometimes projecting offshore into small, but intriguing sea-stacks, the most outstanding example of which are found at Mt. Conero (Fig. 23.6a, b). Namely, the partial removal of a marly intercalation within hard calcareous rocks originated a characteristic headland (Il Pirolo) at the southern end of one of the best coves at the foot of Mt. Conero. At the opposite end of the same cove, another headland stands facing two celebrated sea-stacks (Le Due Sorelle) isolated from the cliff by the complete removal of the previously mentioned marly intercalation. Similarly, a few kilometres to the north, the sea-stack of La Vela stands (Fig. 23.6b), which displays notches coherent with the present-day sea level and tide excursion.

Fig. 23.6 Exposed bedding surfaces, rocky spurs and sea stacks highlight lithological and structural controls on the Mt. Conero rocky shore. **a** The two sea-stacks of Le Due Sorelle are apparent in the *foreground*, the Pirolo spur rises *behind*; **b** La Vela sea stack; **c** a thick calcarenitic horizon originates the Scoglio del Trave natural jetty, closing to the north-west the Mezzavalle cove

Cliff recession left behind a wave-cut platform carved out in bedrock and extending seaward by about 300 m. The shore platform is rather flat, with minor roughness due to the edges of resistant rocks and/or to residual boulders. However, wide sectors are blanketed by sandy patches, cobbles and blocks. Offshore the calcareous cliff of Mt. Conero large amounts of landslide-derived residual boulders are also found, allowing the primary extension of runouts to be traced on the bench as far as 80–100 m offshore, up to 8–10 m of water depth (e.g. close to Portonovo). Conversely, on bare rock platform, characteristic series of bedrock strata edges can usually be observed. Notably, at the northern end of the Mezzavalle bay the so-called Scoglio del Trave surfaces from the rocky bench (Fig. 23.6c). This outstanding

Fig. 23.7 Cliff retreat results in the truncation of regularly spaced gullies and the origin of erosional triangular and trapezoidal facets at Mt. San Bartolo

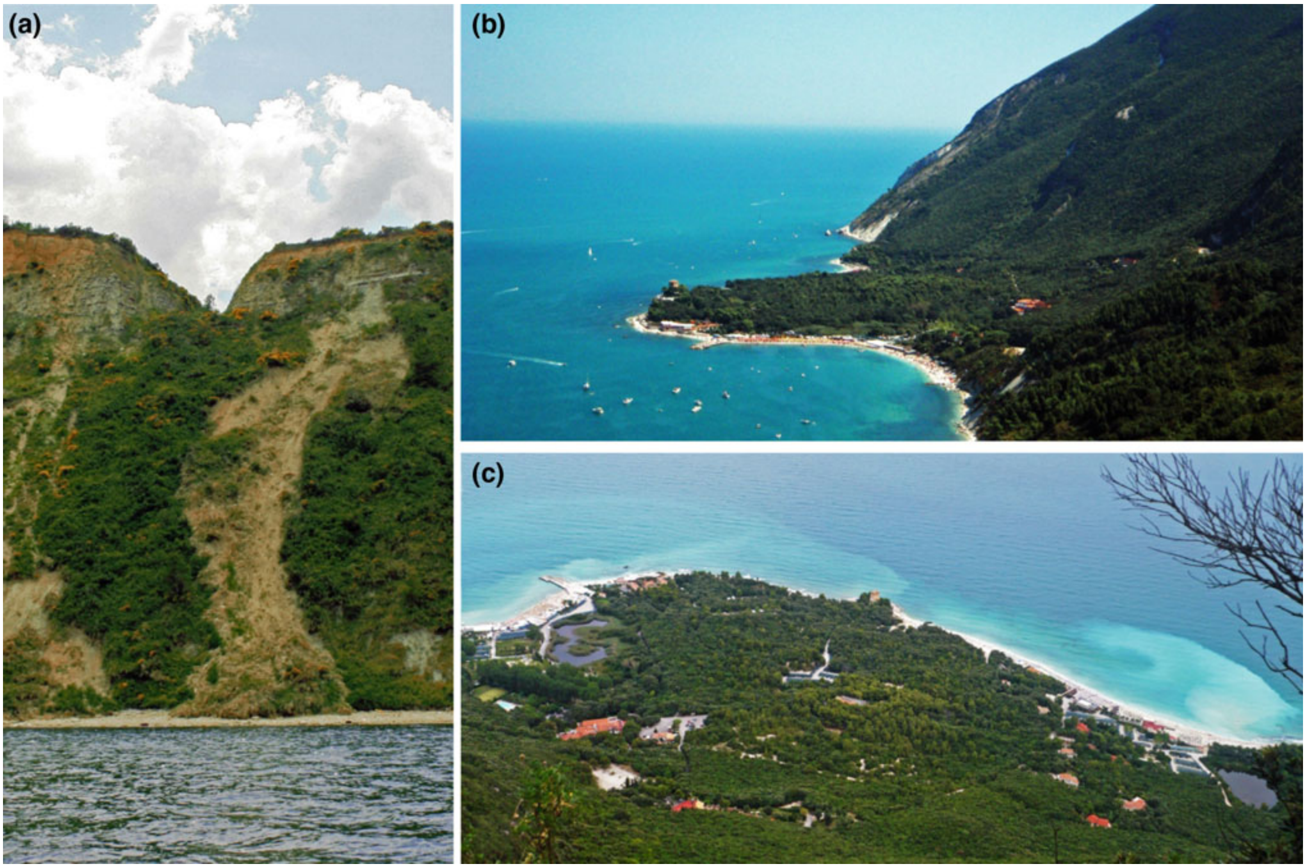

Fig. 23.8 **a** An earth flow at Mt. San Bartolo. **b** The toe of the Portonovo landslide at Mt. Conero and, on its margins (**c**), the two small lakes dammed by spit bars

morphostructure is shaped on a 14 m-thick calcarenitic layer (the *Trave guide-horizon*, upper Messinian) and for fairly less than 1 km, 450 m of which emerged, projects from the cliff as a natural jetty.

23.4.2.3 Beaches on the Rocky Shores

Gravel beaches are well developed in both rocky shore sectors, even though the best examples come from Mt. Conero. Here the Mezzavalle beach (Fig. 23.6c), ending to the north against the Scoglio del Trave, stands as the by far best gravel beach of the whole area. The beach, supplied by calcareous materials from the anticline daylighting a few kilometres to the southwest, lies within a 2.7 km-wide cove, that enlarged and hollowed out favoured by a concomitance of lithological (marl and clay in contact with limestone) and structural factors. To the south, the Mezzavalle beach merges into the Portonovo beach. The latter is somehow peculiar for its origin and position, since it has developed at the toe of a large landslide. The loose calcareous material of the landslide body was reworked to form a beach where several residual boulders occur. The landslide overran the previous shoreline forming two small coves at the toe margin. The subsequent damming of the coves by spit-bars generated two small brackish coastal lakes, the so-called Lago Profondo and Lago Grande (Fig. 23.8b, c). As for the Mt. San Bartolo rocky shore sector, intriguing for the peculiarity of its cobbles is the gravel beach at the toe of the northwestern part of the cliff. Here a part of the cobbles consists of rounded, cemented diagenetic nodules of weird shapes—locally called *cogoli*—directly derived from sandstone daylighting on the cliff face (Colantoni et al. 2004).

23.4.3 Landslides

Landslides affect a large part of the northern Marche coastal area, often as a response to deep-seated gravitational slope deformation (Aringoli et al. 2010). At the inland margin of the coastal plain (Figs. 23.1 and 23.2), landslides set all along the inactive cliff faces carved out of soft Plio-Pleistocene deposits. Here they have substantially remoulded the scarps, leading to the origin of a continuous fringe of slid materials at the footslopes, often smoothed and concealed by colluvium (see Fig. 23.2a). However, landslides assume their greatest geomorphological emphasis in the rocky shore sectors or at their margins, where they exert controls on both shoreline configuration and processes, and contribute to the origin of outstanding landforms (Fig. 23.8).

Footslope undermining by wave action, coupled with slope weakening factors as bedrock stratification, rock mass fracturing and weathering, brought about a wide range of mass movements on the sea-facing slopes. As a rule, in both hard and soft terrains, seaward-dipping layering and/or fault/fracture surfaces facilitate sliding. At the core of the Mt. Conero calcareous anticline, a distinctive cliff-face configuration is found where the depletion of its steeply inclined forelimb produced, primarily by rock sliding, a seaward slope largely matching exhumed bedding planes (Fig. 23.6a). On the other hand, otherwise dipping discontinuities within the rock masses, besides favouring sliding, usually account for rock falls and topples. The development of earth flows (Fig. 23.8a) and debris flows is rather ubiquitous, depending on the local availability of both fine and/or coarse loose materials. A good correlation of rock slides and earth/debris flows with rain and snow melting was assessed in the Mt. San Bartolo sector by analysing historical records (Colantoni et al. 2004). In the Mt. Conero sector, an important triggering factor is the seismicity of the area. In such regard, meaningful are the several rock falls occurred along the cliff during the M 2.9 earthquake of 8th August 2013 and the M 4.4 event of 22nd August 2013, which have had large coverage by mass-media.

At the northern margin of the Mt. Conero rocky shore, the so called Ancona landslide is of great importance for the damages to the town (Crescenti et al. 2005). It is a large rotational slide displacing Plio-Pleistocene pelites undercut by wave erosion. From the geomorphological standpoint, however, the most intriguing failure is the aforementioned landslide of Portonovo (Fig. 23.8b, c), that hollowed out part of a former amphitheatre-shaped cliff face. A large mass of stratified and highly fissured limestone slumped down from maximum heights of about 400 m and avalanched into the sea with a more than 600 m-long blocky runout (Fig. 23.8b). This failure is usually regarded as a poorly defined "pre-historical" event perhaps following the maximum Holocene marine ingression. However, in the same area, several minor failures, at least in part reactivating subordinate sectors of the major landslide, have been reported. These include, for example, a failure following an earthquake in 558 AD, or a landslide that in 1320 AD destroyed a Benedictine monastery located close to the still preserved, famed Romanic church of Portonovo.

23.5 Conclusions

The northern Marche coast is a unique place, where a hinterland with a plenty of classical geological localities perfectly blended with an extraordinary historical and cultural heritage joins famed beaches and eye-catching cliffs. In a relatively small space, the northern Marche seaside embraces several landforms characteristic of wider sectors of the Italian Adriatic coast, ranging from coastal plains joining sandy beaches to steep rocky shores carved out from both calcareous and terrigenous sedimentary formations. Outstanding landforms of high educational and scientific importance, often blended with inherent aesthetic values, occur in the whole area. The necessity to preserve such environmental, historical and cultural qualities led the authorities to establish two regional natural parks in the coastal area, namely the *Parco Naturale del Monte San Bartolo* (operating since 1997) and the *Parco del Conero* (operating since 1991). Although overshadowed by late Holocene deposits and landforms, the coastal plain reflects a long-lasting evolution with an ultimate important advance following the Holocene maximum marine ingression. The advance of the coastal plain contrasts with the rapid recession of the two cliff sectors matching the coastal relief of Mt. San Bartolo and Mt. Conero, where headlands and coves, sea-stacks and natural jetties are part of an intricate and appealing blend of marine and structural landforms. The rapid foreshore erosion, undermining the cliffs, favours bedrock instability to such an extent that mass movements become the dominant processes in the evolution of wide sectors of the cliff faces.

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The Typical Badlands Landscapes Between the Tyrrhenian Sea and the Tiber River

24

Maurizio Del Monte

Abstract

A mixture of special geomorphological conditions and extraordinary cultural interests is collected in the country between the Tyrrhenian Sea and the Tiber River. In the Holocene severe erosion processes shaped Plio-Pleistocene marine claystones, highly uplifted during the Quaternary, producing spectacular badlands landscapes with *calanchi* and *biancane* landforms. C*alanchi* show a resistant caprock, driving a parallel-retreating evolution of rugged steep slopes; *biancane* are rounded landforms, related to clayey outcrops in low-relief areas. Badlands have been greatly modified by anthropogenic activity: most of *biancane* and some *calanchi* were smoothed in the twentieth century, mainly to the widening of sowable land. For these reasons, a very peculiar badlands landscape is recognizable today.

Keywords

Badlands • *Calanchi* • *Biancane* • Volcanic caprock • Central Italy

> Ogni valle è fatta dal suo fiume e tal proporzione è da valle a valle, quale è da fiume a fiume
> *Each valley is shaped by its river, and the same proportion existing between a valley and another is found between their rivers*
> Leonardo da Vinci

24.1 Introduction

Some clayey terrains present in many parts of Italy are affected by accelerated erosion processes, producing badlands landforms known as *calanchi* and *biancane*. Badlands landscapes are frequently considered to be typical of dryland areas. Semi-arid badlands are present throughout the Mediterranean region, the better-known examples being located in various parts of Spain and southern Italy. Nevertheless, they also occur in wetter areas, as in central Italy, where high topographic gradients, bedrock weakness and high intensity rainstorms coexist.

Central Italy has an unbelievably wide variety of landscapes in relation to its extension. Between the Tyrrhenian Sea to the west and the Adriatic Sea to the east, there are about 200 km, along which the traveller crosses coastal, hilly and high mountain landscapes. The structure of the Apennine chain consists mainly of ridges of carbonate rocks of Mesozoic age, elongated in the NW–SE (Apennine) direction and increasing in elevation from the Tyrrhenian to the Adriatic sector, where tectonics raised the highest summits to almost 3000 m a.s.l., with thrusts, faults and crustal deformation still in progress (Fig. 24.1). The great complexity of the geometric relationships between the various formations is derived from the geological history of the Apennines. The orogenic wave has spread from west to east; during the Miocene, it has mainly focused on the Tyrrhenian sector, that in the Pliocene was then subjected to crustal

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thinning and horst and graben construction. For the same reason, on the Tyrrhenian coast belt, between the Pliocene and Quaternary endogenous activity formed several volcanic complexes, some of which are still active. The recent geological evolution is therefore responsible for the uplift of the Plio-Pleistocene marine deposits to several hundred metres above sea level. During this period, on the Tyrrhenian side of central Italy geodynamic processes have caused differential uplift, volcanic eruptions and the origin of horst ridges. The variety of outcropping lithotypes and the tectonic processes have influenced the development of structural landforms. The major ones are represented by morphostructural ridges bounded by NW–SE trending fault scarps, dipping towards the graben depressions (Fig. 24.1). Minor morphotectonic features (e.g. straight channels, saddles and straight ridges) are aligned along the other structural patterns. In the areas in which the main morphostructures are located and/or where harder rocks crop out, landforms are more rugged and valleys are deeper. However, the landscapes between the Tyrrhenian Sea and the Tiber River are mostly characterized by hilly landscapes, with elevations rarely higher than 1000 m, as a result of the widespread outcrops of soft sediments. The Plio-Pleistocene clayey lithotypes recently uplifted are now modelled by very strong exogenous processes and in some areas give rise to characteristic landscapes, with dramatic and very widespread erosion landforms: *calanchi* and *biancane*.

24.2 Geographical and Geological Setting

Several areas in northern Latium and southern Tuscany, between Siena and Rome, have been modelled by fast erosion processes and include typical badlands landforms.

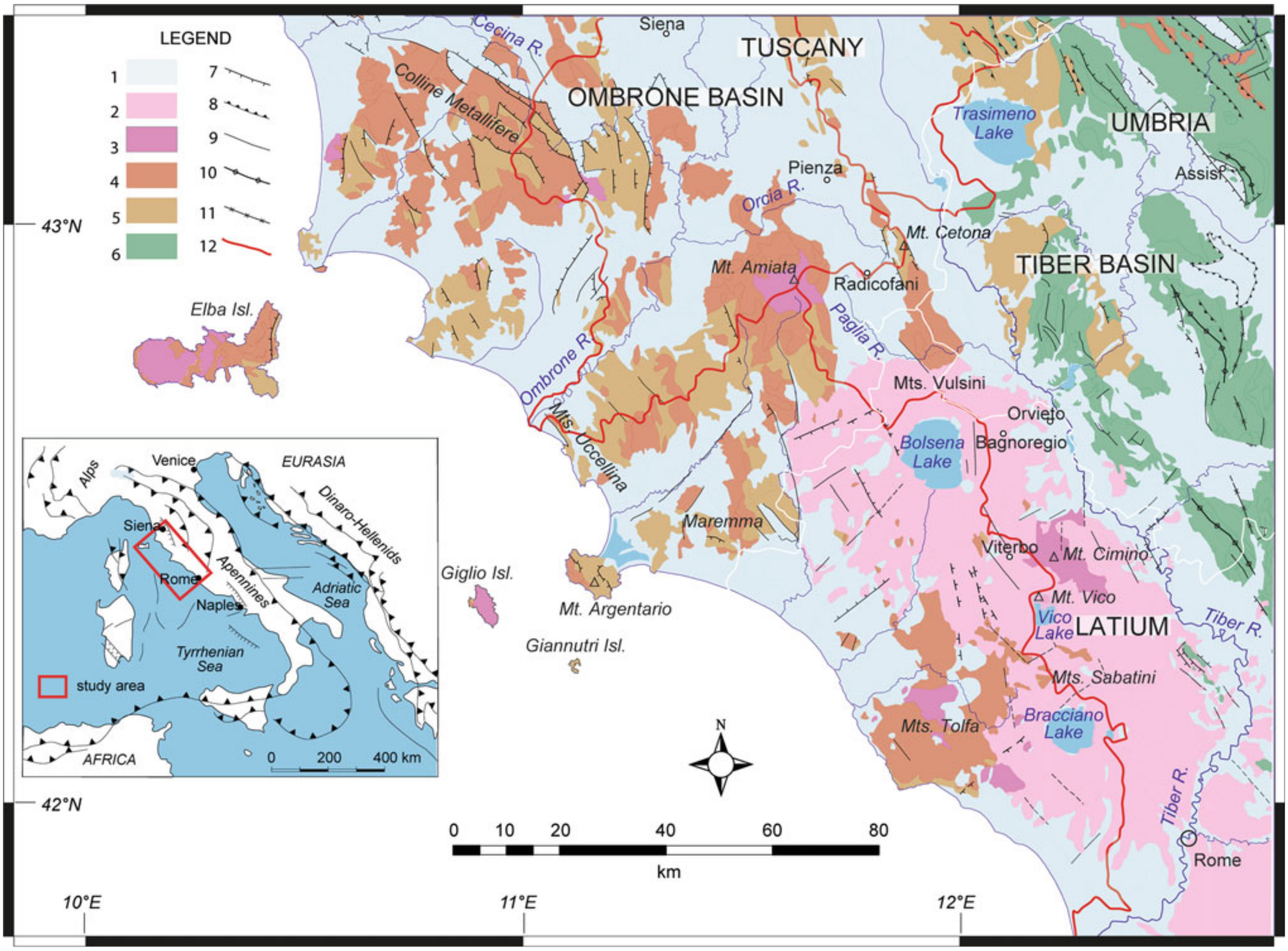

Fig. 24.1 Geological sketch of the study area. *1* Plio-Quaternary undifferentiated marine and continental deposits (and subordinate Messinian evaporites); *2* Pleistocene basic to intermediate volcanic rocks; *3* Plio-Pleistocene (and subordinate Miocene) acid volcanic rocks; *4* Ligurian and sub-Ligurian nappes sedimentary and metamorphic units (Trias to Lower Cretaceous); *5* Tuscan nappe sedimentary and metamorphic units (Paleozoic to Miocene); *6* Umbria-Marche sedimentary sequence (Trias to Tortonian); *7* Normal faults; *8* Overthrusts and reverse faults; *9* Other faults; *10* Axis of anticline; *11* Axis of syncline; *12* Main fluvial basin boundary

A smooth hilly landscape marks the northern portion of the area, where *biancane* slopes are frequent, although often reshaped due to local crop-growing activities. The *biancane* landforms are small clay domes up to approximately 15–20 m high, mostly bare of vegetation on steeper south-facing slopes, where sheet and rill erosion is very strong. *Biancane* are often located near the footslope or at the summits, and their existence is always associated with gentle slopes.

Moving towards the south, the landscape becomes much rougher, and the typical landforms on clayey slopes are represented by *calanchi*, that is systems of rills and gullies separated by sharp and steep ridges (from "*calans*" Latin for "dropping" or "downhill"). They occur particularly in places where horst structures and/or volcanic caprocks are present and slope steepness increases. These areas are concentrated in the eastern and northwestern parts of the Ombrone and Tiber fluvial basins, respectively (Fig. 24.1). *Calanchi* are sometimes bevelled by human activities; overall, the *calanchi* slopes are less reworked than those in the *biancane* zones.

The geological history has contributed to widespread outcrops of lithological units prone to denudation (Fig. 24.1). The building phase of the Apennine orogenic wedge (Oligocene to Tortonian) led to the formation of the major horst-and-graben morphostructures in the study areas. These are mainly NW–SE oriented and composed of sedimentary sequences (Umbria-Marche sequence, Tuscan Nappe, Ligurian and Subligurian Nappe) overthrust towards the NE (Fig. 24.1). The nappes include some metamorphic units (Paleozoic to Trias). The orogenic wedge began collapsing in the Late Miocene. Extensional tectonics, affecting the Tyrrhenian margin of the Italian peninsula, activated several NW–SE striking normal faults, which define the system of horst and graben cut by SW–NE transfer faults (Liotta 1991). A marine transgression led to the deposition of a Plio-Pleistocene sequence of clay, sands and conglomerates within the major depressions. Moving inland, the extensional basins are filled with lacustrine to fluvio-lacustrine continental deposits.

During the Quaternary, the Plio-Pleistocene marine deposits were uplifted by several hundred metres. This strong uplift is related to pluton emplacement and widespread volcanic activity along the Tyrrhenian margin (Acocella and Rossetti 2002), evidenced by the distribution of several volcanic complexes (Fig. 24.1). Quaternary uplift has been particularly strong along a NW–SE elongated zone, which extends from the Colline Metallifere Area towards the Latium volcanoes (Mts. Vulsini, Mt. Vico, Mts. Sabatini), going through Mt. Amiata, Radicofani and Mt. Cetona, where marine deposits crop out at 800 m.

Therefore, the altitude of Plio-Pleistocene marine deposits reaches several hundred of metres above the present sea level; together with the high value of relief amplitude, this underpins a very fast geomorphological evolution in this sector of central Italy.

24.3 Landforms and Landscapes

Fluvial erosion, together with slope denudation, contributes significantly to the morphogenesis of the Tyrrhenian side of central Italy. Many slopes are rapidly evolving and rivers carry high volumes of suspended sediment load.

Mass movements contribute to slope denudation along with water erosion. Apart from some rock falls, slides often occur on steep slopes. However, the influence of gravity is also evident on gentler slopes, where mudflows, soil creep and shallow soil flow are widespread. Due to these prevailing morphogenetic processes, gently undulated slopes typify the regional landscape.

Human impact has significantly affected the landscape of the area for a long time (Amici et al. 2017). Deforestation, grazing and farming are among the most important triggers for accelerated water erosion, tillage erosion and gravitational movements on slopes. Moreover, the effects of farming may become stronger if land-use changes determine cropland abandonment. Water erosion is pervasive on many slopes, due to extensive clayey outcrops, human activities, current climatic conditions and rapid uplift. Sheet erosion is responsible for exposure of roots and colluvium deposition at the footslope. As the slope gradient increases slightly, rill and gully erosion prevail, contributing significantly to badlands development and soil degradation. Ephemeral gullies are often recognizable in croplands and grow rapidly as a consequence of concentrated rainfall. Water erosion on natural slopes leads to typical badlands with *calanchi* and *biancane*. These landforms, in the belt between the Tyrrhenian Sea and the Tiber River, are similar to the badlands of the United States or many other areas, but have their own distinct characteristics.

A *calanchi* slope may seem a reduced model (by one thousand or ten thousand times) of a fluvial system. Thus, on the whole, they appear as "concave" landforms. As described by Alexander (1980), *calanchi* are systems of rills and gullies, connected in thick small networks evolving headwards and separated by sharp and steep divides (Fig. 24.2). In central Italy, some *calanchi* show knife-edged features, shaped as a system of narrow but deep cuts separated by thin and articulated ridges (Fig. 24.2), as to reproduce a drainage network in miniature. On the slopes, the effects of both strong runoff processes and subsurface erosion processes

Fig. 24.2 *Calanchi* on a southward facing slope (Tyrrhenian Sector, Tiber River basin, Latium). A volcanic caprock is recognizable on some slope tops

(tunnelling or piping) can be observed. Many other badlands are made of larger incisions, with a trough-floored aspect, separated by smaller convex ridges, sometimes overgrown and characterized by less intense surface runoff phenomena.

The important role of wash denudation in the area is mainly due to local structural conditions. *Calanchi* morphology is associated with clayey outcrops, alternating with sandy and gravel levels, and frequently with counter-dip slopes, that allow the development of steeper slopes. This type of slope evolution is even more related to the presence of a volcanic caprock, especially in northern Latium, or a more or less cemented sand and conglomerate caprock. If a caprock is absent, slope steepness decreases quickly and the parallel-retreating evolution stops, as described in Scheidegger's evolutive model (1961; Figs. 24.3 and 24.4).

In the Tyrrhenian sector, aspect does not seem to greatly influence the distribution of badlands, but important morphological and vegetational differences can be observed on slopes with different aspect. Wash processes shape the south-facing slopes into very thin and sharp ridges, "blade" crests (Fig. 24.5). At the bottom of these slopes, in parallel-retreating evolution, small pediments can be observed, as already described by Schumm (1962). The north-facing slopes are much more overgrown and characterized by frequent mass movements that give a trough-floored aspect to the incisions, especially during winter.

In other areas of central Italy, like those located in the Adriatic sector, the presence of *calanchi* is even more closely linked to south-facing slopes, where higher insulation restrains vegetation growth; however, in this sector the south-facing slopes are almost always inclined opposite to the dip, which helps to hold a higher slope.

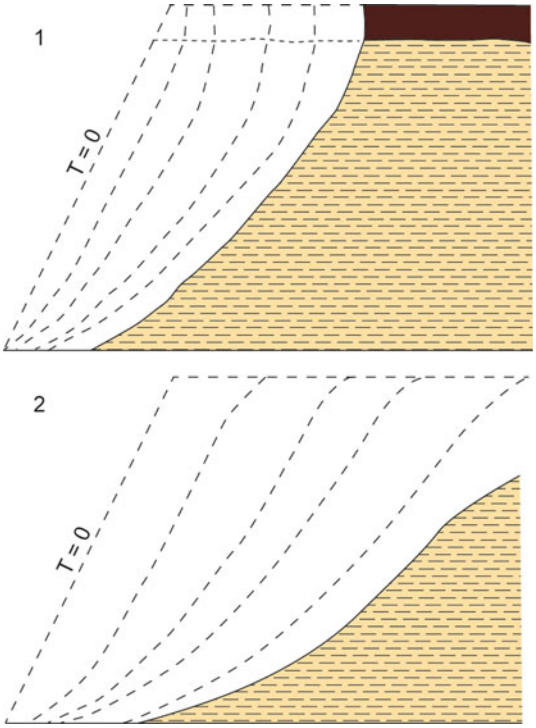

Fig. 24.3 Scheidegger's slope evolution starting from $T = 0$ (initial time): *1* clayey slope with caprock; *2* clayey slope without caprock

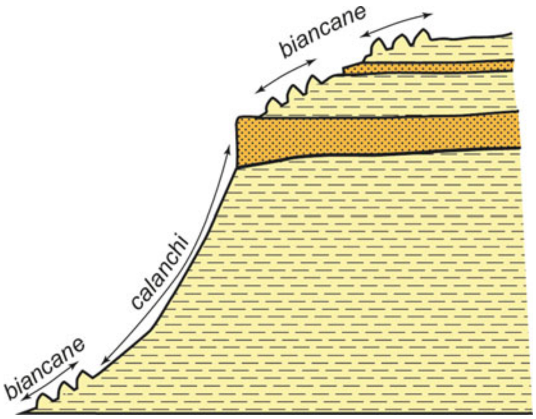

Fig. 24.4 Distribution of *calanchi* and *biancane* on a typical slope of the upper Orcia River Valley (southern Tuscany)

Biancane are typical dome-shaped features a few metres in height and usually found in groups (Torri et al. 1994) to form a "convex" morphology on the whole. These rounded landforms can reach 20 metres in height without a vegetation cover on the steeper south-facing slopes, which are characterised by intense slope wash (Fig. 24.6). The term "biancana" (from "bianco" Italian for "white") probably comes from the presence of a thenardite (Na_2SO_4) crust on their surfaces, due to precipitation from capillary waters. Micro-pediments usually develop at the foot of the *biancane* retreating slopes (Fig. 24.6). They show thin layers of materials transported by runoff, deposited on low angle surfaces and often affected by mud-cracking.

The *biancane* are closely related to areas with low relief. In southern Tuscany, they are found either on the flat tops of ridges, and in the valley floors, next to the lower part of convex slopes (Fig. 24.4). Along the valley bottoms, *biancane* may be residual "inselbergs" related to slope retract. Those present on low-relief summit surfaces cannot be interpreted in the same way; they are due to runoff effects in interfluve areas, where steepness is low and gully erosion is still in the initial stage.

Italian badlands have, often, more vegetation if compared to badlands in other areas of the world (Figs. 24.2, 24.5 and 24.6). Their existence is linked to a series of

Fig. 24.5 A watershed between two small basins in the badlands of northern Latium. The knife ridge has been used for centuries as a passage to cross the Calanchi Valley. A few decades ago it has become too narrow and unsafe, and the trail has been abandoned. Note, on the *top* (*red frame*), the remnants wooden boards of the old path hanging on the verge of falling

Fig. 24.6 Group of *biancane* (Orcia Valley, southern Tuscany). At the foot of the southern slopes, evolving by parallel retreat, some micropediment are growing

favourable factors, dependent on the geological, geomorphological and climatic conditions. The climate of central Italy, especially that of the piedmont and coastal areas, is a basic influencing factor for badlands development. Hot and dry summer followed by a rainy autumn, with heavy rains on several consecutive days, enhances runoff action. During winter, the soil does not dry in depth, and spring rains (although less intense than the autumn ones) often cause an increase of mass movements rather than of runoff intensity.

Both *calanchi* and *biancane* result from the same geomorphic processes and are influenced by some common factors. Impermeable bedrock (clay or marly clay) is a necessary condition to produce strong runoff, where weathering can increase susceptibility to erosion. Thus, aspect generally plays an important role in badlands evolution by conditioning the vegetation cover distribution. However, *calanchi* and *biancane* have significant morphological differences (Ciccacci et al. 2003).

Moretti and Rodolfi (2000) outlined several environmental components that interact in the development of the *calanchi* landscape. Other factors being equal (e.g. aspect, lithological and climatic conditions), slope steepness strongly influences the erosive power of runoff in rills and gullies. In general, *calanchi* are more frequent on scarp slopes and their growth is favoured by sandy, gravel, conglomeratic or volcanic caprocks at the summit, helping to maintain slope steepness (Fig. 24.3).

Noticeable slope steepness favours diffuse mudflows, which strongly contribute to the removal of considerable volumes of sediment (and deposition, generally at the gully bottom), while caprocks are often subject to rock falls at the steep summits of *calanchi* slopes. Since *calanchi* on north-facing slopes are generally less developed and more vegetated, the runoff power is less effective, but may make earth sliding more likely (Fig. 24.7).

Deep piping is widespread at many *calanchi* sites, especially in northern Latium where *calanchi* are more extensive.

Fig. 24.7 Calanchi Valley, with distinctive asymmetry of relief and vegetation cover (Tyrrhenian sector, Tiber River basin, NW of Rome). The north is on the *left*

According to Romero-Díaz et al. (2007), this process is favoured by land-use changes (i.e. cropland abandonment) and by steep hydraulic gradients. In particular, hydraulic gradients increase at the intersections between sub-horizontal bedding and vertical fractures. Deep pipes probably contribute significantly to denudation and evolve rapidly due to collapse.

Ephemeral gullies develop on cultivated or grazing lands, where they create very important paths of sediment movement. On slopes, several small earth pillars are present (with vegetation cover, stones or fossil gastropod shells on the top), whereas other minor landforms are caused by piping processes. Some very high pillars are residual landforms, resulting from demolition of sharp ridges due to falls (Fig. 24.8). On the footslopes, parallel retreat leads to the development of landforms similar to small pediments, as it has already been suggested in previous studies (Schumm 1962; Torri et al. 1994).

Summarizing, in central Italy rill erosion on *biancane* is more significant on south-facing steeper slopes, while the north-facing ones are gentler and generally exhibit a thin, continuous vegetation cover. The N-S *biancane* profile is typically asymmetric (Ciccacci et al. 2003), with the uncovered slopes showing weathered “popcorn surfaces”. According to Farifteh and Soeters (2006), *biancane* are likely to develop on originally gentle slopes, while *calanchi* development is probably favoured by initial slope steepness, due to strong fluvial deepening in response to the lowering of sea level or to regional uplift. Moreover, as outlined by Torri and Bryan (1997) and confirmed by Farifteh and Soeters (2006),

Fig. 24.8 High pillar in the Calanchi Valley (Tiber River basin, northern Latium)

structural factors, such as intersecting fracture patterns, probably control *biancane* formation and evolution.

In addition to runoff, piping and gravitational movements act together in shaping *biancane* slopes, but with some differences with respect to *calanchi* slopes: (a) unlike *calanchi* slopes (where deep piping is more frequent), *biancane* are widely affected by shallow micro-piping, developing at the boundary between the weathered layer ("popcorn surface") and the undisturbed bedrock; (b) *biancane* are less affected by gravitational movements (mainly mudflows along major rills and gullies) compared to more unstable *calanchi* slopes.

24.4 Geomorphological Evolution of *Calanchi* and *Biancane* Landscapes

Results of hillslope-scale monitoring and many field surveys showed the relationship between denudation rates and morphoevolution of the two badlands types. X-ray diffraction analyses performed on samples from the marine Pliocene and Pleistocene sediments of ODP Hole 653A in the Tyrrhenian Sea indicated an acceleration of the uplift/emergence of the areas here described at about 1.6 Ma BP (Della Seta et al. 2009). It is likely that, as a consequence, the landscape has been strongly dissected by fluvial deepening. In particular, as a result of the coupled effect of uplift and shifting from relatively dry to humid climatic conditions in the Early Pleistocene, valley deepening was favoured. Alternating cold/dry and hot/humid climatic phases during the Pleistocene probably determined the discontinuous preponderance of areal denudation or fluvial deepening, respectively.

During the Holocene, under conditions of general post-glacial warming, short-term climatic oscillations occurred in the mid-European region, as deduced, e.g. from lake-level fluctuations (Magny 2004). Recent works outlined the strong relationships among climate, fire, vegetation, and land-use and attested to the paramount importance of fire in Mediterranean ecosystems (Drescher-Schneider et al. 2007; Vannière et al. 2008). As evidenced by these authors, humans started to affect fire regimes since the Neolithic (8000 cal years BP), but during the Bronze Age (4000–3800 cal years BP) a significant increase in using fire as a tool determined considerable changes in fire regime. In addition, human impact increased noticeably since the Roman Age through deforestation, leading to considerable environmental modifications (Buccolini et al. 2007); as a result of human-induced rhexistasy, steep valley slopes and gentler interfluves, together with footslopes, have become the ideal sites for *calanchi* and *biancane* development, respectively.

After deforestation, grazing and farming have become important factors responsible for accelerated water erosion, tillage erosion and gravitational mass movements. Torri et al. (1999) put forward a hypothesis and provided evidences of progressive deterioration of the soil and land condition between 1840 and 1870, which increasingly transformed arable lands into pasture, and eventually, badlands. More recently, land-use changes due to cropland abandonment have amplified the power of water erosion on slopes.

The hypothesized formation and evolution of *calanchi* and *biancane* in the area between Tyrrhenian Sea and Tiber River is substantially in agreement with the model developed by Farifteh and Soeters (2006) for *calanchi* and *biancane* in Aliano (southern Italy), although some differences exist. On the Tyrrhenian side of central Italy the development of *calanchi* and *biancane* is strictly connected to the original slope steepness, which is one of the major factors influencing their distribution (Della Seta et al. 2007). Moreover, the occurrence of *biancane*, even at the summit of *calanchi* slopes, allows one to exclude the possibility that they could represent just residual products of *calanchi*, as proposed by some authors. Observations on present embryonic *biancane* confirm the leading role played by reticular systems of joints in the dissection of original, gently dipping surfaces (Torri and Bryan 1997; Farifteh and Soeters 2006).

Biancane initially grow as small bare symmetrical domes, whose north-facing slopes start to undergo shading as their heights increase. On the 20 years monitored *biancane* (Vergari et al. 2013), vegetation cover is likely to have developed on these shaded, thus moister, north-facing slopes, rather than representing a remnant cap, as stated in the evolutionary model by Farifteh and Soeters (2006), since it wraps the north-facing slopes of the evolved *biancane* from top to bottom. From this perspective, the evolution of *biancane* leads to a progressive increase of the aspect-induced asymmetry typical of evolved *biancane*. Moreover, strong retreat of south-facing bare slopes leads to the formation and rapid widening of micro-pediments at their foot (Fig. 24.6).

Therefore, the evolution of many *biancane* sites in the Tyrrhenian side of central Italy can be summarized as to occur in four main stages (Fig. 24.9). Initially, severe runoff processes affect a gentle slope on fractured clay, cut by intersecting systems of joints. This may take place in response to abandonment of agricultural activities, increase of fluvial deepening, and climatic changes (like those at the end of the Little Ice Age). Many rills and some gullies develop along the joints (Fig. 24.9a). Then, rill and gully networks grow, while under the surface tunnelling processes

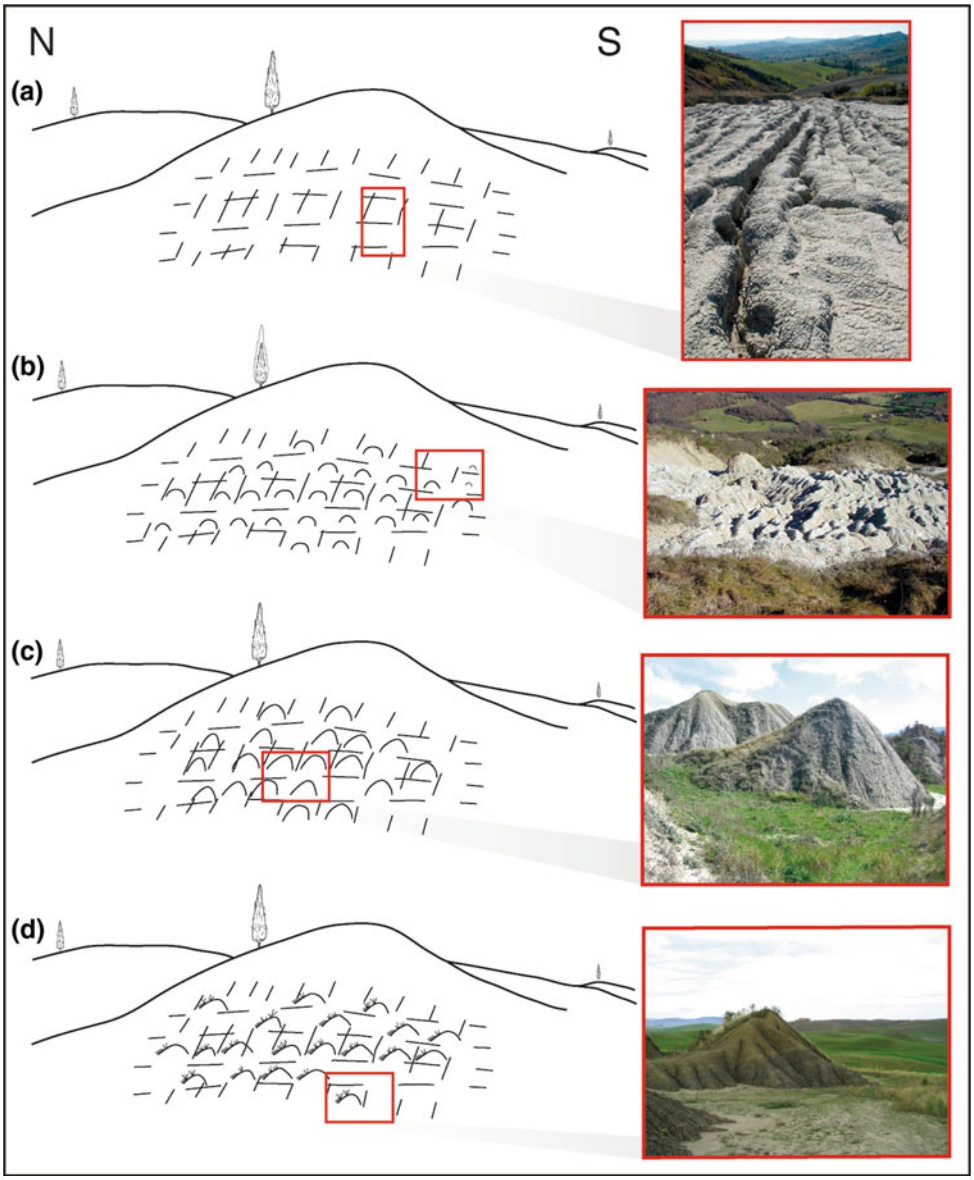

Fig. 24.9 *Biancane* morphoevolution. **a** A gentle slope on fractured clay cut by intersecting systems of joints is undergoing severe runoff processes. **b** Development of embryonic symmetrical *biancane*. **c** *Biancane* hight increases up to 15–20 m. Vegetation on shaded north-facing slopes covers them and prevents further erosion. The south-facing hillsides continue to increase its own slope, then evolve by parallel retreat. *Biancane* become asymmetric. **d** Fast erosion lowers the small domes and leads to the widening of micro-pediments

form a pipe network. Selective rill erosion shapes embryonic symmetrical *biancane* (Fig. 24.9b). When the *biancane* height increases, vegetation on shaded north-facing slopes covers them and controls the progress of erosion. Thus, the power of rill erosion decreases on north-facing slopes and *biancane* evolve asymmetrically; hereafter, the south-facing slopes evolve by parallel retreat and some micro-pediments appear at its foot (Fig. 24.9c). Finally, the south-facing slope parallel-retreating preserves the asymmetry of *biancane*, but fast erosion lowers the small domes and leads to the widening of micro-pediments (Fig. 24.9d).

Regarding *calanchi* evolution, their slopes probably evolve by substantial parallel retreat as long as caprock is present, according to the Scheidegger's model (Fig. 24.3). Some outliers with volcanic caprocks hold ancient villages (i.e. Orvieto, Civita di Bagnoregio) and picture suggestive landscapes (Fig. 24.10). When caprock remnants finally disappear, parallel retreat ceases and slope steepness rapidly decreases, unless the fluvial systems are rejuvenated. This evolution is accompanied by changes in denudation rates, as a function of the increasing mudsliding from the rill and gully heads.

Fig. 24.10 An outlier with volcanic caprock. On the top, the ancient settlement of Civita di Bagnoregio lies (Calanchi Valley, Tiber River basin, northern Latium)

24.5 Conclusions

In the Mediterranean region, soil erosion or, more broadly, severe slope denudation, is one of the most important environmental problems, both for its noticeable impact on human activities and for its consequences in natural environments. In the western sector of central Italy, geomorphic processes produce typical water erosion landforms, such as *calanchi* and *biancane*. These landscapes are very sensitive to land use changes that have occurred in recent times: from natural slopes affected by badlands, the trend has been firstly towards low-impact croplands, then to over-exploitation during the last 50 years, and finally to cropland abandonment. The present modifications are mainly due to an increasing contribution of mass movements to the erosional processes, previously driven mainly by surface running waters.

Anyway, slopes have very degraded soils or bare unstable surfaces, rapidly evolving due to strong wet-dry seasonal contrasts and widespread outcrops of erodible bedrock. However, these strong erosion processes have also created spectacular and rugged landscapes, alongside the cultural landscapes shaped by people over many centuries. Nowadays, the badlands landscapes in central Italy represent an additional resource for the territory, and not just "Bad Lands". Tourists visiting the monuments and cultural landscapes between Rome and Siena are also increasingly attracted by the natural aspects of the landscape, especially the most picturesque ones: *calanchi* and *biancane* landforms.

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The Tuff Cities: A ‘Living Landscape’ at the Border of Volcanoes in Central Italy

25

Claudio Margottini, Laura Melelli, and Daniele Spizzichino

Abstract

This chapter describes a unique landscape produced by the action of endogenous and exogenous factors at the border of the Vulsini Volcanic District between Latium, Umbria and Tuscany regions in central Italy. This area comprises a narrow strip corresponding to the transition between the pyroclastic coherent caprock (volcanic plateau) and the lower Pliocene soft clays. Several morphological features such as mesas, buttes, cliffs, pinnacles and towers represent the remnants of the original volcanic plateau, modelled by continuous mass movements and, since ancient times, hosting human settlements. The mutual relationship between the natural environment and the human presence is the mixing for a unique “Cultural Landscape”. The sites are still affected by geomorphological processes and many efforts are now in progress to maintain and preserve the historical villages on the top of the cliff.

Keywords

Butte • Mesa • Plateau • Vulsini Volcanic District • Central Italy

25.1 Introduction

There are places where the interplay between endogenous factors and morphogenetic agents builds up enchanting landscapes, suspended in a delicate position between being an environmental resource and a natural hazard. In this context, human settlements may be an enhancement of such beauty or become the main reason for its destruction. The “tuff cities” (from the Italian word “tufo”, an igneous rock of explosive volcanic eruption) lay on the border between Umbria, Latium and Tuscany and represent an excellent proof of such unstable equilibrium. Past geodynamic and volcanic events together with modelling by more recent exogenous processes have produced spectacular, wide table landforms, like plateaus and smaller *mesas* and *buttes*, characteristic throughout the whole area. These landforms became favourite and comfortable sites for human settlements and, in time, for secure and defensible historic towns.

These ancient and often precious urban centres are nowadays affected by natural hazards such as landslides that threaten their survival due to strong geomorphological activity. The resulting scenery, where human modifications contrast with and overlap the natural landforms, acquires the value of a “cultural landscape”. Because of the human action, the exact understanding of the original landscape formation and of its further evolution is fundamental for any scientific and management approach.

25.2 Geographical and Geological Setting

Moving between Latium, Umbria and Tuscany, in the northern and eastern portion of the Vulsini Volcanic District, a morphological unit is present characterized by an abrupt passage among flat top areas, steep slopes and carved river

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valley at the bottom (Fredi and Ciccacci 2017) covering roughly 480 km^2 (Fig. 25.1).

The area described in this chapter is a semicircle, from northwest and going to east, with the centre corresponding to the Bolsena Lake. Close to the lake, widespread flat areas are present where altitudes decrease gently moving away from the centre. Here the monotony of the top surface suddenly changes, the rivers deeply engrave the substrate, exposing the underlying rocks and deposits and revealing new and fascinating landscapes.

The drainage network shows a centrifugal pattern, starting from the Bolsena Lake and feeding three main rivers. On the western limit the Fiora River, flowing from north to south, is present while to the north the Paglia River, from WNW to ESE, receives the right bank tributaries from the central-eastern sector of the study area. Moreover, along the eastern part the Tiber River, the main collector, flows from north to south after a sudden curve elbow at the confluence with the Paglia River. The highest elevation values are recorded in the central part of the study area, at Torre Alfina (600 m a.s.l.), Benano (488 m), Sugano (436 m) and Acquapendente (420 m) villages. Altitudes decrease towards the eastern sector where the towns of Civitella d'Agliano (262 m) and Castiglione in Teverina (228 m) are present. All the aforementioned locations define the edge of the top surface, and highlight a morphological layer slightly tilted to the east. The least elevated terrain can be found along the fluvial valleys (Tiber River valley, 57 m).

The geological setting is characterized by two lithological complexes and deposits, corresponding to different paleoenvironments. At the bottom of the sedimentary sequence sea clays are present, covered by a volcanic complex (stratified pyroclastites, ignimbrites and lavas to a lesser extent). Landslide deposits are superimposed on both complexes. In order to delimit the zone where the transition between the volcanic tuffs and the clays produces such a typical landscape, a proper area has been identified. The definition of such an area considers the surrounding of the

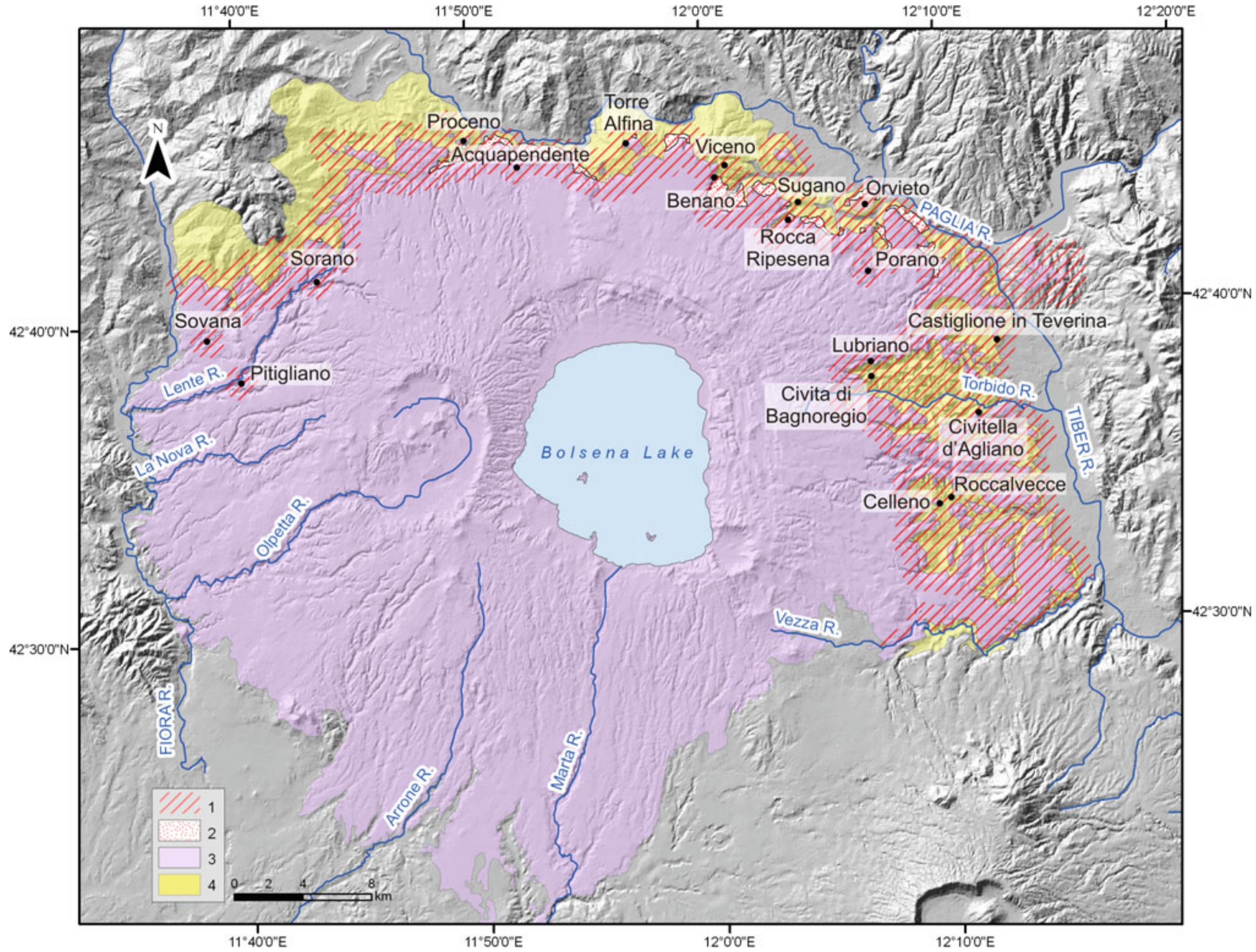

Fig. 25.1 Location map and geological sketch of the Vulsini area. *1* Geographical distribution of flat top areas, steep slopes and carved river valley described in this chapter; *2* debris and colluvial deposits; *3* volcanic caprock; *4* sea clays

stratigraphic limit between volcanic caprock and clays (Fig. 25.1).

The present geological configuration is the result of the geodynamic events that involved the central Apennines. In the Upper Miocene (7.2–5.3 Ma) a regional uplift occurred, followed by an extensional phase in the Lower Pliocene (5.3–3.6 Ma). Due to these events the topographic arrangement was articulated in horsts and grabens with Apenninic direction (NW–SE). The large basins of Paglia-Tiber to the east and Siena-Radicofani to the west constitute the morphological evidence of the vertical displacements involving the whole area (Bertini et al. 1971, Fig. 25.2). In this tectonic phase several transgression and regression cycles have left a large amount of sediments, both continental and marine. During this event a large amount of marine clays has been deposited.

In the Middle and Upper Pliocene (3.6 Ma) due to the uplift, the rise of a ridge and the resulting sea regression occurred. The uplift rate reached the maximum values in the Middle Pleistocene (1.8–0.8 Ma) and was followed by a tectonic collapse. In consequence, several normal faults originated in the area and voluminous volcanic activity occurred. The residual inner basin infill, with brackish sediments and fluvial or fluvial lacustrine depositional environments, evolved first in the area corresponding to the present Tuscany and afterwards in the Tyrrhenian coast of Latium (De Rita et al. 1983). In the Late Pleistocene (0.8–0.1 Ma) the volcanic cycle ended and a continental conglomeratic sequence developed (De Rita 2004). The eruptions occurred at over one hundred distinct centres, mostly located around or within the volcano-tectonic depressions of Bolsena and Latera. The arrangement of these centres forms a polycentric volcanic complex. Consequently, the Vulsini volcanic complex does not have a conical shape, but is characterized by gentle slopes with calderas and numerous minor volcanic forms such as craters and cones. The Vulsini Volcanic District developed in a time interval of approximately 450,000 years (Nappi et al. 1995), starting from about 600,000 and terminating some 100,000 years ago, and covers an area of approximately 2300 km^2 (Fig. 25.2). In this time interval, in different eruptive centres in the area periods of eruptive activity alternated with periods of quiescence. The volcanism associated with the high volatile content of the magma was mainly explosive, with paroxysmal activity. As a consequence, large pyroclastic deposits were produced and volcano-tectonic subsidence occurred, with associated formation of large calderas. The evolution of volcanism can be summarized into five periods of activity producing many volcanic complexes, partially overlapping (Fig. 25.2, Vezzoli et al. 1987).

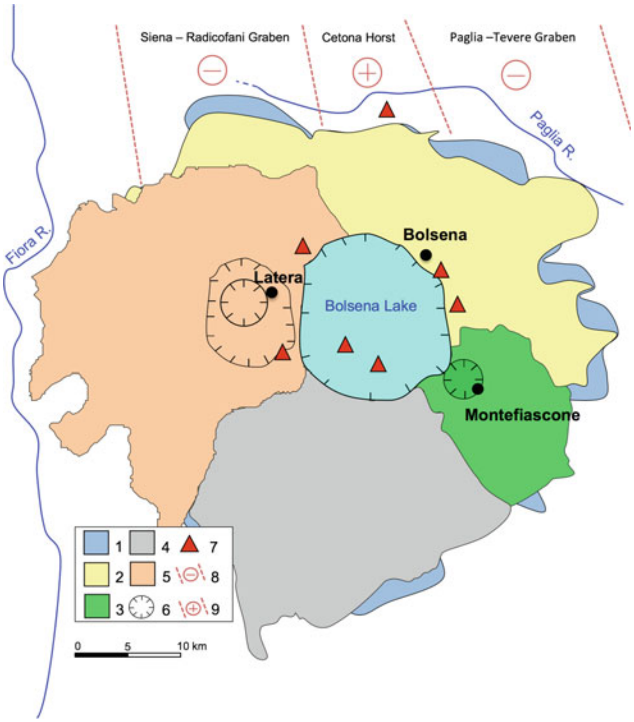

Fig. 25.2 Volcanic complexes of the Vulsini area (modified after Vezzoli et al. 1987): *1* Paleo-Bolsena (600–450 ka); *2* Bolsena (490–320 ka); *3* Montefiascone (300–200 ka); *4* South Vulsini (400–100 ka); *5* Latera (380–100 ka); *6* border of the main eruptive centre; *7* minor eruptive centre; *8* graben; *9* horst

25.3 Landforms: The Interaction Between Geological Structure and Exogenous Morphogenetic Processes

Geological and structural setting are the main causes of morphological configuration of the area. The presence of hard and fractured volcanic plateau rocks on the plastic clay basement is the main predisposing factor triggering erosion, transport and sedimentation phenomena. In addition, the tectonic events have activated the necessary relief energy to allow geomorphic agents to shape the topographic surface. The action of tectonic forces and the attempt of geomorphic agents to rebalance their effects are resumed in Fig. 25.3.

After the marine regression, in early Pleistocene normal faults have displaced and uplifted the sea clays along the eastern edge of the area. The fault scarp created a natural barrier to the volcanic products coming from southwest (Fig. 25.3a). When the geomorphic agents, in particular fluvial processes, started to shape the topographic surfaces, tectonic discontinuities played a major role influencing the development of the drainage pattern. As an example, the tracing of the paleo-Paglia River identifies a natural drainage line at the base of the fault scarp (Fig. 25.3b). The strong contrast of competence and erodibility between clays and massive tuffs has encouraged the erosion of the former and

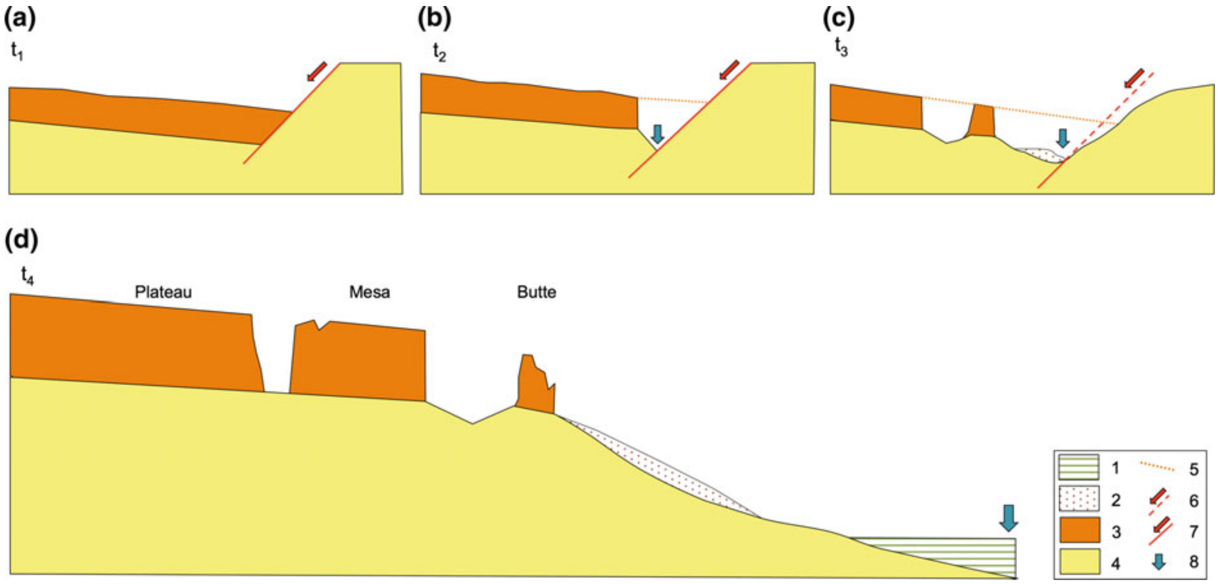

Fig. 25.3 Evolution of the entire area with reference to Paglia River drainage pattern: *1* alluvial deposits; *2* talus; *3* tuff caprock; *4* clays; *5* initial top of the volcanic caprock; *6* fault scarp; *7* fault plane; *8* paleo-Paglia River track (modified after Cattuto et al. 1994)

gradual deepening of the valley eastward. Progressively eroded at the base, the plateau reached the state of imbalance along the whole margins. Starting from this situation and because of the subsequent erosive action, especially by the right side river network, fragmentation of volcanic caprock started (Fig. 25.3c; Gregori and Melelli 2012). Where rivers are characterized by strong erosive capacity (mainly in the upper portion of the drainage basins), the demolition of the plateau is so exasperated that the volcanic cover is left in the form of completely isolated portions of different sizes such as mesas, buttes, cliffs, spires and towers (Figs. 25.3d and 25.4).

Nowadays landslides affect the volcanic caprock while slope processes, including mass wasting, runoff and fluvial ones model the underlying clays (Garbin et al. 2013).

The caprock is affected by cracks, in many cases open, due both to the cooling process of the volcanic products and to tectonic stresses. The result is the presence of different sets of discontinuities, isolating wedges of the pyroclastic sequence (tuffs and lavas). The weathering processes such as thermoclasty and frost shattering enlarge the fissures, whilst water presence increases the interstitial pressure both along the discontinuities and at the base of the volcanic cliffs. Tensile stresses develop evolving in shear and rotational landslides, in particular at the clays upper stratigraphic limit. The weight of the tuffs and volcanic wedges together with water infiltration are the main causes of decay of the geotechnical characteristics of the clayey basement. The consequent deformation of clays is the main reason for the subsidence of the upper strata of fractured rocks. As a consequence, along the edge of the plateaus, and even more on the isolated reliefs like mesas and buttes, falls and topples affect the borders of the volcanic sequence. The most evident consequence is progressive retrogression of the frontal slopes. Accumulation zones overlay the foot slope becoming debris and colluvial deposits.

In addition the Pliocene clays are subject to geomorphological processes where gravity and runoff play a fundamental role in slope adjustment. The weathering causes the decay of the geotechnical characteristics in particular between 0.5 and 1 m of depth. The absence of a vegetation cover (or even the presence of shrubs) makes the runoff more effective. Sheet, rill and gully erosion are widespread and contribute to the origin of badlands (Fig. 25.5).

Along the south-facing slopes badlands show their highest expression (Vergari et al. 2013; Del Monte 2017). Mudslides and mudflows are the most widespread landslide types. Moreover, the presence of volcanic caprock in some areas assures slope parallel retreat where both the slope angle remains high and the runoff continues in time. On the contrary, where the hard caprock on the top was dismantled, the entire hillside gradually diminishes in slope angle. Then the slope acquires a “convex–concave” geometric configuration and evolves with a “slope decline” model. It is therefore evident that the processes acting on the cliffs and on the underlying clays are not independent but closely linked (Ciccacci et al. 2003).

The drainage river network plays a fundamental role in the morphological evolution. Rivers are far from their equilibrium profiles since they are still attempting to rebalance the effects of tectonic forces. As a consequence, incision and headward stream erosion are ongoing, deepening and extending valley sides occur, while the basal clays are undercut and removed, leading to undermining at the bottom

Fig. 25.4 The “mesa” of the town of Orvieto, Umbria (after Ficola and Coletti 2011)

of the slopes. The steepness increases and slope stability decreases, favouring landslides affecting both the basal clays and the volcanic caprock.

Even if these conditions are the basis of widespread natural hazards, the resulting landscape is unique in terms of cultural and aesthetic values. The consequence is that the main reason of instability of these areas is at the same time the decisive factor contributing to their attractiveness. The slope profiles, where highest cliffs rest on gentle hills “scratched” by badlands are particularly suggestive since the skyline calls to mind the picture of ships floating on a choppy sea. To promote and enhance this uniqueness the only possibility is to preserve these areas and their value.

25.4 A Unique Cultural Landscape Around the Tuff Cities

Isolation guaranteed by the cliffs was in the past the main reason to develop human settlements on the top of the mesas and along the border of the plateaus. Moreover, the fertility of the volcanic soils (Santi et al. 2003) encouraged agricultural exploitation. The volcanic cliffs, easy to dug but sufficiently stable, were utilised since prehistoric times as refuges and later and still nowadays as storage or shelter for farm equipment. Over the centuries, this volcanic rock has allowed ancient populations (e.g. Etruscan, Romans and mediaeval) to exploit the territory by building necropolises, roads, workplaces, animal recoveries and cemeteries (Fig. 25.6).

In many cases a wide network of wells and tunnels cross the underground portion of the cliffs. These systems are nowadays still in use and sometimes even further excavation is taking place. Moreover, volcanic rocks offered the *pozzolana*, a main component of cement for buildings. In the least elevated areas clay deposits guaranteed huge amount of materials for handicraft production.

At the same time, the landscape was shaped, altered and sometimes protected by human presence. In some cases deforestation and inappropriate agricultural techniques have accelerated gravitational and fluvial processes. Likewise, an erroneous control of drainage network was the triggering factor for mass movements and soil loss. Nevertheless, human presence has sometimes slowed the paroxysmal

Fig. 25.5 Panoramic view of typical badland landscape

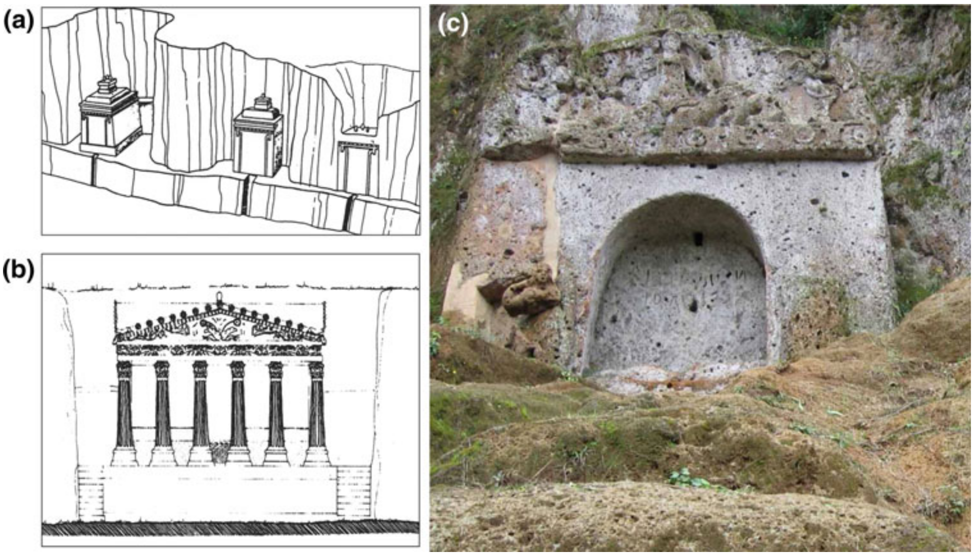

Fig. 25.6 Sepulchral monument types in Sovana: **a** dado (*cubic*), semi-dado and false dado tombs; **b** temple-style tomb; **c** the "Tomb of the Siren", so called because it is decorated with sculptures in high relief depicting a mermaid with two people (drawings **a** and **b** are modified after Nappi et al. 2004)

evolution. Landslide consolidation and reinforcement of the slopes as well as limiting river erosion are the most commonly executed actions.

The problem of historic urban settlement and heritage conservation, in geomorphologically hazardous areas, like the tuff cities, is generally ruled by two different approaches:

Fig. 25.7 The town of Civita di Bagnoregio (Latium) laying on a mesa

(i) a cultural heritage-driven approach, mainly focused on the preservation and conservation of the built heritage, where the main concerns and expertise are in archaeology, architecture or art conservation;
(ii) an engineering/geology-driven approach that exclusively takes into account stabilization and reinforcement of the physical landscape and structures.

Usually one approach is used without regard to the other, so that some aspects of the problem are underestimated or not even considered.

The town of Civita di Bagnoregio (Fig. 25.7), located on the eastern side of the area, is an excellent case where people have tried for centuries to hinder natural degradation of the cliff (Bandis et al. 2000). The town, of Etruscan or Villanovian origins (seventh century BC), experienced great expansion from the Roman Age to the late Middle Age, when the quarters Ponte and Carcere, now disappeared, where added to the original urban nucleus. Topographical and cadastral maps, dating back to the beginning of the eighteenth century as well as other historical maps and documents, have proved the progressive shortening of the cliff due to landslides that have caused, in different times, the disappearance of portions of the town. Many historical accounts recording landslides and stabilisation works, since 1373 AD, have been collected and analysed in order to reconstruct in detail the evolution of the urban setting and cliffs.

As a general remark, in the area described in this chapter, where the human settlements are present at least from the Bronze Age, a unique cultural landscape running from Pitigliano, Sovana, Sorano, Proceno, Acquapendente, Torre Alfina, Lubriano, Civita di Bagnoregio, Orvieto, Porano, Viceno, Benano, Sugano, Rocca Ripesena, Castiglione in Teverina, Celleno, Civitella d'Agliano and Roccalvecce is well recognisable (Fig. 25.8).

The link between landscape, landforms and human presence is so important in this area, to justify the term of *Anthropogenic mesas* for the majority of tufa plateaus. Due to this fact the area offers a unique opportunity to be a sort of guide for similar situations, becoming a Cultural Landscape where the natural background and the human presence are strictly related one to each other.

25.5 Conclusions

Many historical villages around the Vulsini Volcanic District in central Italy are located on high land with a flat top and surrounded by steep, cliff-like sides. This morphological contrast is a characteristic feature at the border of the volcanic plateau. The reason for such typical landform assemblage resides in the coexistence of rigid pyroclastic rock overlying plastic clays, with different competency and erodibility contrasts, affected by the combined action of endogenous and exogenous forces in space and time. The outer boundary of the area is at the base of the slope, bordered by the drainage network of three main rivers: Fiora, Paglia and Tiber.

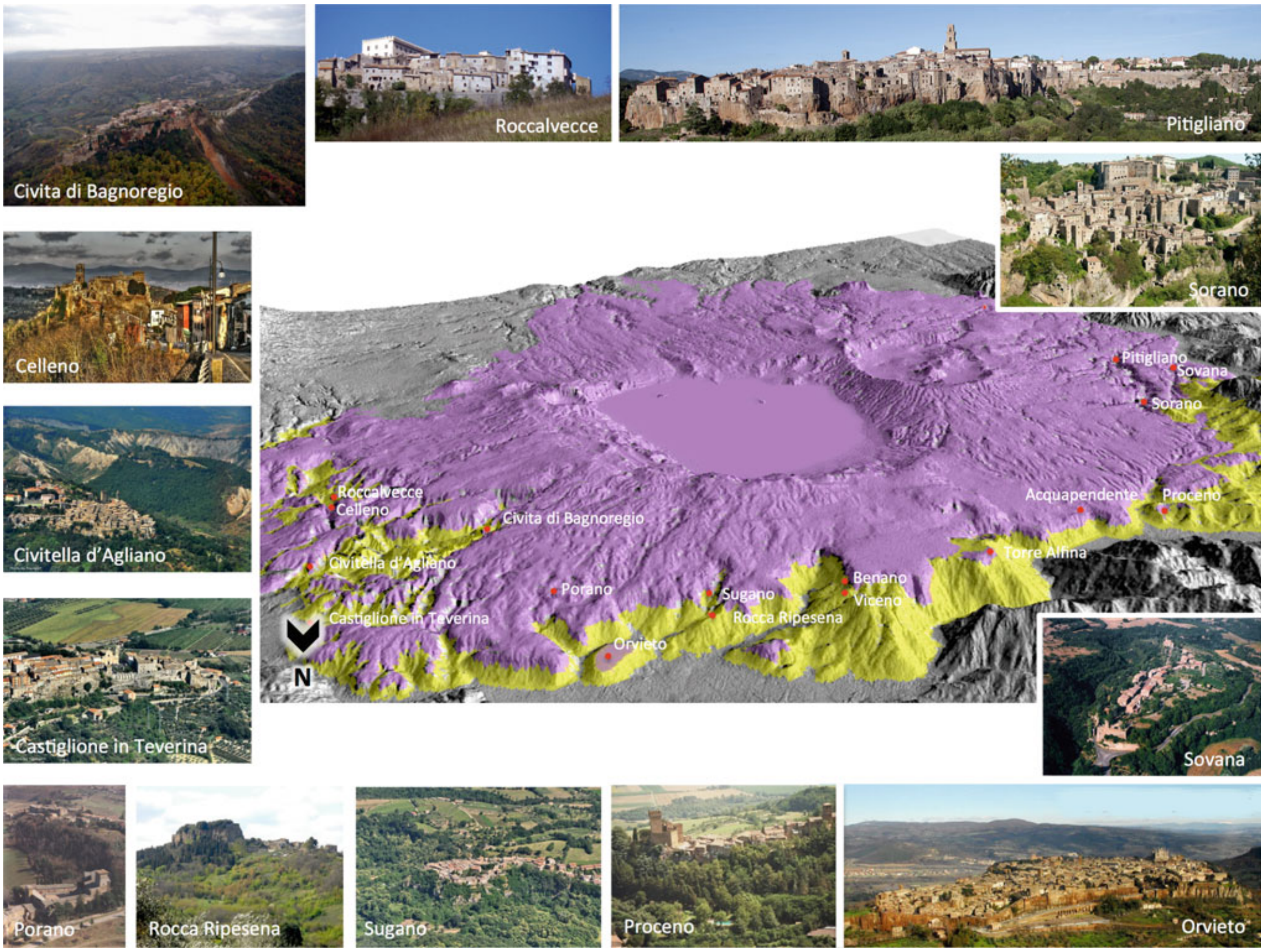

Fig. 25.8 The Vulsini area on a 3D model. Volcanic caprock is outlined in *purple* and sea clays in *yellow*. The panoramas of the most representative human settlements located in this cultural landscape are also included

The volcanic caprock is geomorphologically unstable, due to erosion at the toe of the hillsides, caused by fluvial action. Slope erosion affecting clays and fluvial processes, often characterized by headwater erosion, induce the caprock fragmentation and instability conditions, in particular along the edges. Several portions of different size, named mesas, buttes, cliffs, pinnacles, and towers, represent the remnants of the original volcanic plateau.

Nowadays gravitational activity is the main morphogenetic process that shapes the plateau, with rock slides and falls. On the top areas humans have found a favourable location for the development of settlements, since ancient times. In fact, this peculiar landscape formed an excellent natural defence against external aggression. The easy retrieval of building materials and the high fecundity of the land, due to the volcanic bedrock and temperate climate, have represented further benefits despite geodynamic unstable equilibrium of the area. People have been able to take advantage of the strategic positions offered by these headlands, creating towns of great historical, cultural and architectural values. However, their extreme fragility, due to the unrelenting action of exogenous agents and instability conditions, have represented a constraint to the development of settlements in modern period and nowadays they represent a wonderful historical urban landscape (Margottini and Spizzichino 2014), mainly demonstrating typical Middle Age villages.

Unfortunately, geomorphological processes are clearly still active and this is the cause of an uncertain future for the survival of these cultural landscapes. Increasing awareness is essential, in order to combine tourism exploitation with the rising of attention from policy makers and stakeholders within the social, economic and cultural conditions. The proposed candidature of the city of Orvieto and, in the near future, of Civita di Bagnoregio to include in the UNESCO World Heritage List is a great step in this direction, as is the proposal to create a national geopark in the whole area described in this chapter.

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A Route of Fire in Central Italy: The Latium Ancient Volcanoes

26

Paola Fredi and Sirio Ciccacci

Abstract

In the western portion of Latium (Central Italy) a series of ancient, generally evident volcanic edifices and numerous lakes hosted in depressions is present. They are directly or indirectly tied to severe volcanism which occurred between 2 and 0.08 Ma ago. From a geomorphological point of view, it is possible to identify different volcanic landscapes, whose appearance mainly depends on the magma chemistry. The landscape of the Tuscan-Latium Magmatic Province, which was fed by silicic magmas, is typified by numerous lava domes, rising up from a generally flat ignimbritic plateaux. The landscape of the alkaline potassic volcanism shows strong differences that are tied to the existence or not of well-identified central volcanic edifices. In the first case the landscape is dominated by the presence of outstanding volcanic relief; in the second one many different minor emission centres are scattered over large flat areas, mainly built up by pyroclastic flows.

Keywords

Volcanic landforms • Extinct Pleistocene volcanism • Latium

26.1 Introduction

The landscape of Latium is extremely diverse as a consequence of its complex and lively geological history, its varied outcropping rocks and various, often intense, exogenous processes. Mountains, hills, gorges, and wide fluvial valleys follow one another from the inner zone of the Apennine chain as far as the plains of the Tyrrhenian coastal zone. The most distinguishing feature of the western portion of Latium, close to the Tyrrhenian coast, is without doubt the presence of a series of ancient, generally evident volcanic edifices and numerous lakes that are hosted in depressions and are directly or indirectly tied to past severe volcanism. In fact, the volcanic landscape is such a distinctive characteristic of Latium that it makes this region unique in Central Italy.

Latium volcanism belongs to the *Tuscan-Latium Magmatic Province*, which developed, starting from the end of the Pliocene, in a structurally depressed belt that is parallel to the Tyrrhenian coast and is bordered in the east by the highest sector of the Apennines.

Even if some authors think that some of these ancient volcanoes are not completely extinct, there are no eyewitnesses reports of their eruptions. However, Latium volcanoes and their products have strongly influenced the lifestyle of ancient inhabitants, who were probably unaware of living in volcanic areas. Many volcanic products have an important role also in modern life. For example, obsidian that was produced by the volcanic eruptions of the Ponziane Islands is suitable to create sharp tools, which favoured the development of prehistoric settlements in these islands. Many Etruscan necropolises were carved into volcanic "tufa", produced by Monti Sabatini volcanism. This rock, actually the deposit of pyroclastic flows, is easy to cut but is characterised by high strength. These same "tufa" are commonly used as building stones even today, and quarries are important man-made landforms in these areas. The Ancient

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Romans used lavas from the Colli Albani volcano to pave their roads. Small lava blocks that resemble truncated, square-based pyramids and locally called "sanpietrini" were used during the reign of Pope Benedetto XII to pave San Pietro square, and they still represent the traditional pavement of many streets and squares in the centre of Rome.

The archaeological site of *Tusculum*, in the Colli Albani volcanic area, is of particular interest both from a volcanological and historical point of view. At this site, the "Sperone" stone crops out; it is a deposit of welded scoriae that were emitted by low lava fountains ejecting from radial and tangential fractures, which are related to the collapse of the caldera that characterises this volcanic relief. This stone was used by the Romans to build houses in the antique town *Tusculum*, but it constitutes also the load-bearing structure of the *Colosseum.*

In the second half of the fifteenth century, the discovery of a large quantity of alum, which is a mineral used at that time to paint clothes and tan hides, changed the Tolfa volcanic area into an industrial district that was among the most important ones in Europe.

When volcanic activity ceased, slow pedogenetic processes affected the volcanic rocks and led to the formation of very fertile soils, which are rich in minerals crucial for agriculture. The cultivation of vineyards, already practised by the Ancient Romans, is still an important resource for the economics of the Vulsini and Colli Albani volcanic areas.

Although it is likely that nobody watched the dramatic eruptions of Latium volcanoes, there are many witnesses to their late, mainly hydrothermal activity, which is easily recognisable even today. Close to Viterbo, a town in northern Latium, the thermal baths of Bullicame, which were very famous among the Ancient Romans, and the springs of Polla di S. Sisto, are still frequented. Again, the "Caldara di Manziana", which is one of the most important geosites of Latium, is a depression from which large quantities of gas escape, testifying to the hydrothermal activity of the late stage of Monti Sabatini volcanic activity. These are only a few among the many examples, but they all demonstrate the significance of Latium volcanism for the past and present human activities.

26.2 Geographical and Geological Settings

To understand the origin and evolution of the volcanoes in Central Italy, and specifically in Latium region, it is necessary to go back in time to approximately 5 million years ago. At that time, the western sector of the Apennine chain, which had almost completely emerged, began to thin and sink, as a consequence of the horst and graben tectonics that was associated with the birth of the Tyrrhenian Sea. During this tectonic phase, a striking, mainly NW–SE-oriented fault system led to the formation of deep depressions that were successively flooded by marine ingression. Approximately from 4 to 3 million years ago, these large fractures allowed a huge quantity of crustal, chiefly acid magma to ascend along a large number of conduits that fed the volcanism of Latium. This impressive phenomenon followed a straight southward route; it started in Toscana (Mt. Amiata) and then moved to Latium, where Mt. Cimino, Tolfa and Cerite-Manziate lavas (from 4 to 2 Ma ago) and successively lavas from Monti Ceriti and Ponziane Islands (from 1.5 to 0.9 Ma ago) were progressively emplaced.

During the last one million years the fault activity renewed and a transversal fault system (NE–SW oriented) developed. During this magmatic phase, which is called the alkaline potassic phase, magmas generated in the upper mantle rose up to the surface through the newly formed fractures, causing a spectacular sequence of volcanic events that lasted until very recent times.

This new, high potassium content volcanism concentrated in four areas. From north to south, these areas correspond to the following four volcanic districts: Monti Vulsini District, Cimino-Vico District, Monti Sabatini District and Colli Albani District (Fig. 26.1). Probably due to complex tectonic arrangement of the mainly carbonate basement, the rising magma often concentrated in small and isolated chambers that fed numerous emission centres that were scattered over large areas. Locally, in contrast, the activity concentrated at certain places, building central volcanic edifices. Referring to the four alkali potassic volcanic districts, the scattered or central volcanic activity alternates from north to south: the Vulsini and Sabatini District had mainly scattered activity, while in the Cimino-Vico District and Colli Albani District, the locally concentrated volcanic activity gave rise to central volcanic edifices (Peccerillo 2005).

26.3 Landforms and Landscapes

The volcanic districts of Latium show peculiar characteristics if compared with other volcanic areas of Italy. The emplacement of lava flows, fall deposits and, chiefly, huge pyroclastic flows tied to the explosive volcanic activity produced wide plateaux, gently dipping outward from the central areas where the main volcanic centres were located. From a geomorphological point of view, it is possible to identify different volcanic landscapes, which mainly depend on the magma chemistry: the landscape of the Tuscan-Latium Magmatic Province, which is fed by silicic magmas, and the landscape of the alkaline potassic volcanism, whose diversity is related to the presence or absence of well identified central volcanic edifices.

Although the acid, viscous magmas of the Tuscan-Latium Magmatic Province had likely built volcanic landforms, the

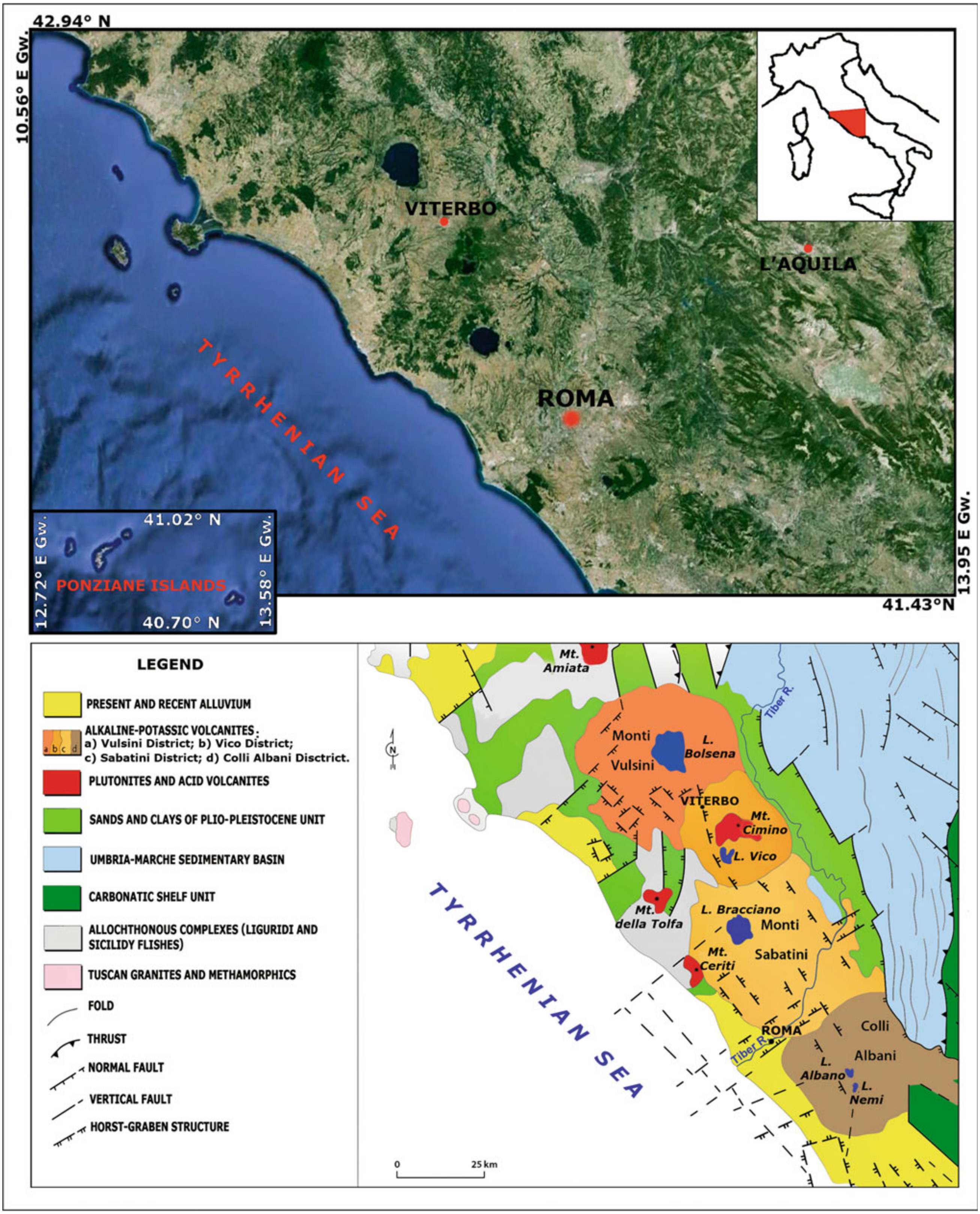

Fig. 26.1 Geographical setting of Latium (Google Earth © 2015—Image Landsat) and geological sketch of the tectonic arrangement in which volcanism developed (modified after Caputo et al. 1993)

products of the more recent, alkaline potassic volcanism are much more common and surely dominate most of the Latium territory. It is the latter that can be reasonably considered to be the main maker of the volcanic landforms of Latium.

26.3.1 The Volcanic Landscape of the Tuscan-Latium Magmatic Province

The volcanic districts of Latium nourished by silicic magmas are represented by the Cimino Volcano and the Tolfetano-Cerite Volcanic System, whose activity was markedly explosive. Their landscape is dominated by large ignimbritic plateaux, interspersed by dome-shaped lava landforms with steep slopes (typically lava domes) that often attain high elevations above sea level.

At present, more than 50 subconical hills are preserved in the area of the Cimino Volcano. They originated from the accumulation of lavas of rhyolitic to trachydacitic composition; Mt. Cimino (1053 m a.s.l.) stands out among them (Borghetti et al. 1981; Fig. 26.2). The lava domes (approximately 20) prevail in the Tolfetano-Cerite Volcanic System. They are slightly elevated, with Mt. Santo being the highest (430 m). They show different morphological characteristics, which mainly depend on the varying content of silica; the higher this content, the steeper and higher are volcanic constructions (De Rita et al. 1994).

26.3.2 The Volcanic Landscape of the Alkaline Potassic Districts

The morphology of the areas affected by this type of volcanism varies greatly, and the variety of landforms strictly depends on the predominance of central or scattered volcanic activity. In the first case, the landscape is dominated by low relief surfaces, which are mainly due to the emplacement of pyroclastic flows that have obliterated any pre-existing morphology. These generally flat areas are interrupted by the presence of easily recognisable central volcanic edifices, truncated at their summits by caldera depressions, inside of which secondary and more recent cones have originated. In the second case, the emission centres are largely spread over a wider area, and easily discernible volcanic edifices are lacking.

The landscape of the areas where central volcanic activity occurred (the Vico Volcano and the Colli Albani Volcano) shows easily discernible central volcanic edifices. They were typical stratovolcanoes and are truncated at their summits by large depressions due to caldera collapses. Smaller and steeper cones rose up in a later phase from the caldera bottom.

26.3.2.1 Vico Volcano

The Vico Volcano history (Mattias and Ventriglia 1970; Buonasorte et al. 1990) is schematically shown in Fig. 26.3a. The present landscape is dominated by the Vico Volcano caldera, inside which the more recent 325 m-high lava cone of Mt. Venere developed (Fig. 26.3b). The caldera depression has a very irregular shape, which roughly resembles a horseshoe. The depression-specific profile is derived by the coalescence of at least four circular landforms; each of these landforms is tied to one of the main ignimbritic eruptions, which were responsible for the caldera collapse.

The largest part of this depression is now occupied by the Vico Lake (Fig. 26.4), a volcanic lake in Italy at the highest altitude (510 m), which can be considered to be the most outstanding feature of the Vico Volcano area. Historical data indicate that the lake was larger in the past and Mt. Venere, now completely emerged, was previously an island. In fact, the water level of the lake was artificially lowered by approximately 20 m in the Etruscan era. The ancient population dug an underground tunnel in the pyroclastic flows

Fig. 26.2 View of Mt. Cimino Volcano, the highest relief among the Latium volcanic areas

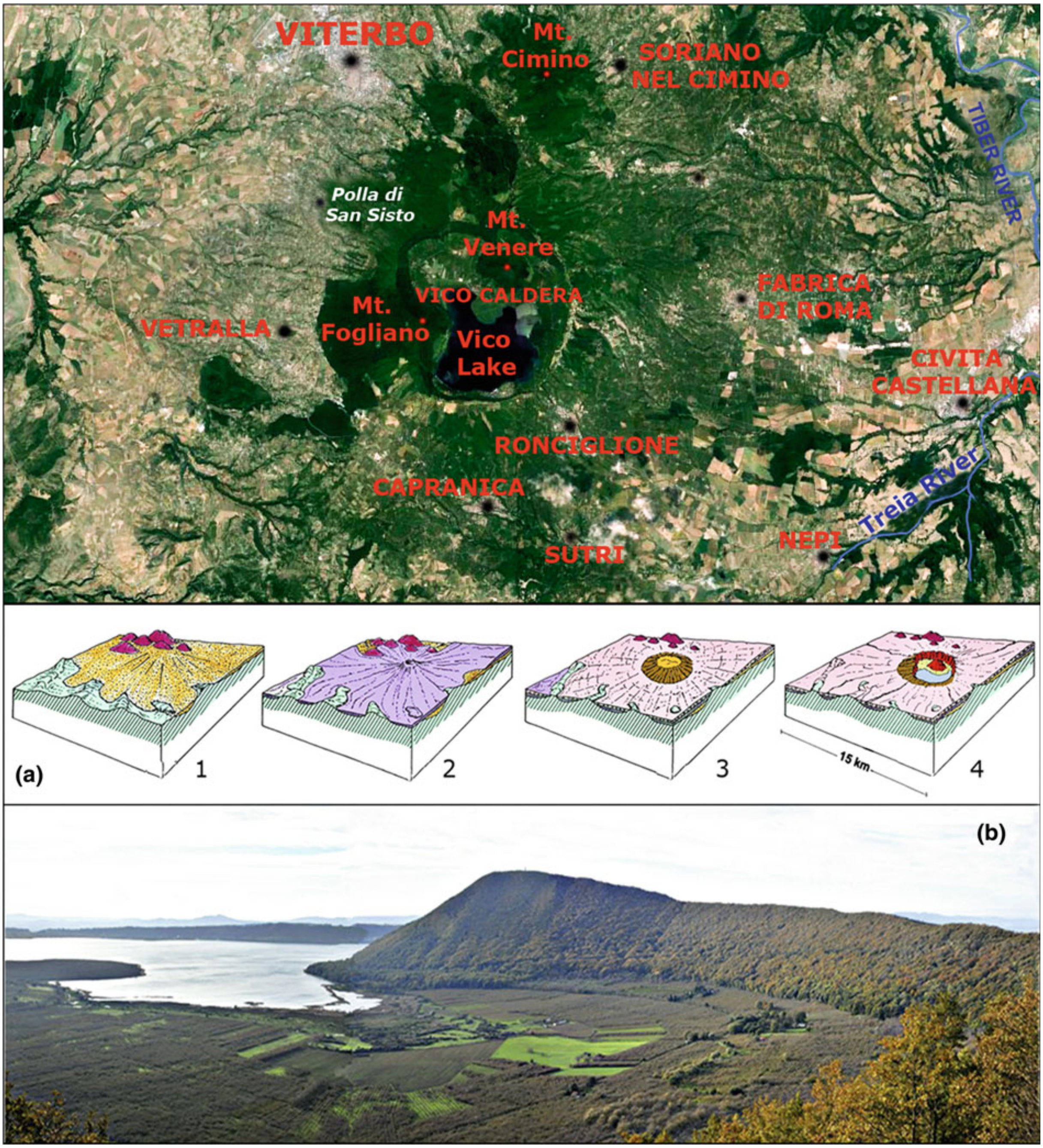

Fig. 26.3 *Top* satellite image of Vico Volcano (Google Earth—Image © 2015 DigitalGlobe). **a** Volcanological and morphological evolution of the Vico Volcano. *1* 0.8–0.4 Ma ago; explosive activity produced fall deposits and pyroclastic flows; *2* 0.35–0.2 Ma ago; mainly effusive activity: the central volcanic edifice was built up; *3* 0.2–0.15 Ma ago; Plinian eruptions produced pyroclastic flows; collapse of the volcano summit and the formation of the Vico Caldera; *4* 140–95 ka ago; a lake originated inside the caldera; phreatomagmatic activity produced the "final tuffs". At the end, lava flows formed the Mt. Venere cone. **b** Panoramic view of the Vico Caldera and its lake

that drained the lake waters from the lake's southwestern end beyond the caldera walls, towards the Treia River (a Tiber tributary). Their aim was to control the water level fluctuations and to gain dry land suitable for agriculture. Successively, the eminent Farnese family restored the Etruscan tunnel in the sixteenth century, and the water level was lowered by approximately three more metres. These human interventions had an important role in the morphological evolution of the caldera bottom, where wide swampy areas—rich in organic matter—developed on the blackish and greyish lacustrine clays. Some of these areas—especially those on the northern and eastern sides—were completely dried out and used to grow almond trees, an agriculture practice that continues to characterise this area.

Fig. 26.4 The Vico Lake viewed from the south shore. The Mt. Venere cone is on the *right*; on the *left* is the Mt. Fogliano relief

Nevertheless, swampy areas are still preserved at places along the waterside.

The caldera rim attains the maximum altitude at Mt. Fogliano (965 m). The inward slopes are very steep as a consequence of the collapse; they are drained by centripetal short and ephemeral watercourses that directly join the lake The outward slopes result from the emplacement of pyroclastic flows, fall deposits and subordinate lava flows and represent the lower reaches of the higher ancient volcano, before the caldera collapse. In contrast to the caldera inner slopes, they are gently dipping and deeply cut by a general centrifugal drainage network. In fact, the present morphogenetic processes are mainly associated with channelled surface waters.

26.3.2.2 Colli Albani Volcano

Although the Colli Albani Volcano (also called Latium Volcano or simply Castelli Romani; Fig. 26.5) and its products are spread over a much larger area (1600 km^2) than the Vico Volcano (850 km^2), the two volcanic areas show geomorphological similarities.

As in the case of the Vico Volcano, also the Colli Albani Volcano landscape is dominated by a gently sloping volcanic relief that is truncated by the summit caldera, inside which a younger cone is present. This relief, called Tuscolano-Artemisio, is the remnant of an old stratovolcano that was active from 0.6 to 0.3 Ma ago, when the caldera collapse occurred. The caldera depression is circular in shape and stretches over an arc of 230°, having a diameter that ranges from 10 to 12 km, and a maximum altitude of approximately 900 m. The younger and smaller volcanic Faete Edifice, which was active from 0.3 to 0.2 Ma ago, rises from the flat caldera bottom (“atrio”) to 949 m at Mt. Cavo. This younger edifice has a summit called Campi di Annibale. The Tuscolano-Artemisio circular relief is interrupted at its western reach by the eccentrical craters of Albano, Nemi and Valle Ariccia, which originated during the final hydromagmatic phase from 200 to 20 ka. At present, the Albano and Nemi craters are the sites of pleasant small lakes (Caputo et al. 1995; De Rita et al. 1995; Karner et al. 2001; Fig. 26.6).

The denudational processes that are presently acting in the Colli Albani area are mainly due to running water and subordinately to gravity. Sheet, rill and gully erosion are typically found on the highest and steepest parts of the volcano slopes and where less resistant lithologies crop out. The differential action of weathering and slope wash is responsible for the origins of the scarps, which are especially evident along the inward-facing slopes of the main crater depressions. Here, massive and lithified pyroclastic flow deposits are interbedded with the less resistant pyroclastic fall products and hydromagmatic deposits. Trough-floored, flat floored and V-shaped valleys derive from the dominant action of the channelled surface waters. The trough-floored valleys owe their origin to the combined action of fluvial incision and slope processes (Ciccacci et al. 1986).

26.3.2.3 Monti Vulsini and Monti Sabatini Volcanoes

The landscape of the Monti Vulsini and Monti Sabatini volcanic districts lacks a clearly defined central activity and is much flatter than the landscapes discussed so far. Among the main notable features are the presence in the central sectors of wide volcano-tectonic depressions, which host Lake Bolsena (Monti Vulsini) and Lake Bracciano (Monti Sabatini), and the scattering of many emission centres over very large areas.

The Monti Vulsini Volcanic District extends for approximately 2200 km^2 (Fig. 26.7) and is characterised by the presence of the large Bolsena Lake in its central part (Fig. 26.8a). The most evident volcanic landforms are the Montefiascone caldera and the Latera caldera (Buonasorte et al. 1991) to the west and southeast of the Lake Bolsena depression, respectively. The eastern and northern edges of

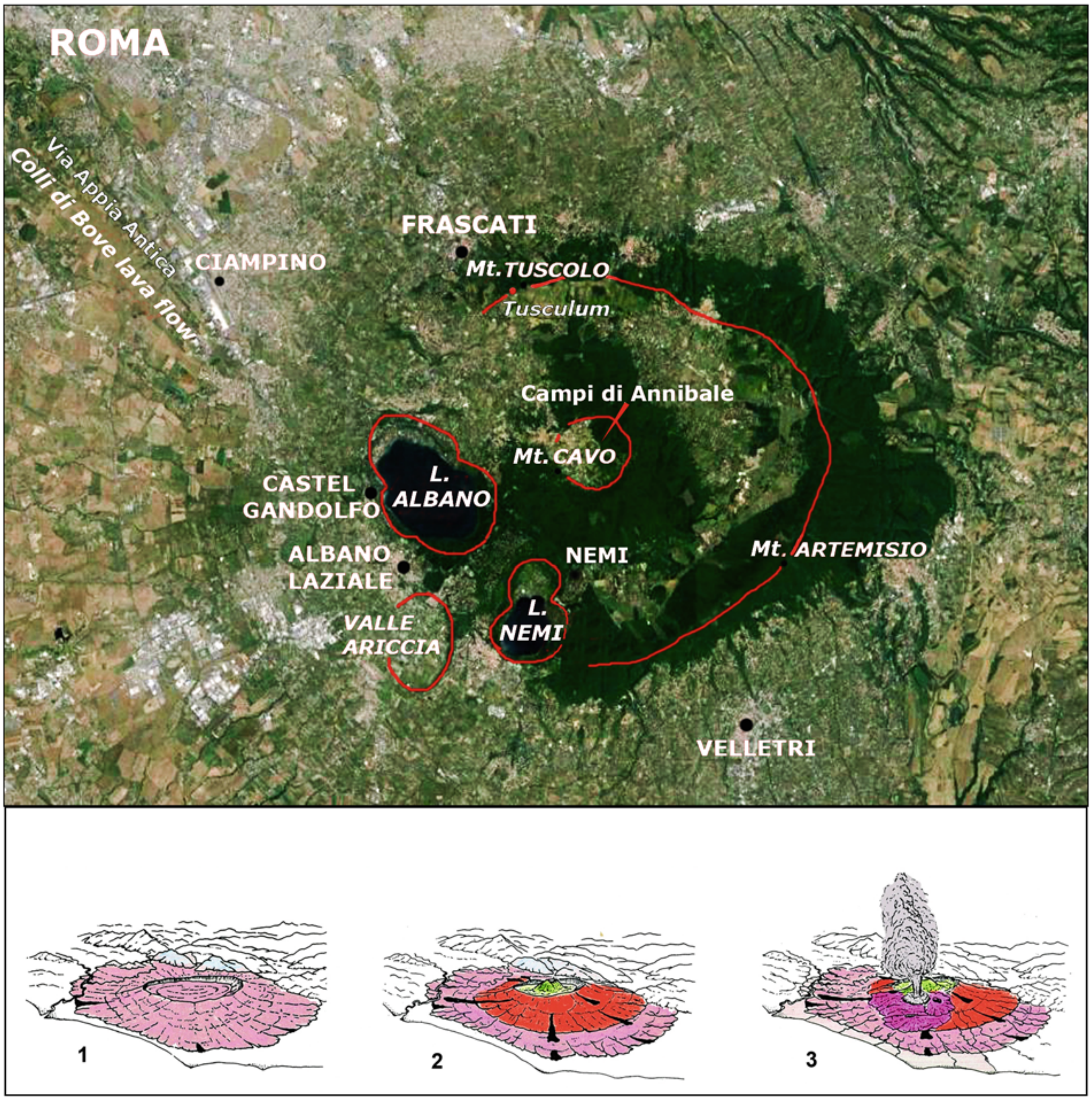

Fig. 26.5 *Top* satellite images of Colli Albani Volcano (Google Earth—Image © 2015 DigitalGlobe). *Bottom* schematic evolution of the Colli Albani Volcano: *1* Tuscolano-Artemisio period (0.6–0.3 Ma ago); *2* Faete period (0.3–0.2 Ma ago); *3* hydromagmatic period (0.2–0.02 Ma ago)

the lake depression clearly show the presence of steep slopes, which are N–S and NW–SE oriented and are the surface expressions of faults that are responsible for the origin of the tectonic-volcanic depression.

The Latera caldera is the result of a collapse that occurred approximately 60 ka ago at the summit of a former large stratovolcano, which was built between 0.3 and 0.1 Ma ago. The caldera rim has a typical elliptical shape and is broken westward in effect of more recent volcanic events, which produced numerous scoria cones and the huge lava plateau of Selva del Lamone. This plateau resulted from the fissure eruption of numerous lava flows between 170 and 50 ka ago that extended southwestward for approximately 8.5 km. The morphological evolution of this sector of the Vulsini volcanic area was deeply influenced by the emplacement of the lava flows that caused the inversion of the relief. In fact, they are likely to have filled a former valley, thereby producing a new divide and forcing the stream to develop a new valley along the previous divide. To the north of Latera caldera, a gently northward dipping surface is present. It is made of pyroclastic flows that erupted from the ancient Latera stratovolcano and is affected by efficient incision by streams forming a centrifugal drainage network. This area is also important from an archaeological point of view. In fact, it is

Fig. 26.6 Lake of Nemi, viewed from Mt. Cavo. The lake occupies the southern part of two coalescent craters, typically 8-shaped, which originated about 180 ka ago

the site of the famous “Tagliate etrusche” (Etruscan cuts, Fig. 26.8b): very deep and narrow roads dug in the pyroclastic flows by the Etruscans approximately 2500 years ago, probably to reach their necropolis or, according to another interpretation, to canalise surface running water. In fact, the man-made landforms are here as important as the natural landforms.

The Montefiascone caldera, on the southeastern margin of Bolsena Lake, is the result of the collapse of the homonymous former volcano that erupted the pyroclastic flows of the Vulsino southwestern plateau between 0.3 and 0.1 Ma ago (Nappi and Marini 1988). This smaller circular caldera (Fig. 26.7) is bordered by very steep and well-preserved slopes. The town of Montefiascone, which is famous for its esteemed wine (known as “Est Est Est” since the Middle Ages), is built on one of the scoria cones located around the Montefiascone caldera.

The superimposition of different pyroclastic flows that erupted from the oldest and now erased stratovolcano of the complex (Bolsena Volcano) has given rise to the roughly horizontal plateau of the eastern Monti Vulsini sector, gently sloping eastward, where it is bordered by the scarp due to the Tiber River’s deepening. The plateau is affected by vigorous stream erosion that reached the underlying Plio-Pleistocene clays. In the more distal portion, the plateau is so strongly dissected that tabular hills, similar to mesas or buttes, are common. The caprock is made of pyroclastic products, while the lower slope sections are shaped in the Plio-Pleistocene shales. The very different resistance to erosion of these lithologies has favoured the development of wonderful landscapes, which are the sites of charming towns such as Civita di Bagnoregio and Orvieto.

The landscape of the Monti Sabatini Volcanic District (1700 km^2) resembles that of Monti Vulsini. Additionally, a lake depression (Lake Bracciano) dominates in the central sector (Biasini et al. 1993; Fig. 26.9).

The most evident volcanic landforms are in the eastern sector, where the Sacrofano-Baccano Volcanic Complex has developed (Ciccacci et al. 1986). The wider and older Sacrofano caldera originated approximately 0.36 Ma ago at the expense of a former volcano; its western margin was successively interrupted by the more recent collapse of the Baccano caldera. The northern slopes of the two calderas are the headwaters of Treia River, which drains countercurrently with respect to Tiber River before joining it close to Civita Castellana town. The middle Treia valley is strongly incised in the low relief pyroclastic plateau. Splendid landscape views occur in the area. The Mt. Gelato waterfall (Fig. 26.10a) or the residual tuff cliffs where the Etruscan town of Narci and the mediaeval town of Calcata (Fig. 26.10b) were built are suggestive examples.

The central sector of the Monti Sabatini is dominated by Lake Bracciano (Fig. 26.10c). It is also rich of circular or sub-circular secondary depressions produced during the late hydromagmatic phases of the volcanism (maars; Sottili et al. 2011) and located mainly on the eastern and northeastern edge of the lake. Among them, the most important are the Monterosi and Martignano craters, hosting small lakes, the Stracciacappa crater, which was once the site of a shallow sheet of water and is now completely and artificially dried out, and the Trevignano crater, which is actually an inlet of Bracciano Lake. The landscape of the sector to the north of Bracciano Lake is interrupted by numerous scoria and lava cones; the cone of Mt. Rocca Romana, which overlooks the lake, is the highest relief (612 m) of the Monti Sabatini volcanic district.

26.3.3 The Ponziane Islands

The Ponziane Islands archipelago is composed of five main volcanic islands. The northwestern islands of Ponza

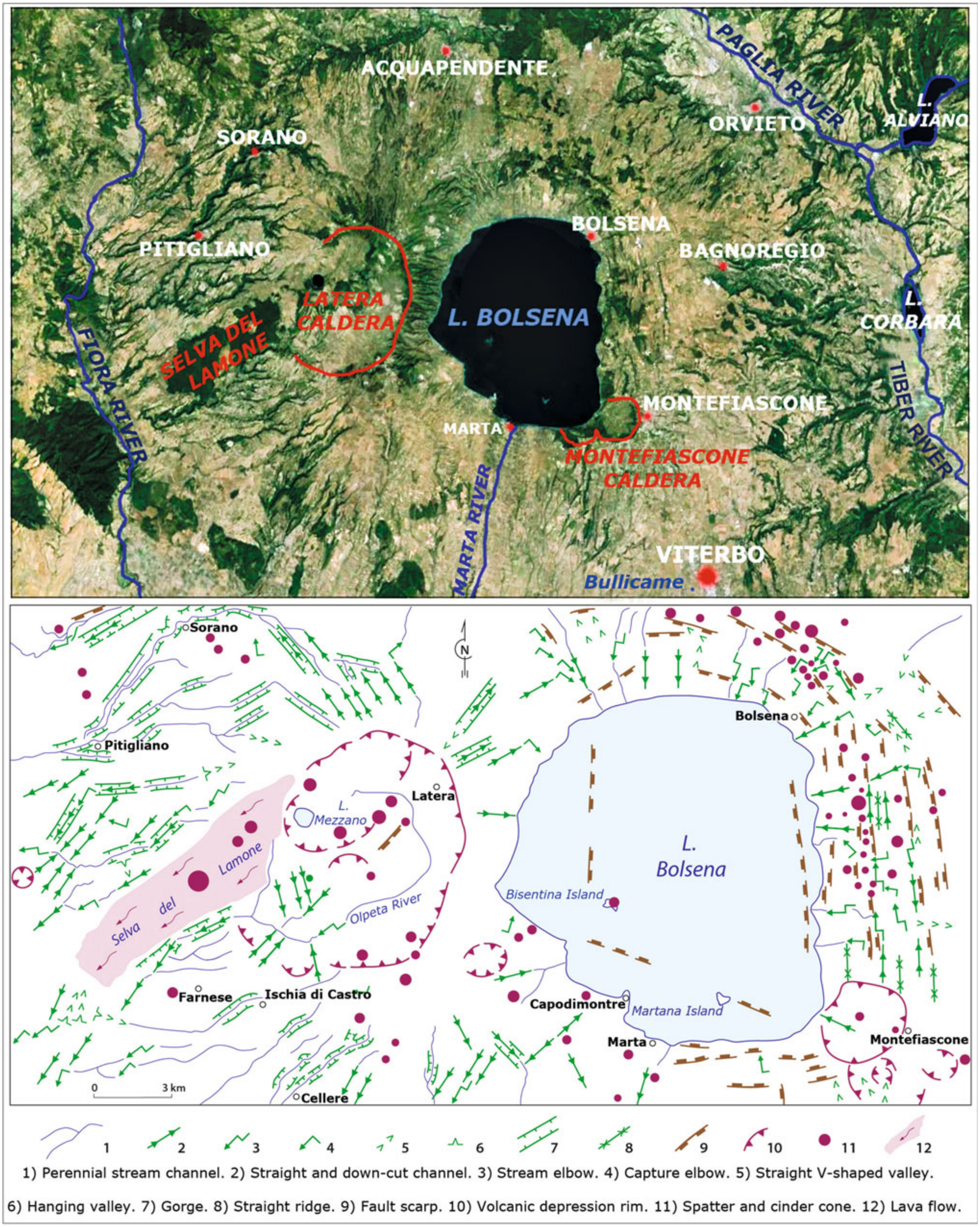

Fig. 26.7 Satellite image of the Vulsini Volcanic District (Google Earth Image © 2015 DigitalGlobe) and related morphological sketch (modified after Buonasorte et al. 1991)

Fig. 26.8 **a** The lake of Bolsena and Montefiascone caldera viewed from Montefiascone town. **b** Tagliata Etrusca in the pyroclastic flows of the Latera Volcanic Complex; Pitigliano is neighbouring

(Fig. 26.11a), Palmarola and Zannone are an emerged portion of the Tyrrhenian Platform and were marked by an ancient (approximately 1.5–1.1 Ma old) acid and mainly underwater volcanic activity, which produced rhyolitic lavas. The southeastern islands of Ventotene and Santo Stefano are characterised by an alcalino-potassic chemistry (0.7 Ma old). Ventotene extends for approximately 3 km and attains maximum altitude of 139 m; it is an emerged portion of the Ventotene central volcano, which rises for 900 m from the bottom of the Gulf of Gaeta. The smaller island of Santo Stefano (Fig. 26.11b) is the summit, which emerged as a part of a secondary cone of the same volcano.

26.4 Scientific and Cultural Value of the Latium Volcanoes

The volcanic landscape of Latium has specific peculiarities that derive from the activity of both endogenous and exogenous processes, which make this region unique in the Italian context. Volcanic events are responsible for the primary general imprint. Volcanic cones, calderas, volcano-tectonic depressions, craters, volcanic lakes and gently outward sloping pyroclastic plateaux erased the former landscape and prepared a very specific scenario for the subsequent action of erosional and depositional processes, which are mainly related to the action of running surface water. The entire volcanic district was affected by marked fluvial downcutting in response to an increased volume of relief. As a consequence, narrow and deep valleys were formed. Their cross sections often show step-like profiles, which derive from differential erosion of the pyroclastic flows, lava flows and fall deposits, each having specific strength and different resistance to surface processes.

Furthermore, the general radial centrifugal pattern of the drainage networks is often disturbed by the presence of fractures and faults that affected the volcanic cover in very recent times and the morphological evolution as well.

Taking these considerations into account, it is easy to understand why the volcanic areas of Latium have a precious scientific and aesthetic value. In fact, many interesting places have been chosen to be Regional or Provincial Parks or Reserves: the Regional Natural Reserves of Selva del Lamone, Lago di Vico and Monterano; and the Regional

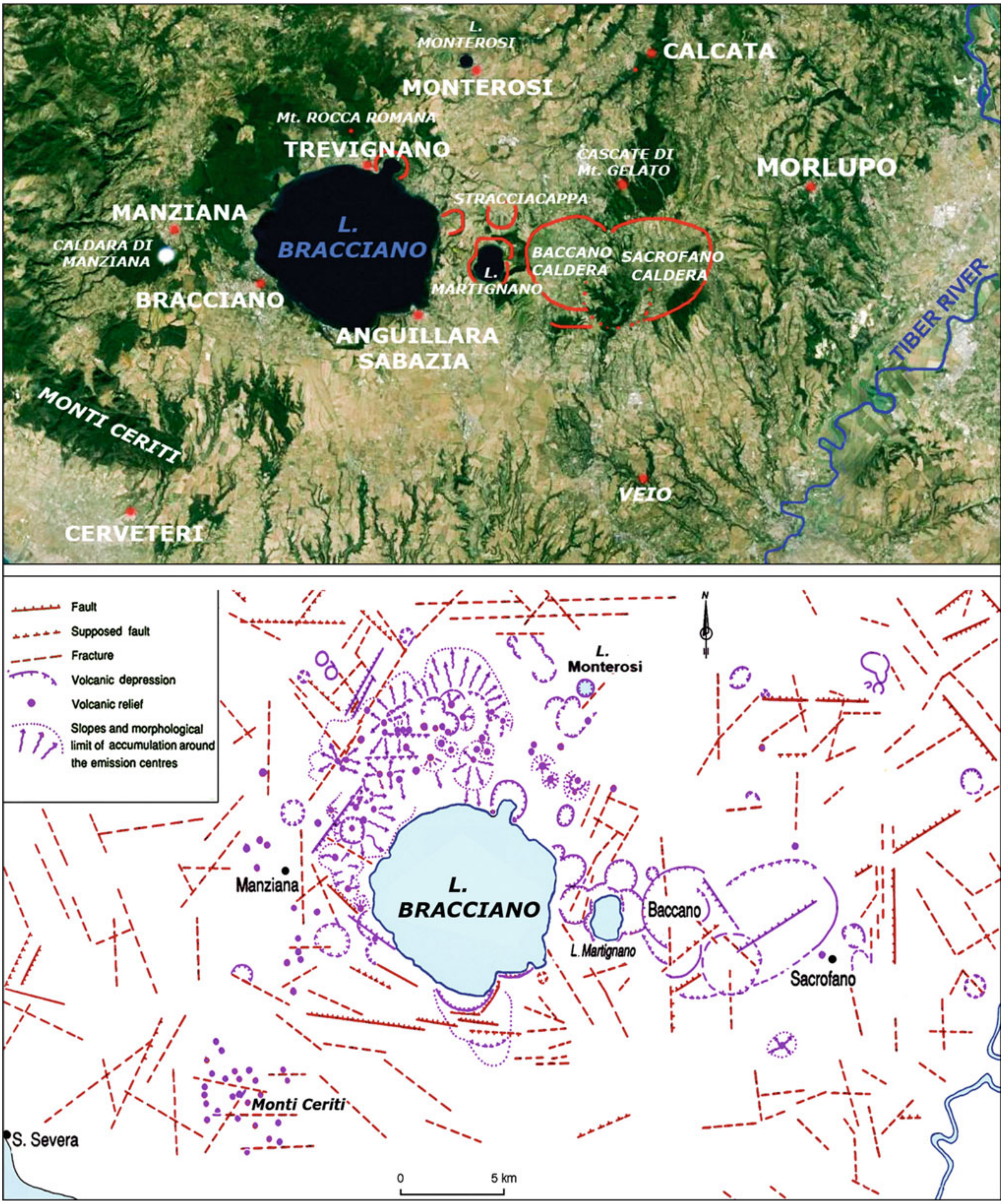

Fig. 26.9 Satellite image (Google Earth Image © 2015 DigitalGlobe) of the Monti Sabatini Volcanic District and related geomorphological sketch (modified after Caputo et al. 1993)

Fig. 26.10 **a** Mt. Gelato waterfall, along the Treia River. **b** The beautiful and suggestive town of Calcata in the Treia valley. This town was built on the "Red tuff with black scoriae" that was erupted from the Vico Volcano (180 ka ago). **c** View of lake Bracciano from the Odescalchi castle

Natural Parks of Bracciano-Martignano, Appia Antica and Castelli Romani are only selected examples from the approximately thirty parks and reserves of the provinces of Rome and Viterbo.

Furthermore, the beauties of the natural landscape go along with the historical and cultural value of the entire volcanic area of Latium, where the evidence of Etruscan and Ancient Roman civilisations as well as of the Mediaeval and Renaissance periods is ample.

Many Etruscan works still survive. The necropolis, which were carved into the Monti Vulsini, Vico and Monti Sabatini pyroclastic flows, found at Tarquinia, Vulci, Cerveteri and Sutri, are wonderful but not isolated examples. Roads, such as the already cited Etruscan Tagliate of Pitigliano, or aqueducts, such as the Città di Veio aqueducts, or reclamation works, such as the channel that drains Vico Lake, hold out against the elapsing time.

The Ancient Roman period is attested to by still better-preserved evidence. The very *Aeterna Urbs* was built close to the Tiber bends and over seven hills topped by the Monti Sabatini and the Colli Albani pyroclastic flows. Furthermore, there are aqueducts (such as the aqueduct of Via Appia), roads (such as the Via Appia Antica that runs as far as the Roma periphery on the Colli di Bove lava flow erupted by the Colli Albani Volcano), and even ship remnants, such as those found in the 1920s in Nemi Lake and thought to be Caligula's ships.

The small towns that date back to the Middle Ages and attained their maximum magnificence in the Renaissance periods are also very interesting. Orvieto, for example, with its wonderful cathedral, was built on the Vulsini volcanic plateau, while other examples include Capranica, Sutri and Viterbo in the area of the Cimino and Vico Volcanoes, Bolsena in the Monti Vulsini district, Calcata, Bracciano and

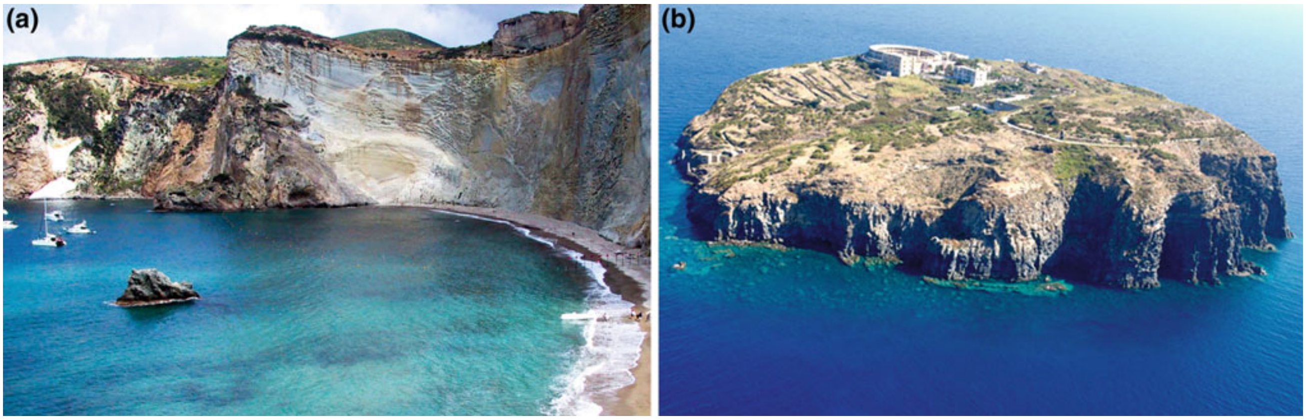

Fig. 26.11 **a** Cala dell'Inferno on the Ponza Island. This suggestive cove is a portion of an ancient volcanic cone that is composed of acid volcanites and is deeply eroded by wave action. **b** Santo Stefano Island is the emerged part of a secondary cone that belongs to the Ventotene Volcano

Anguillara Sabazia in the Monti Sabatini District, and Castel Gandolfo, Albano Laziale and Frascati in the Colli Albani area.

Altogether, the volcanic district of Latium is a harmonious combination of physical, historical and cultural landscapes of worldwide relevance.

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27

Relief, Intermontane Basins and Civilization in the Umbria-Marche Apennines: Origin and Life by Geological Consent

Marta Della Seta, Laura Melelli, and Gilberto Pambianchi

Abstract

The landscape of the Umbria-Marche Apennines (Central Italy) shows a rhythmic sequence of “whaleback” anticlinal ridges separated by longitudinal synformal valleys. In this topographic arrangement, flat-floored tectonic depressions appear which enclose a wide range of landforms, and witness the continuous balance between tectonic forces, Quaternary climatic phases and drainage network adjustment. Fault scarps and triangular facets characterize the bordering slopes where thick talus deposits and landslides highlight the gravitational component. Karstic landforms as dolines and caves and fluvial features testify to the action of water. The resulting landscape is, for a visitor, like an incomparable geological handbook.

Keywords

Drainage network • Human settlements • Intermontane basin • Orthoclinal and diaclinal valleys • Central Apennines

27.1 Introduction

By picturing a travel itinerary through the main cities of Central Italy, we could start leaving Rome northward and running upstream, across the wide and flat alluvial plain of the Tiber River. Most of this landscape is surrounded by arcuate mountain ranges, which are the magnificent result of competing natural forces. Their topographic growth started tens of millions years ago from the bottom of an ancient ocean (Tethys). These ranges are presently separated by longitudinal valleys and cut by transverse gorges that allowed the connection between Northern and Central Italy. In fact, the river network of the Umbria-Marche Apennines started to set up after the emersion of the ridges from the sea, but underwent continuous readjustments (Fubelli et al. 2014); in particular, Quaternary tectonics was responsible for the opening of several depressions bounded by normal faults (Cavinato and De Celles 1999; Melelli et al. 2014). The latter are represented by Plio-Pleistocene intermontane basins, mainly clustered on the Tyrrhenian slope of the Apennines and interrupting the architecture of the mountain ranges. These morphostructures evolved due to geomorphological processes and in many cases, their endorheic drainage was captured by external rivers due to their erosional power and headward erosion. The geomorphological evolution of the intermontane basins was also strongly influenced by the Quaternary climatic phases, which have been responsible for superimposition of the different sets of erosional and depositional landforms described in this chapter.

Some of these basins are still the theatre of active seismicity along their border faults (Galadini and Galli 2000), as

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testified by the 1997 Umbria-Marche earthquake that caused eleven casualties and destroyed or strongly damaged noticeable examples of the Italian architecture and painting. The reason for these severe consequences lies in the fact that since the Iron Age the intermontane basins have been colonized by humans, due to the presence of several favourable topographic and environmental conditions for their settlements.

27.2 Geographical and Geological Setting

Observing the pattern of the major rivers of Central Apennines, the different arrangements of watercourses flowing towards the Tyrrhenian Sea, and those moving into the Adriatic Sea become evident. The former are organized in large drainage basins and a rectangular pattern following NNW–SSE and NE–SW directions is characteristic. The second set comprises shorter rivers with smaller drainage basins, a parallel pattern and a direction perpendicular to the Adriatic coast (Fig. 27.1).

The maximum altitude values increase towards east and partly fit with the regional watershed (Molin and Fubelli 2005). Here the axis of the Apennines chain assumes the maximum heights, waning in both opposite directions towards the coastlines.

This physiographic configuration is inherited from the geological history of Central Apennines where three major palaeogeographic domains are recognizable from NW to SE (Fig. 27.1). The Ligurian units are characterized by pelagic and turbiditic successions deposited on an oceanic crust. The adjacent Tuscan and Umbria-Marche Domains are characterized by sedimentary successions with a decreasing percentage of the calcareous component moving upward and a total thickness of about 1200 m. The Latium-Abruzzo Domain, in the southeastern portion, represents a carbonate platform. In the Cretaceous, the opening of the Atlantic Ocean to the west triggered Miocene to Pliocene orogenesis of the Apennines, with the first compressive deformation along a NE–SW direction that progressively migrated eastward. At the same time, a superimposed extensional tectonic phase accompanied the eastward migration of the thrust front and was responsible for the opening of the Tyrrhenian Sea since the Tortonian (Cavinato and De Celles 1999).

The first folds emerged above the sea level between the Middle and Late Pliocene, and, initially, widespread areal erosion processes shaped a smoothed and low-relief surface on the top of the ridges. This surface is presently preserved in hanging remnants and is known as the "Summit Paleosurface" (Late Pliocene–Early Pleistocene).

Since the Early Pleistocene the reliefs grew up again, thus triggering the third and last evolutionary step responsible for the present landscape: the diffuse morphogenesis in a generalized continental environment. Extensional faults cut mainly the western slopes of the anticlines, thus contributing to the origin of several intermontane basins. A sudden and strong uplift involved the whole Central Apennines with a maximum rate along the axis of the chain (D'Agostino et al. 2001), producing high slope gradients. The intermontane tectonic depressions are bounded by high-angle normal faults. The evolution of the basins in space and time has followed the migration of the extensional front: the oldest ones to the west are filled by marine sequences, the eastern ones, most recent, by continental deposits (Fig. 27.1).

The non-coincidence between the highest peaks and the regional watershed in the Central Apennines, as described in Fig. 27.2, is among consequences of this evolution.

In addition, during the Quaternary, climate changes influenced erosional and depositional activity of rivers and the shaping of slopes. Four orders of fluvial terraces testify to these climatic oscillations and are recognizable as relict alluvial plains, at different heights, up to 200 m above the present valley floor (Nesci et al. 2012).

27.3 Landscapes and Landforms

The landscape of the Umbria-Marche Apennines has a strong tectonic fingerprint, since it is a puzzle of compressional mountain ridges and mainly extensional intermontane basins, mostly connected by a structurally controlled drainage network (Fig. 27.2). The mountain ranges reflect the "whaleback" anticlinal fold arrangement and are characterized by landforms influenced by lithological contrasts and by the attitude of rock strata (Fig. 27.3).

These ranges are separated by longitudinal ("orthoclinal") valleys and cut by transverse ("diaclinal") gorges. The orthoclinal valleys generally developed along the axes of synclines. The diaclinal streams cut the homoclinal structural slopes and segment them into triangular remnants of dip slopes, called "flatirons".

Apart from synclinal valleys, several intermontane basins mark the landscape of the Apennines as almost rectangular flat-floored depressions, bounded by normal faults, generally NW–SE oriented. They are characterized by similar features, so, let us start looking at these typical landforms (Fig. 27.3).

The planar, steep slopes bounding the basins correspond to fault slopes and in some cases preserve an original fault scarp morphology. Several streams dissect the slopes, isolating triangular or trapezoidal facets (Figs. 27.3 and 27.4) which are witnesses of the fault scarp. The stream power along the steep slopes is enough to form spectacular alluvial fans in the junction with the piedmont zone. The fault slopes often underwent large gravitational phenomena, such as deep-seated gravitational slope deformations (DGSDs), which in some cases evolved to catastrophic rock slope

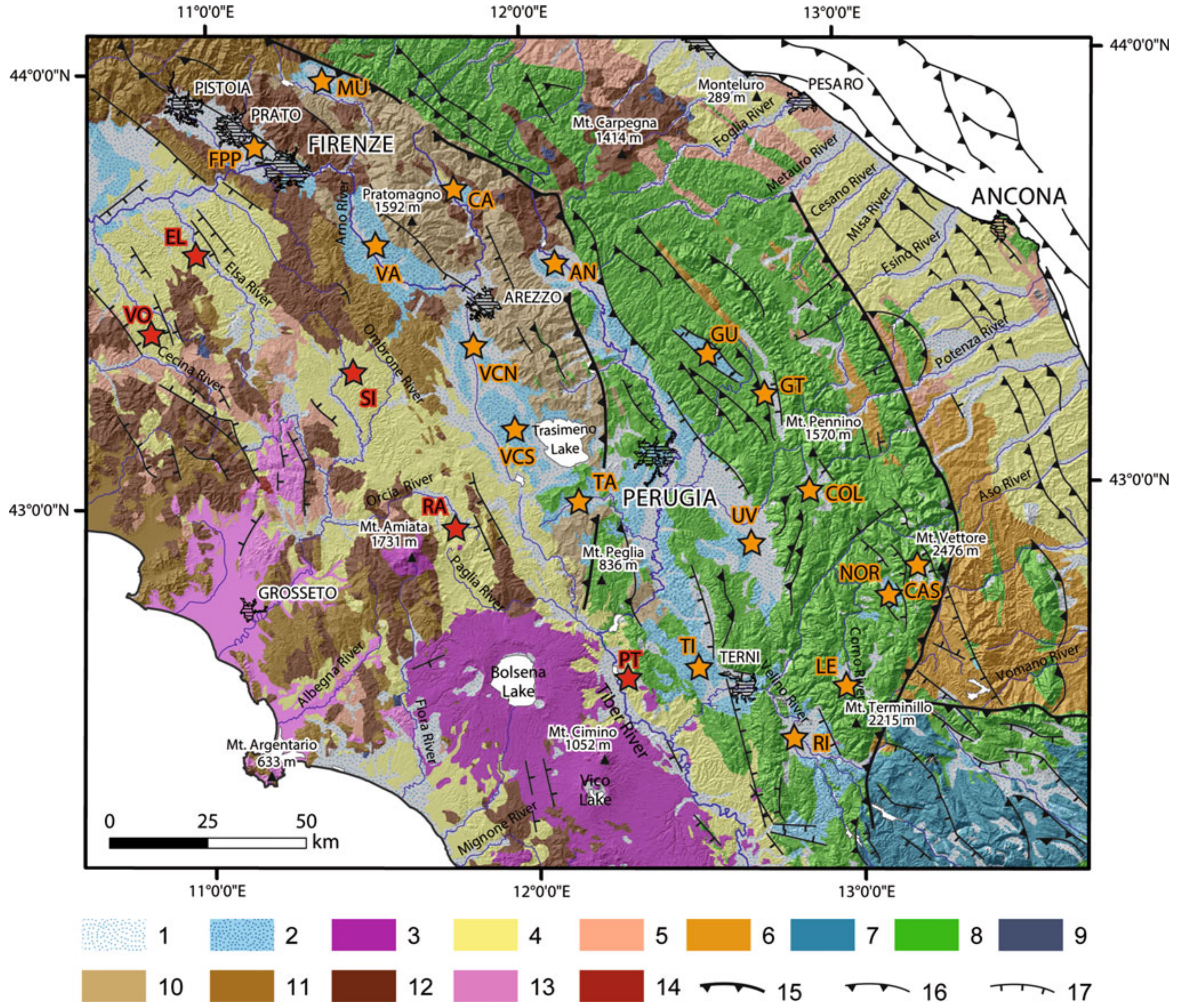

Fig. 27.1 Location map of the study area and intermontane basins of the Central Apennines. Main geological units in Central Apennines: *1* continental Pleistocene–Holocene deposits; *2* continental Villafranchian deposits; *3* Pleistocene volcanic products; *4* Plio–Pleistocene marine sediments; *5* Messinian evaporitic and lacustrine deposits; *6* Tortonian–Messinian terrigenous deposits; *7* Triassic–Miocene Latium–Abruzzo sedimentary units; *8* Triassic–Miocene Umbria–Marche sedimentary units; *9* Miocene Epiligurian units; *10* upper Oligocene terrigenous deposits of the Tuscan units; *11* upper Cretaceous–Oligocene Tuscan units; *12* upper Cretaceous–Eocene Ligurian units; *13* Paleozoic–lower Cretaceous metamorphic units; *14* upper Miocene plutonic rocks; *15* major thrust front; *16* thrust fault; *17* normal fault. Major basins: *AN* Anghiari, *CA* Casentino, *CAS* Castelluccio, *COL* Colfiorito and Plestini, *EL* Val d'Elsa, *FPP* Firenze–Prato–Pistoia, *GT* Gualdo Tadino, *GU* Gubbio, *LE* Leonessa, *MU* Mugello, *NOR* Norcia, *PT* Paglia–Tevere, *RA* Radicofani, *RI* Rieti, *SI* Siena, *TA* Tavernelle, *TI* Tiberino, *UV* Umbria Valley; *VA* Val d'Arno, *VCN* Val di Chiana North, *VCS* Val di Chiana South, *VO* Volterra

failures (Melelli and Taramelli 2010; Bianchi Fasani et al. 2014; Fig. 27.3). Thick talus deposits can be recognized at the footslopes. In some cases they appear stratified and cemented, suggesting periglacial origin (e.g. *grèze litée*), and are linked with Quaternary cold climatic phases (Coltorti et al. 1983).

Since several intermontane basins developed on calcareous bedrocks, they are often also shaped by karstic processes, which leave their fingerprints through the genesis of dolines, swallow holes and caves. More difficult to be identified is a peculiar type of landform, which testifies for the lively morphodynamics of the intermontane basins. It is represented by remnants of relict surfaces hanging at different elevations within the basins. Each surface is correlated to an ancient local base level of erosion (e.g. an alluvial plain), generally embedded in an older one.

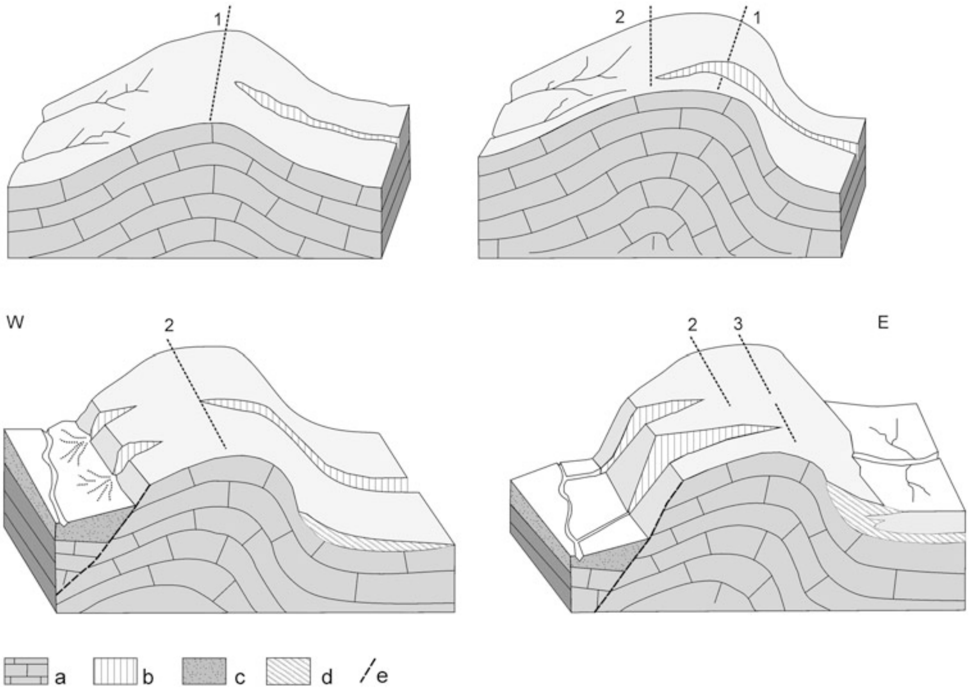

Fig. 27.2 Morphotectonic evolution of the Central Apennines. Compressive and uplift phases: the relief grows up. The initial watershed divide (*1*) migrates westward (*2*). Extensional phase: the normal fault systems create the intermontane basins mainly along the western flanks of the folds. The new base levels at the bottom of the intermontane basins force the rivers, flowing westward, to strong erosional activity along the drainage divides. The watershed migrates eastward (*2* and *3*). *Legend*: *a* calcareous bedrock, *b* river cutting, *c* fluvial and lacustrine deposits filling the basins, *d* debris deposits, *e* drainage divide

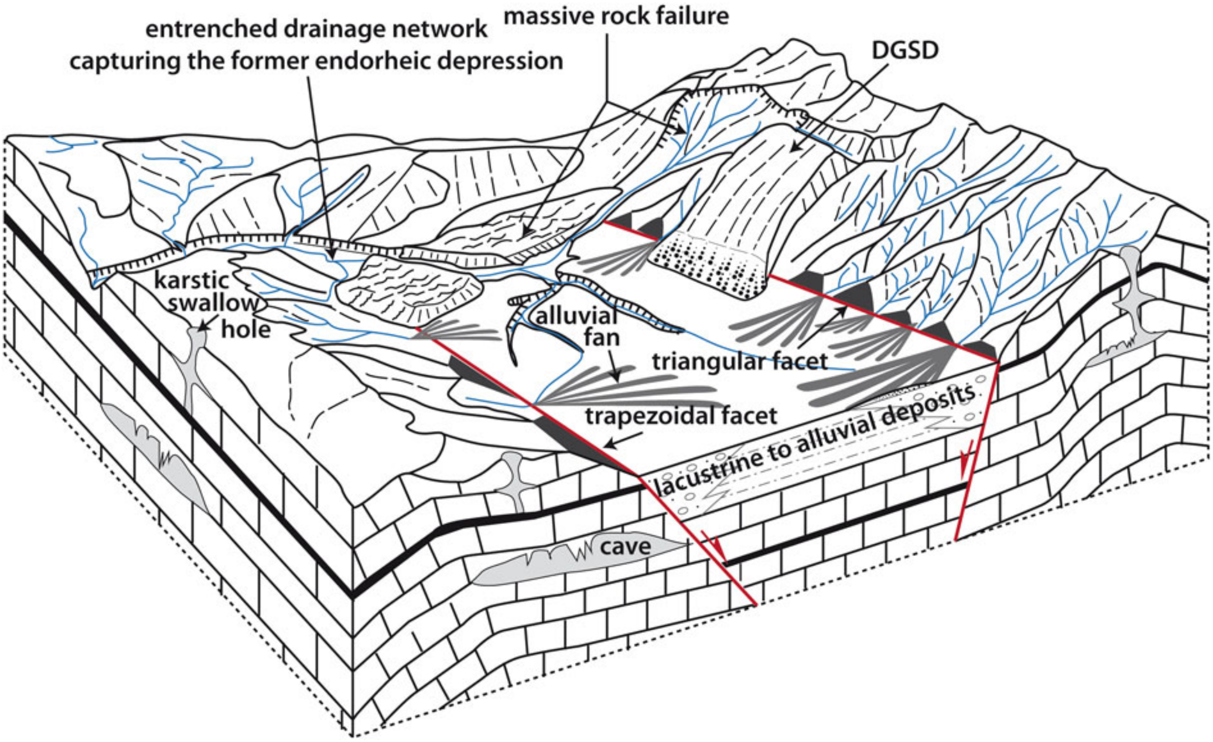

Fig. 27.3 Block diagram with landforms common to intermontane basins (*DGSD* deep-seated gravitational slope deformation)

Fig. 27.4 Triangular and trapezoidal facets and alluvial fans along the eastern margin of Gubbio basin (after Ficola and Coletti 2011)

27.4 Geomorphological Evolution

The morphoevolution and the typical landforms resulting from the interaction between geomorphological processes and geological/climatic factors are very similar in all intermontane basins of Central Apennines. However, an excellent example where all these landforms find their best display is the Pian Grande di Castelluccio, or "Great Plain of Castelluccio" (CAS in Fig. 27.1; Umbria, 1350 m a.s.l.). Even if the area encompasses geological and geomorphological characteristics similar to the other intermontane basins, a wide number of peculiarities are shown, too. As a result, the description of the geomorphological evolution of the Pian Grande is a unique opportunity to guide the reader in the landscape of the intermontane basins. The entire range of landforms is an excellent example of the interaction among litho-structural factors, morphogenetic forces and climatic changes.

The Pian Grande is inside the National Park of Sibillini Mountains, extending on an area of 70,000 ha, across the Marche region and the southeastern part of the Umbria region. The basin has a quadrangular shape with a length of about 5 km along the NE–SW direction and a width of about 2 km. The structure is related to a first extensional tectonic phase with maximum stretching oriented N 50°–60°, resulting in normal faults with a NNW–SSE direction. The rotation towards a N–S, N20°E direction generates a partly left-side transtensive movement along the same faults planes, obtaining the present outline. The thickness of the continental Quaternary deposits is about 400–500 m.

The landscape is magnificent, due to the giant mountains embracing the basin, with the highest peak of Mt. Vettore, abruptly joined with the 200 m lower plain (Fig. 27.5).

The top of the reliefs, subject to rise during the compressive tectonic phase, preserve the remnants of the Summit Paleosurface, while the steep slopes abruptly connect them to the plain along the normal fault planes.

The western slope of Mt. Vettore was generated by two normal faults, one at the bottom of the slope, along the junction with the valley floor, and the second one just below the crest of the mountain, along the track named "Cordone del Vettore" (Fig. 27.5). The pathway, to an inexpert eye, appears as a footpath cutting transversally the slope and dividing it into two branches in the south direction.

Fig. 27.5 Pian Grande with Mt. Vettore in the background (*left*). The faults lines ("Cordone del Vettore") are recognizable along the upper part of the slope. In the foreground the Mergani River shows the angulated pattern (*photo* P. Mulazzani)

However, it is the morphological evidence of an active fault scarp. Moreover, the sudden increase of local relief due to the Pleistocene uplift and fault activity is the main reason for the pattern of the drainage network, cutting the slopes along the maximum gradient and following the main directions of tectonic discontinuities. The same process causes mass movements on the slopes, such as the tectonic–gravitational collapses in the Pian Grande (Gentili and Pambianchi 1994; Dramis et al. 1995). One of the main peculiarities of the area is the endorheic drainage system. As further proof of the fact the Mergani River, at an altitude of 1257 m, flows inside the karstic swallow hole, along the southwestern boundary of the basin (Fig. 27.5). The path of the short river, strongly angulated, follows the main tectonic directions. The swallow hole testifies that karstic morphogenesis affects the relief. For this reasons some authors define the Pian Grande as a polje. However, all the tectonic-karstic basins of Central Italy show a common peculiarity: thick deposits on the basin floor (more than 100 m) related to fluvial and lacustrine environments. This is the main difference with the polje s.s. of the Dinaric Alps, where the base of the depression coincides with the calcareous bedrock.

The calcareous bedrock and the karstic morphogenesis are the processes responsible for different evolutions of some basins. Where the tectonic activity of fault systems is lower than the regional uplift, fluvial erosion prevails and the fluvial-lacustrine deposits are eroded. Main streams generally find a threshold at the boundaries of the basin (Fig. 27.6, from 1 to 5a). The prevailing calcareous composition of bedrock triggers karstic morphogenesis and the main fault planes become preferential pathways for groundwater flow (Fig. 27.6, from 1 to 5b). The karstic morphogenesis contributes to the shaping of the basins, probably since the early extensional stage. When the underground drainage system is not well organized, the marsh-pond conditions have persisted since historical times. On the contrary, in the Pian Grande morphogenesis is in a more advanced stage, the emptying is complete and there are only deposits on the bottom, indicating past fluvial and lacustrine environments.

Climatic changes mark the surface with characteristic landforms. At the junction between the slopes and the bottom of the basin, wide and stratified debris deposits originated in the cold climatic phases (Coltorti et al. 1983) are evident, resulting in the area named Piè di Vettore, where alluvial fans are also present. Glacial landforms occur along Mt. Vettore and Mt. Rotondo. The main evidence of glacial erosion is rock walls in a semicircle pattern and thresholds with counter slope, upstream and downstream steps. The main activity is dated to the end of Middle Pleistocene. One of the most suggestive evidence is probably the Pilato's Lake, also known as the "lake with the glasses" due to the two circular and interconnecting basins. Its formation is due to the dam caused by Upper Pleistocene glacial deposits and by the overlapped and more recent scree deposits. The lake is also well known because of the presence of *Chirocefalo Marchesonii*, a small endemic crustacean, measuring 9–12 mm and with the particularity of swimming with the belly facing up. According to numerous legends about the origin and name of the lake, it was believed that the corpse of Pontius Pilate was thrown into the lake, considered also the Averno Lake or the entrance for the Underworld.

Moving down to Pian Grande from the top of Mt. Vettore is like reading a book whose pages, placed vertically, tell the story that, since 300 Ma, involved this part of the Apennines. Knowing this geological evolution is the necessary condition to understand the genesis of this landscape where —quoting the French geographer H. Desplanques (1911–1983)—"*the contrasts overlap almost for fun*".

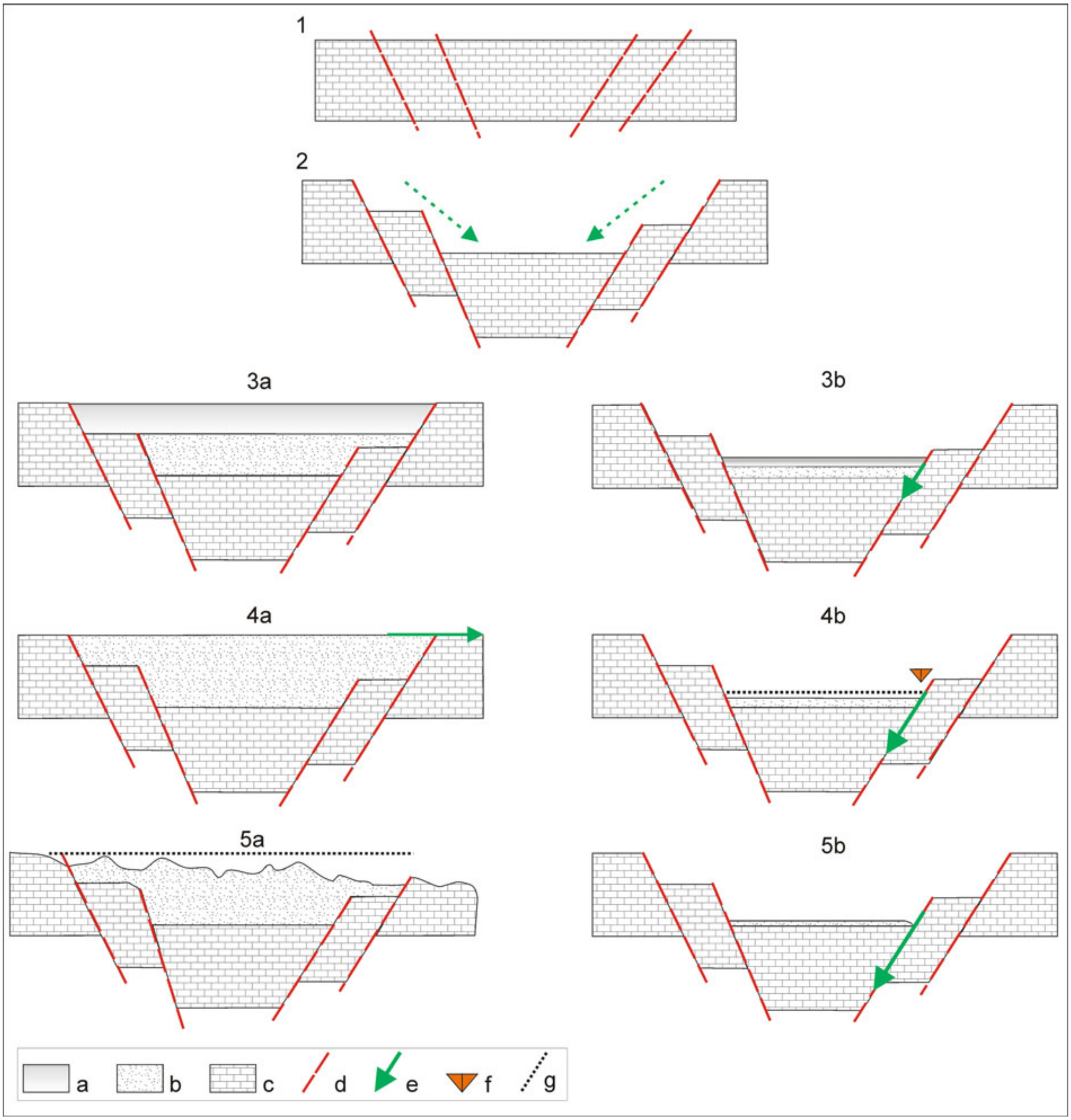

Fig. 27.6 Different evolutions of continental intermontane basins according to bedrock lithotypes. From 1 to 5a: without karstic morphogenesis, from 1 to 5b with the contribution of karstic morphogenesis. *Legend*: *a* lakes and swamps, *b* fluvial-lacustrine deposits, *c* bedrock, *d* faults, *e* water flow direction, *f* karstic sinkhole, *g* original level before emptying

27.5 Intermontane Basins and Human Settlements

Geomorphological and climatic conditions and the natural resources of this part of the Apennines have strongly influenced human settlement. The low-lying morphology and the richness in water were the most relevant attracting factors. However, local flooding conditions have transformed the same territories as adverse areas to human settlements since the Prehistory (Radmilli 1960; Barker 1984).

One meaningful example of this contradictory relationship is the evolution of the landscape in the Umbria Valley (UV in Fig. 27.1), the southeastern branch of the ancient Tiberino Lake (Umbria, Fig. 27.7), an intermontane basin where subsidence prevails. The tectonic origin of the depression is well evident along the eastern boundary, near

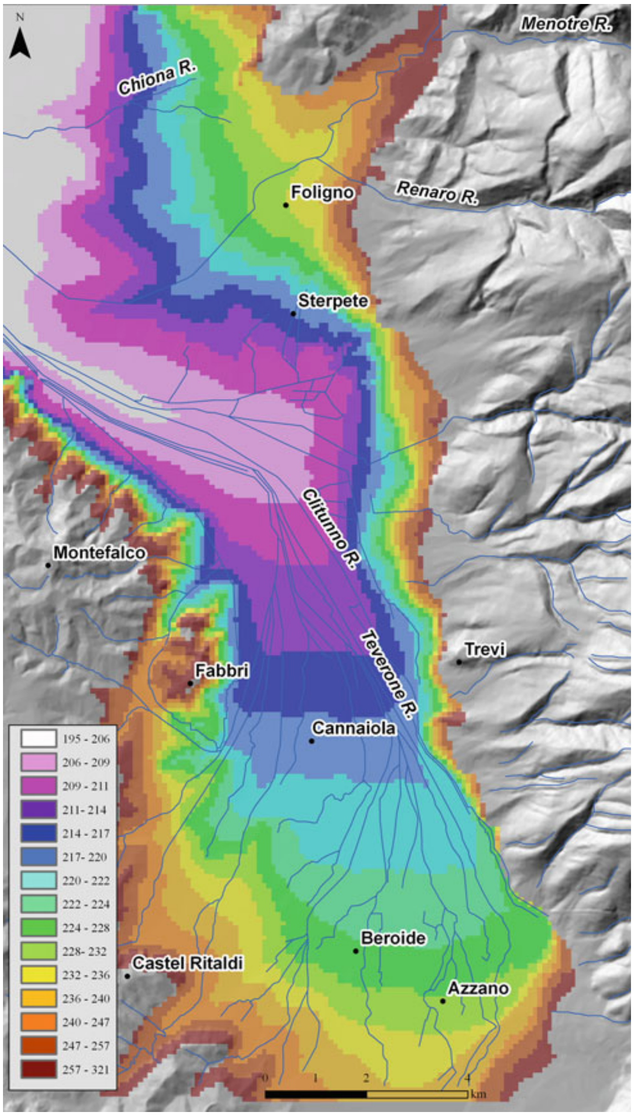

Fig. 27.7 Digital Elevation Model (90 × 90 m) of the Umbria Valley. The altitude values are divided in contrasting colours in order to highlight their spatial distribution. The technique emphasizes the large alluvial fan of Foligno in the northern part of the area and the coalescent alluvial fans along the eastern margin of the basin

the Umbria-Marche pre-Apennine, located where an abrupt contact with the bottom of the valley is marked by extensive alluvial fans. Flooding events and humid climatic periods characterized the area in alternate phases in space and time. The present surface drainage, with parallel rivers and channels flowing northward, is the result of human labour to reclaim the area.

Since pre-Roman times, a *Lacus Umber* probably occupied a large portion of the central and northern part of the valley up to an altitude of 219 m a.s.l. In the Roman Period (753 BC–476 AD) important and dense human settlement (city and major roads such as the Via Flaminia) is suggestive of good environmental conditions. Important roads ("strade consolari") were built radially from Rome ("Urbe") throughout the Italian peninsula.

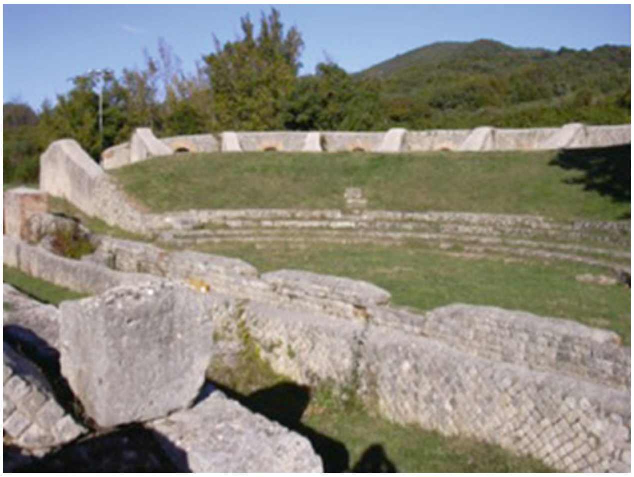

Fig. 27.8 The theatre of the Roman city of *Carsulae*

In the Umbria-Marche Apennines the most important ones are the Via Salaria (so called from the Latin "salis", to indicate the road to transport salt), more to the south, and the Via Flaminia to the north. These pathways, crossing the Apennines and exploiting the natural passage offered by the intermontane basins, reached the Adriatic Sea from where a thriving commerce started towards the east.

Along Via Flaminia road (so called because it was built by Gaius Flaminius, the Roman consul, between 225 and 220 BC), many important towns as Terni, Spoleto, Foligno were built, some of these at the edges of the main intermontane basins. One of the most important towns was *Carsulae* (Fig. 27.8), located to the north of Terni town (Umbria). It took considerable importance in the age of Augustus (27 BC–14 AD). According to historical sources this Roman city decayed rapidly and mysteriously in the fourth century AD, perhaps due to particularly intense seismic events. Recent geomorphological research also showed the presence of very large landslides that might have contributed to the rapid abandonment of the city (Aringoli et al. 2009).

At the same time, in the Umbria Valley the lowering of the lake level led to the rise of the largest alluvial fan of the valley to the north, which began to act as a watershed inside the basin. The ancient *Lacus Umber* was then split into two pools, smaller in size and depth: *Lacus Clitorius* (more to the south), alimented mainly by the Clitunno River and a relic *Lacus Umber*, or *Lacus Pertius* more to the north. A climatic phase characterized by low temperatures and more abundant rainfall began, ensuring higher flow rates to major waterways. Swampy conditions spread throughout the area.

In the Dark Ages (476–1000 AD), a warm climate characterized the region, followed in the Late Middle Ages (1000–1492 AD) by a new warm phase and by an economic decay that brought the surface water conditions into chaos. Dante Alighieri (1256–1321 AD) in the Divine Comedy, referring to the nearby Val di Chiana, mentioned the malarial conditions that plagued the lowlands ("*Qual dolor fora, se de li spedali di Valdichiana tra 'l luglio e 'l settembre e di Maremma e di Sardigna i mali fossero in una fossa tutti'nsembre, tal era quivi, e tal puzzo n'usciva qual suol venir de le marcite membre*."—"What pain would be, if from the hospitals of Valdichiana, 'twixt July and September, and of Maremma and Sardinia all the diseases in one moat were gathered, such was it here, and such a stench came from it as from putrescent limbs is wont to issue." Divine Comedy, Inferno, poem XXIX). Marshy areas persisted and between 1300 and 1850 AD, in a period partly coinciding with the Little Ice Age as a result of heavy rains and copious river discharge, the area went back to natural conditions. In 1400 AD, the zone took the name of *Padule* (marshy area) as clearly detectable on historical maps. In the following centuries, inundation events occurred and frequent malaria epidemics spread again. The solution seemed to be found in 1770, when the Topino River was deflected and its path shortened, and then, between 1844 and 1857, with further and final reclamation. These actions testify to the constant effort to live in these areas in spite of such natural hazards.

From a geomorphological point of view, it is clear that today one of the most important morphogenetic contributions to these areas is given by human activities and it is evident that intermontane basins still represent a unique opportunity for human settlement.

The exploitation of the aquifers with the consequent problems of subsidence, groundwater pollution due to the use of pesticides for agricultural practice, and the presence of industries and infrastructures are irreversibly transforming considerable portions of the areas, often damaging the landscape and the natural resources. Knowing the geological and geomorphological history of these areas could be a unifying key to connect the intermontane basins of Central Apennines in an ideal network. The identity of these areas, as physiographic units with a well-defined geological heritage, is a chance to promote knowledge, economic progress and scientific improvement.

27.6 Conclusions

The intermontane basins of the Umbria-Marche Apennines are excellent locations to understand the geological history of this part of Central Italy. The lithological, stratigraphic and tectonic arrangement of bedrock allows to unravel geological events responsible for the genesis of the present landscape. In addition, landforms generated by present and past morphogenetic processes testify to the morphoevolution of these spectacular morphostructures.

For this reason, the intermontane basins can be considered "morpho-evolutive geosites" that are areas with natural peculiarities also readable in a temporal sense. The correct method to observe the landscape of the basins is therefore to interpret it through a space-time travel, placing landforms on the geological timescale and investigating the sequence of the natural events responsible for the construction of the present landscape. In this context, the type and the mutual arrangement of the outcropping lithologies are related to the time span between the Jurassic and the Pliocene. The tectonic style with folds elongated in the prevalent NW–SE direction and cut by transtensive and normal fault systems, testifies to the following extensional tectonic stage and the contemporary uplift that affected the entire study area. The signature of the most recent geomorphological evolution is recognizable in slope geometry and landforms, especially along the mountain fronts bordering the bottom of the basins.

Morpho-structural landforms demonstrate that basins are graben or semigraben, while strong gradients generated by the activity of master faults help to maintain active morphogenesis. The attempt of slopes and drainage network to balance the system triggers morphogenetic processes, mainly fluvial and gravitational. To confirm the above statements, several intermontane basins include geosites with characteristics of uniqueness and excellence from both scientific and geotouristic point of view.

In a mostly mountainous morphological context, the flat areas have always represented privileged sites for human settlement. The ease of transfer and the fertile nature of the land represented unique opportunities for ancient populations. Despite this, the evidence of human presence also on the adjacent slopes provides interesting information about climate change during the Quaternary. Historical sources refer to periods of economic and social regression, when high rainfall, flooding, the origin of swamps and marshes affected the basins and, at the same time, the resident populations moved along the surrounding slopes. Thus, the intermontane basins record in landforms and in historical events the mutual relationship between humans and environment and the non-always easy balance between these two components, according to the statement of the American historian William James Durant (1885–1981) that “Civilization exists by geological consent, subject to change without notice”.

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The Terminillo, Gran Sasso and Majella Mountains: The 'Old Guardians' of the Tyrrhenian and Adriatic Seas

28

Tommaso Piacentini, Marcello Buccolini, and Enrico Miccadei

Abstract

Terminillo, Gran Sasso and Majella, the highest mountains of the Central Apennines, are spectacular landmarks showing outstanding geological and geomorphological variability and complexity. Geological features are related to a Neogene NE-verging thrust belt; geomorphological features are related to the superimposition over time of structural, slope, fluvial, glacial and karst landforms. With the support of the words of d'Annunzio, a great poet from Abruzzo, we can describe these mountains as "old guardians" of the Apennines from the Tyrrhenian to the Adriatic side of Central Italy. Here, the landscape can be deciphered by earth scientists and results from an intricate geomorphological history. Nevertheless, the same landscape can be discovered and comprehended by everyone.

Keywords

Mountain landscapes • Glacial landforms • Karst landforms • Structural landforms • Central Apennines

28.1 Introduction

"*Candide cime, grandi nel cielo forme solenni … Dai culmini virginei che splendono sotto le stelle pie…*" (Elettra, Alle montagne, G. d'Annunzio 1903; Snow white peaks, big in the sky majestic landforms… With virgin summits shining under the pious stars…). With these words Gabriele d'Annunzio, a great early twentieth-century poet from Abruzzo, conveys his perception of the mountains of the Central Apennines, "old guardians" dominating the landscape of Central Italy, from the Tyrrhenian Sea to the Adriatic Sea. And with the support of d'Annunzio's words (texts from Orlando 2003), we now try to describe the landscape of the main mountains of Central Italy.

Terminillo, Gran Sasso and Majella, the highest mountains of Latium-Abruzzo area, are spectacular places where geological and geomorphological environments show beautiful examples of variability and complexity in a relatively well-connected small area. Due to the spatial coexistence of many well-preserved elements of an intricate structural and landscape evolution, the complex Mesozoic and Cenozoic paleogeography finds its expression in this "field laboratory". Since the beginning of the 1900s large and significant rock exposures have allowed earth scientists to decipher the fabric of the landscape's geological history. This is characterized by an ancient (Mesozoic-Cenozoic) tropical environment with bahamian-like lagoons, coral atolls and deep seas in the early stages, and by a recent mountain landscape, with glaciers, large intermontane basins inhabited by mammoths, passing through a complex alternation of tectonic, slope, karst, fluvial and marine landscapes in the late (Quaternary) stages. Acknowledging this natural beauty, since the beginning of the 1900s, a specific protection policy for the safeguarding of this landscape has been implemented, first and foremost through the creation of a system of national and regional protected areas (e.g. Park of Abruzzo, Lazio and Molise; Park of Majella Mountain; Park of Gran Sasso and Laga Mountains; Protected area of Reatini mountains; Park of Simbruini mountains; Park of Sirente

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Velino and several local protected areas). Moreover, during the last few decades geotourism activities have also been progressively introduced (Miccadei et al. 2011).

28.2 Geographical Setting

The Terminillo, Gran Sasso and Majella mountain groups are located in Central Italy which, from west to east, is composed of the wide Tyrrhenian coastal plain, followed by a volcanic belt and by the western piedmont of the Apennines chain. The chain represents the axial part of Central Italy. To the east, it is bounded by the Adriatic piedmont through an abrupt morphological limit, and, further east, by a very narrow coastal plain backed by steep coastal slopes (Fig. 28.1a). The Central Apennines are an asymmetric mountain range, with the highest peaks shifted towards northeast, characterized by alternating ridges (up to 2900 m high) and valleys (elevation from ~1500 m to <250 m), longitudinal or transversal to the ridges, and by intermontane basins (i.e. Fucino Plain, Sulmona basin, L'Aquila basin; elevation from >1500 m to ~250 m) (Fig. 28.1a) (Piacentini and Miccadei 2014). The Gran Sasso ridge (2912 m a.s.l.; Figure 28.2a) and Majella Mountain (2793 m; Fig. 28.2b) are the highest peaks of the Central Apennines, but they are located in their northeastern most side, less than 30 km from the Adriatic coast, overlooking the gentle piedmont and hilly area from the steep front of the chain. On the southwest side, Mt. Terminillo (2217 m; Fig. 28.2c) is surrounded by several minor ridges gently sloping towards the Tyrrhenian piedmont and the volcanic areas.

28.3 Geological and Geomorphological Setting

The ridges of the Central Apennines are made of Mesozoic and Cenozoic limestone and marly-limestone related to different paleogeographic domains, from an ancient tropical environment with bahamian-like lagoons, carbonate platforms, coral reefs and atolls, through submarine slopes and scarps, to deep seas and basins (ISPRA Geological Map of Italy, Sheets 349, 357, 358, 359, 369, 378). The ridges are elongated in directions ranging from NW–SE to N–S and are separated by narrow valleys incised in Neogene arenaceous and pelitic deposits, subparallel or transversal to the ridges, or by wide intermontane tectonic basins partially filled with Quaternary continental deposits. The eastern slope of the chain, corresponding to the main thrusts, abruptly drops down into the Periadriatic piedmont. To the west, the chain slope, corresponding to normal faults, is moderately steep and the landscape is characterized by a broad piedmont hilly zone with individual low ranges, extinct volcanoes, and broad tuffaceous plateaus (Fig. 28.1b) (D'Alessandro et al. 2003; Piacentini and Miccadei 2014).

Geologically, the chain is a NW–SE-oriented thrust belt verging NE, and made of thick pre-orogenic Triassic-Miocene carbonate platform, slope, ramp and pelagic facies. The kinematic history of thrusting is recorded by Miocene-Pliocene synorogenic foredeep sediments, which were progressively involved in the thrust deformation as the chain was migrating towards the Adriatic foreland (Fig. 28.1b; Cosentino et al. 2010).

Since the Late Pliocene the thrust belt has been affected by extensional tectonics and regional uplift and has been subject to the geomorphological effects of climate fluctuations (Piacentini and Miccadei 2014). After the emersion of the area and the first morphogenetic stage induced by compressional tectonics (Miocene), uplift and extensional tectonics (Upper Pliocene—Pleistocene) have induced the rise of the Apennines, strong changes in topography, and the development of drainage systems, outlining the present morphostructural setting. The morphogenesis has been influenced by bedrock features related to a complex paleogeografic pattern (i.e. depositional carbonate architectures, calcarenites and breccias bodies, large-scale unconformities), by tectonic features, and by Quaternary climate changes, that still today are intrinsic factors for the Central Apennines' landscape shaping.

28.4 Landforms of the "Old Guardians" of the Apennines

"… *Nelle rocce di sopra, a picco, non un filo di verde non un lembo d'ombra: erte, come solcate da arterie d'argento, terribilmente belle ed ignude incontro al cielo.*" (Terra vergine, G. d'Annunzio 1882: … In the sheer rocks above, not a bit of green nor a patch of shadow: steep, furrowed by silver arteries, terribly beautiful and bare towards the sky).

28.4.1 Mount Terminillo

The rugged relief of Mt. Terminillo and surrounding peaks, commonly considered as a part of the Reatini mountains, is located about 80 km northeast of Rome. It reaches its highest elevation (2217 m a.s.l.) on its namesake peak and consists of several ridges over 2000 m (e.g. I Sassatelli, Mt. Terminilletto, Mt. Elefante, Mt. di Cambio). Its slopes, sometimes showing high cliffs, are limited to the north by the Leonessa intermontane basin and to the east and south by the Velino River valley which, until the early reclamation works carried out in Roman times (271 BC), bogged down into the Rieti intermontane basin to the west (Fig. 28.3).

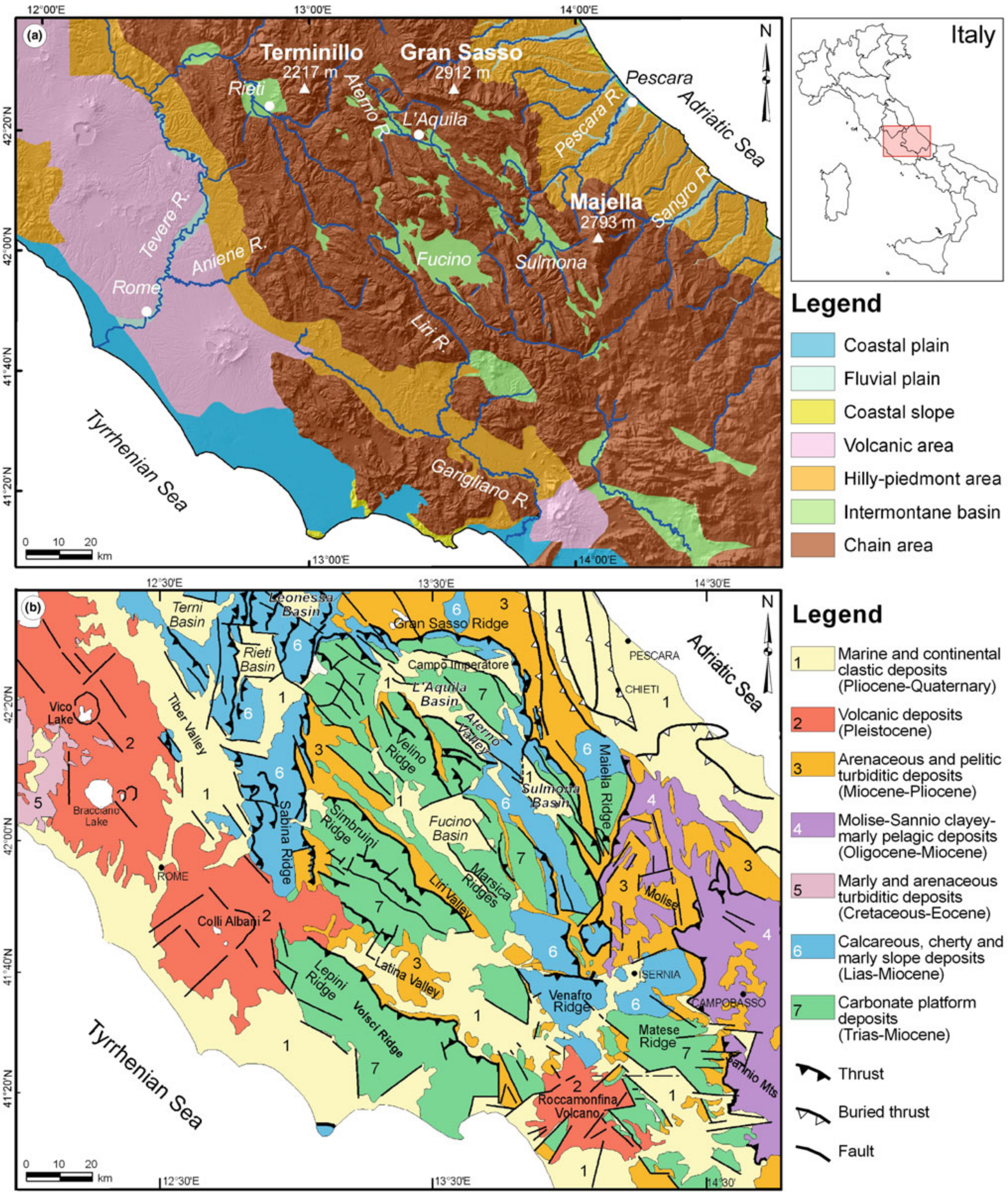


Fig. 28.1 Physiographic scheme (**a**) and geological sketch (**b**) of Central Italy (modified after Piacentini and Miccadei 2014; Cosentino et al. 2010; shaded relief from SRTM DEM based on data provided by the OpenTopography Facility with support from the National Science Foundation under NSF Award Numbers 1226353 & 1225810)

Fig. 28.2 Panoramic views of: **a** Mt. Terminillo; **b** Gran Sasso ridge; **c** Majella Mountain

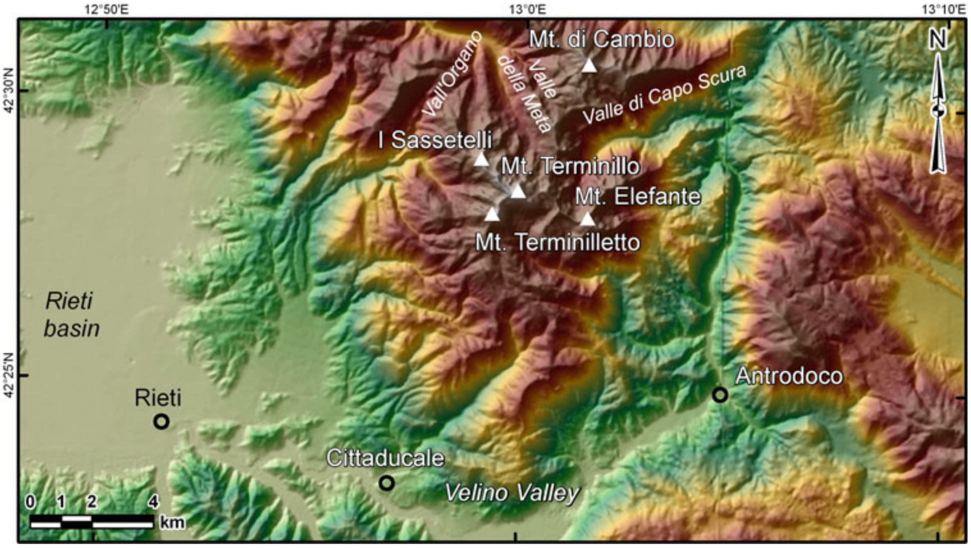


Fig. 28.3 Orography of Mt. Terminillo area (elevation map from ASTER DEM a product of METI and NASA)

Due to regional tectonic processes, this area represents a junction point between ridges pertaining to two different ancient Mesozoic paleogeographic domains: the Latium-Abruzzi carbonate bahamian-like platform domain (shallow sea) and the Umbria-Marche-Sabina pelagic basin domain (deep sea) (ISPRA Geological Map of Italy, Sheet 357).

The general morphostructural setting is characterized by anticline and thrust ridges and by fault-line valleys, influenced by the passive role played by structure in the geomorphic evolution. It indeed bears traces of selective erosion of Meso-Cenozoic calcareous and calcareous-marly sequences, with thick strata of calcarenites and calcareous breccias, deposited in a transitional domain between a carbonate platform and pelagic basin areas. Only the western slope facing the Rieti basin is a fault slope related to the effects of active extensional tectonics at the boundary of the basin. The ridges are cleaved, frequently interrupted by deeply incised valleys, both parallel and transversal to the general N–S trend of the Massif.

After the thrusting phase and the beginning of mountain building (Early Pliocene, about 5 million years ago), the Terminillo landscape was characterized by a smoothed-out surface with a few prominent peaks. The remains of this landscape are now preserved in low relief surfaces hanging at high elevation. Regional uplift, extensional tectonics and Quaternary climate fluctuations have induced the dissection of the landscape, the formation of high local relief, steep slopes and deep valleys, as well as the progressive development of the drainage network and of a large cover of continental deposits.

In this complex interaction, a wide range of processes has contributed to the development of different types of landforms: structural, slope, fluvial, karstic, glacial and periglacial, and locally anthropogenic.

The presence of rocks with different erodibility is responsible for the formation of landforms of selective erosion such as structural scarps and saddles. Olistolites made of Jurassic massive limestone (Calcare Massiccio, Lower Lias), embedded into younger marly-limestone pelagic deposits (Corniola, Middle Lias), and levels and lenses of calcarenites and calcirudites, embedded into the whole marly-limestone Terminillo Middle Jurassic—Lower Cretaceous succession, outline distinctive structural scarps (Fig. 28.4a).

Mt. Terminillo's summit area shows typical features of a high mountain landscape (above 1800 m) of the Apennines, with relict landforms and deposits connected with Pleistocene glacial processes which mainly developed along the northern and eastern mountain sides (Giraudi 1998a). The most common and marked landforms are glacial cirques, with steep walls. The NNW downstream movement of these glaciers produced distinctive U-shaped valleys (2–5 km long, Valle della Meta, Vall'Organo and Valle di Capo Scura) and left indelible traces in the landscape such as erratic boulders, *roche mountonnée*, lateral, ground, as well as terminal moraines (up to >20 m high and several tens or hundreds of metres long) and kettle-holes (Fig. 28.4b), a proof of a currently extinct Pleistocene glacial activity.

As far as the periglacial processes related to the current snowfall are concerned, an important role as a morphogenetic factor is played by avalanches. Indeed, a large number of avalanche tracks is present, especially along the northeastern Terminillo mountain side. When avalanches cut unconsolidated sediments (e.g. scree slope deposits), their erosive action, due to both the snow and debris involved along its route, is evident and downstream large mixed fans are present.

Karst landforms (dolines) are present all over the calcareous ridges within flat or gently wavy areas at the ridges' summit or in the valley bottoms; dolines' size is usually about few tens of metres. Karst microlandfroms (karren) mostly affect the calcareous rocky slopes. Groups of dolines and doline fields have developed within the ancient glacial cirques and valleys, particularly in the concave-up plucking zone of the old glaciers.

Finally, slope processes (i.e. mass movements and scree production) provide an important contribution to shaping the landscape in relation to lithological setting, local relief and climate conditions (freeze-thaw). Due to rock-scarp weathering, the base of the steep slopes of the Terminillo and surrounding peaks is covered by scree slope deposits and several talus cones. Often, slope processes affect the scarps of ancient glacial cirques and cover glacial moraines, giving the slopes a complex concave–convex morphology (Fig. 28.4b).

28.4.2 Gran Sasso

"*Vanisce il Gran Sasso da lungi, titan soffocato entro il torpore della fumea sanguigna…*" (Versi d'amore—Canto Nuovo G. d'Annunzio 1882: Vanishes the Gran Sasso from afar, a titan suffocated within the torpidity of the sanguineous smoke…).

The Gran Sasso ridge rises along the northeastern side of the Central Apennines, less than 30 km away from the coast. It is the largest massif of Central Italy, an arch-shaped ridge pointing towards NE, turning from E–W in the northern part to N–S in the southern part, incorporating the highest peak of the whole Apennines (Corno Grande, 2912 m) as well as other high peaks above 2500 m (from west to east: Pizzo Intermesoli, 2635 m; Corno Piccolo, 2655 m; Mt. Prena, 2561 m; Mt. Camicia, 2564 m) (Fig. 28.5). The main peaks are surrounded by steep slopes up to more than 1000 m high. Towards the north the slopes drop down to the piedmont area, at an elevation lower than 1000 m, while towards

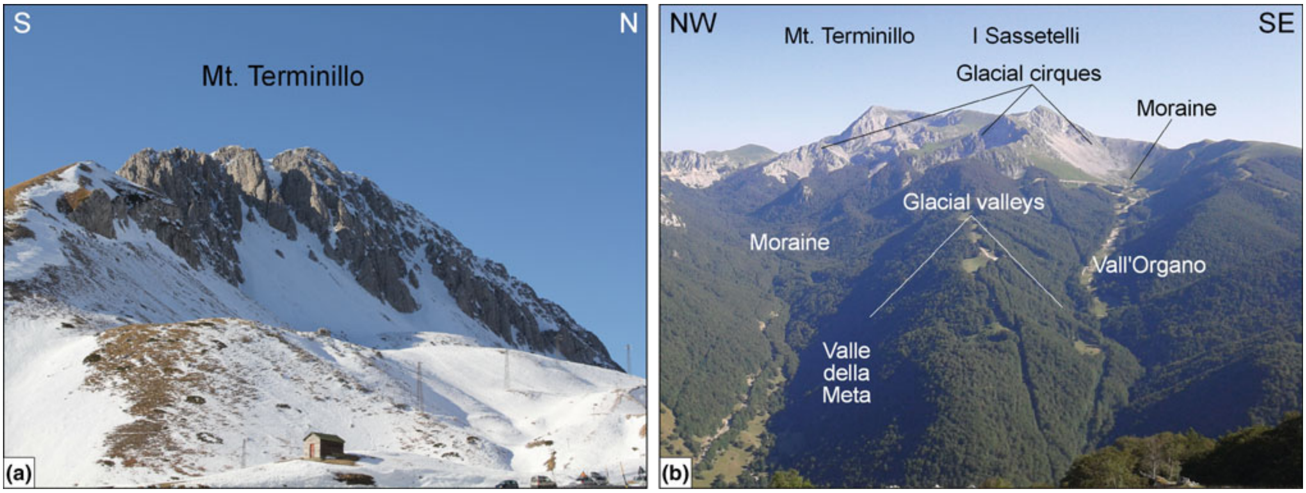
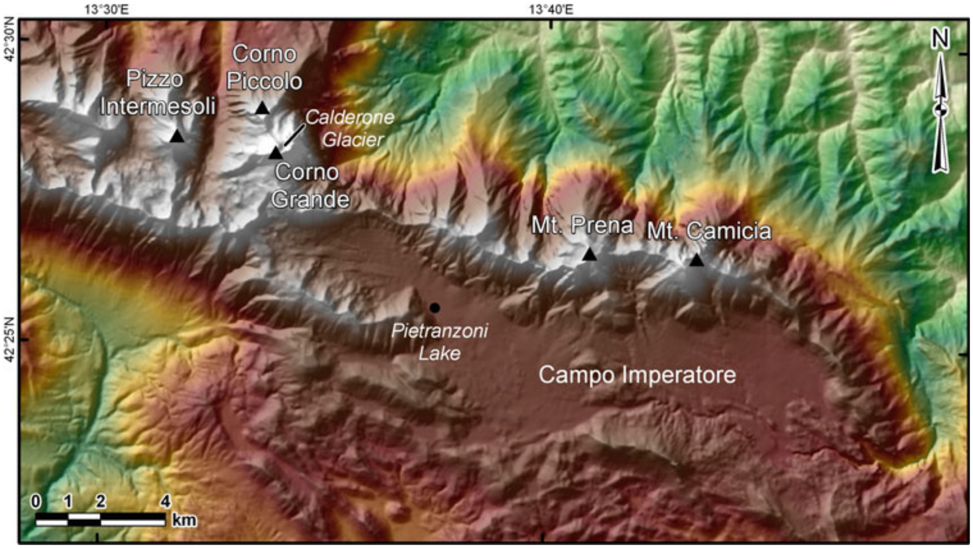


Fig. 28.4 Landforms of Mt. Terminillo (2217 m): **a** Eastern side of Mt. Terminillo; a large structural scarp is present on rugged massive calcareous levels; **b** Northeastern side of Mt. Terminillo; glacial cirques in the *upper part* of the slope and U-shaped glacial valleys with moraines (*photo* F. Chiaretti)

Fig. 28.5 Orography of the Gran Sasso area (elevation map from Abruzzo Region DEM; http://www.regione.abruzzo.it/xcartografia/)



the south the ridge slopes down to the Campo Imperatore intermontane basin, higher than 1500 m. Therefore, the overall shape of the massif is an arched, asymmetric NE-verging ridge which defines the abrupt boundary between the Apennines and the Adriatic piedmont.

The Gran Sasso area experienced an intense compressional tectonics and subsequent tectonic uplift. Here, the oldest rocks of the Central Apennines (bitumen dolomites overlain by limestone and dolomites), Triassic in age, are uplifted to more than 2000 m. These rocks were overthrusted during the Neogene on calcareous and marly rocks pertaining to Cretaceous slope and pelagic basin facies and on Neogene foredeep arenaceous and pelitic rocks. Then they have been uplifted and displaced by Quaternary extensional tectonics along NW–SE to E–W normal faults; in some cases extensional tectonics has reactivated—and inverted—previous thrusts and compressive tectonic structures, outlining a very intriguing geological and geomorphological setting (ISPRA Geological Map of Italy, Sheet 349).

The general morphostructural setting is characterized by thrust ridges, deeply incised by selective erosion of ancient geological structures due to compressional tectonics, and by faulted homocline ridges, large fault escarpments and a large high-elevation tectonic basin (Campo Imperatore, >1500 m; Fig. 28.6a), resulting from active extensional tectonics and developing along a complex fault system along the northern border of the basin and at the base of Mt. Prena and Mt. Camicia ridge (Fig. 28.7) (Galli et al. 2002).

The landscape of the Gran Sasso area is the result of various very active geomorphological processes: slope processes deeply affecting all the bare flanks of peaks and

Fig. 28.6 Corno Grande (2912 m). **a** Large glacial valley on the western side of Campo Imperatore, at the footslope of the Corno Grande, including the Pietranzoni lake; **b** Calderone glacier (northern side of the Corno Grande peak; *photo* P. Scoppola); **c** 180° panoramic view of the Calderone glacial cirque from the terminal moraine (*photo* F. Ciavattella); **d** Calderone cirque and terminal moraine; in the foreground a talus cone developed on the slope below the terminal moraine (*photo* F. Ciavattella); **e** Tectono-karst basins with small karst lakes on the southern side of Campo Imperatore

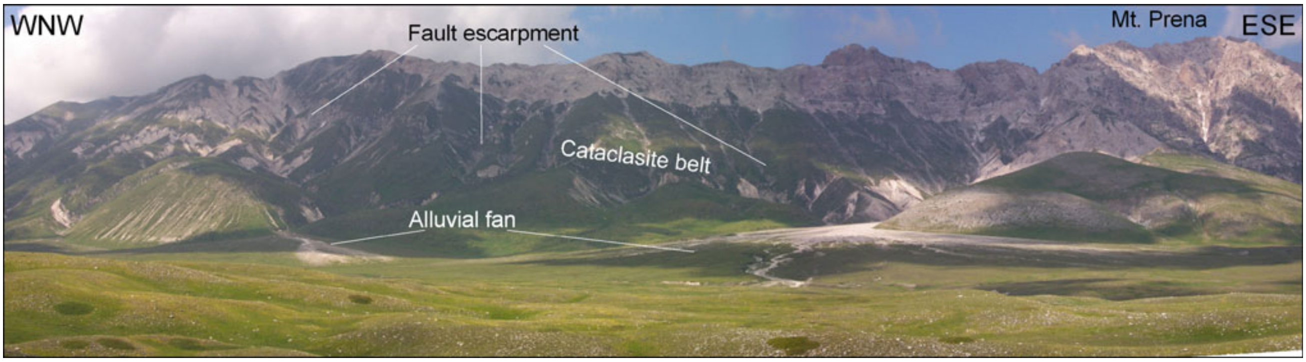


Fig. 28.7 Gran Sasso ridge (~2500 m) and Campo Imperatore (~1600 m). Large fault escarpment at the boundary of Campo Imperatore (southern side of the Mt. Prena ridge); in the *lower part* active alluvial fans, fed by erosion of highly jointed and fine grained cataclasite, cover an ancient moraines system

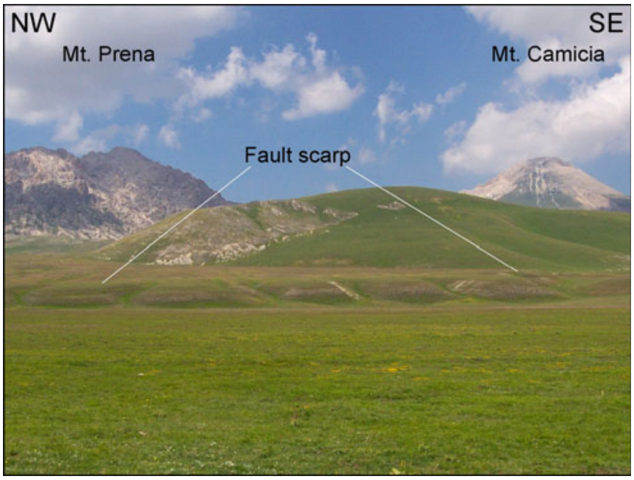


Fig. 28.8 Campo Imperatore area (~1600 m). A small fault scarp affecting a recent alluvial fan

ridges; fluvial processes that occur at the base of the main slopes; karst processes affecting the flat and wavy areas surrounding the main peaks. Moreover, from the highest elevation down to the Campo Imperatore area, well-preserved evidence of glacial processes is present, while in the summit area of Corno Grande, the last glacier of the Apennines has survived, the Calderone glacier (Fig. 28.6b, c, d), a very small and almost dead remnant of the last Pleistocene glacial stage. Ancient and recent tectonic landforms characterize the whole Gran Sasso area (Figs. 28.7, 28.8) (Galli et al. 2002; Santo et al. 2014).

The main glacial landforms are large glacial cirques edging the main north-facing slopes and large U-shaped glacial valleys (2–6 km long, 1–1.5 km wide) incising the northern side of the main ridge down to less than 1600 m. On the southeastern side of Corno Grande, the landscape is dominated by a glacial amphitheater (some 9 km long ridge with elevation ~2000–2500 m) sloping down into a large glacial valley (~10 km long and 2.5 km wide) and a system of moraines (up to >30 m high) covering the western part of Campo Imperatore and incorporating the small outstanding Pietranzoni lake (Fig. 28.6a).

The main glacial features, except for the Calderone glacier, which is still present although mostly covered by debris, are the legacy of the Pleistocene glacial advances, and particularly that of the Last Glacial Maximum (Late Pleistocene, ~20,000 years ago), which deeply affected all the Central Apennines (above ~1500 m) (Bisci et al. 1999; Jaurand 1999; D'Orefice et al. 2000). Glacial landforms have been eroded, covered and reworked by fluvial, slope and karst processes (Figs. 28.6d, 28.7).

Several active alluvial fans are present at the boundary of Campo Imperatore along the large fault escarpment on the southern side of Mt. Prena and Mt. Camicia (eastern part of the Gran Sasso ridge; Fig. 28.7), fed by erosion of highly jonted and fine grained cataclastic calcareous rocks. The recent activity along this fault escarpment is documented by clear geomorphic evidence, such as several metre-high fault scarps displacing the depositional top-surface of recent alluvial fans (Fig. 28.8; Galli et al. 2002).

All around the Gran Sasso ridge, at elevations ranging between 1500 and 2000 m, karst processes deeply mark the flat and gently wavy landscape with large doline fields and WNW–ESE elongated tectono-karst basins of variable size (from few hundreds of metres long to >3 km long, from few tens of metres to 1 km wide; Fig. 28.6e) due to the effects of karst processes on faulted and highly jointed calcareous bedrock.

28.4.3 Majella Mountain

The Majella Mountain, even more than the Gran Sasso, rises abruptly from the northeastern piedmont of the Central Apennines at about 25 km from the coast, and is the easternmost massif—the closest to the coast and the second highest in the Apennines—its main peak being Mt. Amaro (2793 m) (Fig. 28.9).

The general morphostructural setting is characterized by a large anticline ridge, faulted in the western side, exhumed and deeply dissected in the northern and eastern sides.

Due to its location and morphological features, the Majella Mountain offers different contrasting features: the eastern side, overlooking the Adriatic Sea is connected with the hills at its base through a homoclinal slope generally characterized by spectacular deep valleys with cliffs that reach 1000 m in height; the western side is a major tectonic escarpment, generally homogeneous, compact and steep, facing a large and deep fault-line valley, the so-called *Macchia di Caramanico*.

Since the Majella is formed by calcareous rocks, karst morphology is ubiquitous, and has been active since the first emersion of the area as an island in the subaerial environment. South of Mt. Amaro, paleo-karst phenomena are characterized by discontinuous outcrops of bauxite and their effects are related to peculiar paleoclimatic conditions. Actually, in the Paleocene—Early Miocene interval, the paleoclimate was warm-humid tropical and during the Middle-Late Miocene it was still warm, though drier. In this context, superficial karst phenomena were favoured, with consequent areal erosion and levelling, responsible for the tabular configuration of the Majella summit (Fig. 28.10a, b). When the climate became arid (Pliocene), karst phenomena were no longer favoured, fossilizing previous landforms. During the Pleistocene, karst processes were reactivated, controlled by the alternation of glacial and interglacial phases.

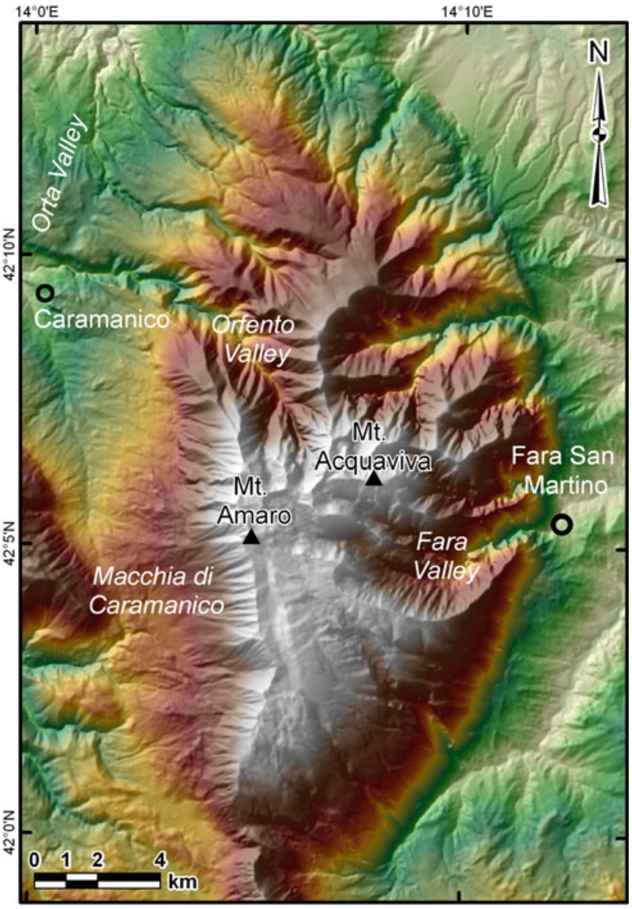


Fig. 28.9 Orography of the Majella Mountain area (elevation map from Abruzzo Region DEM; http://www.regione.abruzzo.it/xcartografia/)

The major karst landforms are both on the surface and underground. In areas with low elevation and low gradient, separating the above-mentioned tabular areas, surface landforms have developed (karren and dolines). The dolines are often present in groups and are of different types, mainly funnel-shaped and flat-bottomed, but also collapse dolines occur, especially north of Mt. Amaro. The karstification of the Majella determined the indented profile of its divide, that is located at altitudes slightly lower than the flat summit and testifies to the presence of a shallow karst network. It is also outlined by the development of caves located mainly in the eastern and northern mountain sides with a prevailing horizontal attitude. Among these, the most spectacular ones are the *Cavallone* cave, with a total length of about 850 m and a vertical development of 20 m, and the *Bove*, *Asino* and *Nera* caves.

The main valleys dissecting the mountain sides are long (4–10 km) and deep (up to 800–1000 m) canyons (Fig. 28.10c, d), the origin of which is related to both karst phenomena and tectonic evolution. Considering the landscape evolution from the beginning, from the stage of karst summit levelling, the chain uplift was not continuous, but followed a succession of intermediate phases. In each of these phases, the relative sea level lowered to a new base level and this caused the formation of cliffs and the lowering of karst level. Consequently, canyons were carved through both upstream regressive surface erosion and downstream collapses of underground channel roofs. A subsequent phase of tectonic activity caused a further partial lowering of the coastline and the process started again, resulting in the progressive elongation of the canyons. Within the Majella canyons, at least three levels of fossil karst caves can be found at different elevations, testifying to different stages of erosional deepening. To summarize, it can be argued that, after a long period characterized by a tropical forest-type landscape, the “Majella island” rose up and the karstification did not develop deeply, because of unfavourable climate conditions and the continual rejuvenation of the karst system. The large canyons result from a combination of climate and tectonics: the uplift virtually prepares the slopes and climate induces karst and fluvial deepening.

Finally, the activity of glaciers (which have now totally disappeared) was also important in the geomorphological evolution of the Majella and left several relict glacial

Fig. 28.10 Landforms of the Majella Mountain. **a** Mt. Amaro (2793 m), glacial and karst landscape of the summit Majella area; **b** Mt. Acquaviva (2737 m), karst surfaces; **c** Orfento River valley, Sfischio waterfall, ~60 m high; **d** Orta River valley: an example of the steep structural rock scarps (up to 50–80 m high, locally >100 m) of the main canyons incising the Majella Mountain slopes

landforms. Glacial cirques (0.5–1.5 m wide) are generally emplaced on pre-existing karst surfaces, mainly located on the northern and eastern mountain sides at elevations higher than 2000 m and affected by rock glacier development (Fig. 28.10a) (Dramis and Kotarba 1992; Giraudi 1998b). At the foot of the glacial cirques, U-shaped glacial valleys (up to >6 km long) contain terminal moraines generally arranged in two systems (up to >20 m high) and, at lower elevations, moraine deposits are reworked by fluvial activity.

28.5 Conclusions

Exploring the landscape of Terminillo, Gran Sasso and Majella, the highest peaks of the Central Apennines, and following Gabriele d'Annunzio's feelings, the rocks of these mountains seem to be "*disposte in cerchio e digradanti, danno immagine d'un colosseo construtto per opera ciclopica, corroso da secoli e da intemperie, o acquistano aspetti umani, come solitari fantasmi a guardia della valle, o ancora si accavallano come dorsi di pecore silenziose… Ad ogni stagione le pietre della montagna appenninica cambiano colore e sembrano davvero contenere in se un carattere, una vita, un giudizio pensante*" (text of D. Maraini in Orlando 2003; arranged in a circle and declining, they look like a coliseum built by Cyclops, corroded by the centuries and the elements, or they take on a human appearance, like lonely ghosts, guardians of the valley, or, again, they pile up as the backs of silent sheep… At every season the rocks of the Apennines mountains change colour and really seem to contain in themselves a character, a life, a thinking judgement).

For this reason, many geological and geomorphological investigations have been carried out for more than a century. Research has tried to reveal landscape evolution since the emersion in the subaerial environment, which definitively occurred between the Late Miocene and the Early Pliocene, and relate it to tectonic forcing in combination with climate-driven geomorphological processes (glacial, slope, karst, fluvial).

On the other hand, tourists and visitors have been able to 'perceive' the landscape and the natural environment thanks to a preservation policy based on several National Parks and reserves. Now the 'perception' of geological history and landscape evolution could contribute to the enhancement of these areas. Over the last decades, geotourism activities have been implemented and they should now be developed further in order to increase the awareness of the general public towards geological and landscape evolution, but also towards geological hazards and the related risks.

It should now be clear why Terminillo, Gran Sasso and Majella are more than spectacular places; why they have attracted scientists from all over the world to a "field laboratory" of rocks and landscapes, to try and decipher the landscape evolution; and why everyone can understand and comprehend the landscape variability and its complex geological and landscape history…

Here… "*Il monte ingombra col suo dorso enorme i cieli. E tu non l'odi respirare?*" (La notte apollinea, G. d'Annunzio 1898; The mount obstructs the sky with its enormous back. Don't you hear it breathing?).

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Aeternae Urbis Geomorphologia— Geomorphology of Rome, Aeterna Urbs

29

Maurizio Del Monte

Abstract

The city of Rome includes a lot of well-known historical and cultural sites, but also peculiar geomorphological features and very typical natural landscapes. A "man-made layering", thick and wide, hides the details of some plano-altimetric variations of the original surface. Nevertheless, natural features are still recognizable among the usual tourist attractions. The geomorphology of Rome reflects the paleogeographical conditions before the city foundation, thus allowing us to recognize the evolutionary stages of the ancient *Caput Mundi* (Capital of the World) landscape, starting from several thousand years ago until today. The geomorphological evolution and the geological and climatic framework have contributed to the economic and cultural development of the area. The history, urban planning and geomorphological characteristics of Rome are closely connected.

Keywords

Urban geomorphology • Tiber River • Seven Hills • Rome

> "*Rome is the capital of the world*" (Johann Wolfgang Goethe)
> "*To live in Rome is a way of losing your life*" (Ennio Flaiano)

29.1 Introduction

Rome is one of the most popular tourist destinations all over the world. Visitors of Rome's well-known historical and cultural sites can be often surprised to find a wealth of natural scenery and landscapes (Fig. 29.1).

Among the reasons for the fame of the *Aeterna Urbs* are its environmental and geomorphological features. Some natural features have been removed by millennia of urbanization; others have been modified, or covered by a wide and worldwide unique "man-made layering", but are still recognizable among the classic tourist attractions.

Geological and natural heritage can represent, itself, an attraction for people (Panizza 2001; Coratza and Giusti 2005; Gregori and Melelli 2005; Reynard 2008). Nevertheless, explanations and interpretations of natural features of the Roman landscape are not generally available in tourist guidebooks.

In this chapter a geomorphological overview of the Roman landscapes is carried out. Then, the geomorphological evolution of the area is described. Finally, it is shown how the geological and climatic framework influenced the development of the city, contributing to enhance its historical heritage. The link between nature and culture led to the synthesis of a great part of the "Cultural Landscape" (UNESCO 2005) of Rome's city centre.

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Fig. 29.1 A view of St. Peter's dome in winter, occasionally in an unusual snowy scenery. The picture is taken from a garden on the top of Gianicolo ridge towards north

29.2 Geographical Setting

Rome, the capital of Italy, is located on the Tyrrhenian side of central Italy, west of the Latium-Abruzzi Apennines (Fig. 29.2).

Many monuments and several large public parks are located in the Rome's historical centre. Features of Rome's ancient history are inscribed not only on monuments, but also on a varied landscape, characterized by hilly relief with the presence of ancient volcanoes, and the Tiber fluvial system. The Tiber River separates two very distinct types of landscape.

On the east side of the Tiber River (left bank) there are the famous Seven Hills ('*Septimontium*'): Quirinale, Viminale, Esquilino, Capitolino (also known as Campidoglio), Palatino, Celio and Aventino, which hosted the first human villages approximately 2000 years BC (Del Monte et al. 2013). Fords across the river were located adjacent to each hill. The Seven Hills were formed by erosion processes of the Tiber fluvial system, which deepened the volcanic plateau of the Latium Volcano (Colli Albani volcanic complex; cf. Fredi and Ciccacci 2017). This plateau covers the left slope of the Tiber River valley, extending from southeast of Rome to the main course of the Tiber. A series of small flat-bottomed valleys, which are drained by the tributaries of the Tiber, separates the Seven Hills; three of them appear today as isolated domes (Aventino, Capitolino and Palatino), while the others are small ridges (Fig. 29.3).

On the west side of the Tiber River, the floodplain ends at the foot of the Monte Mario—Gianicolo ridge. While this ridge reaches 139 m above sea level and shows an uneven top, the Seven Hills have altitude of 50÷60 m a.s.l. and flat tops. The Vatican Hill is located on the right side of the Tiber, between Monte Mario and Gianicolo. This area, once unhealthy, was reclaimed in the first century BC. Its name is probably of Etruscan origin; since prehistoric times, it was a place devoted to religious rites.

The evolution of the urban area of Rome was controlled by the development of the hydrographic network during the peak sea level lowstand that corresponded to the Last Glacial Maximum (LGM, 22–18 ka BP), which led to deepening of the main valley thalwegs. This was followed by a phase of fluvial deposition and valley-floor gradual aggradation due to sea level rise (17–5 ka BP) (Bellotti et al. 2007).

The bedrock in the historical centre of Rome consists mainly of clays and marls with foraminifers (Pliocene—Early Pleistocene), which were deposited during a period of extensional tectonics that produced several NW–SE oriented horsts and grabens (parallel to the Apennines). Three major marine depositional cycles have been recognized in this period (Bozzano et al. 2006). The first cycle (Lower Pliocene) included the deposition of blue clays, while coarser-grained sediments of shallower water facies were deposited during the second and third cycles (Lower Pleistocene). The bedrock is overlain by up to 800-m-thick epicontinental deposits that are related to slow and progressive crustal uplift. A series of depositional cycles of fluvial-marsh and marine-marginal environments began at 0.88 Ma BP (Bellotti et al. 2007).

Only the later fluvial deposits are located in the historical centre of Rome. These units are interdigitated with a thick layer of pyroclastic deposits produced by the Sabatini and Colli Albani volcanic complexes (Giordano et al. 2006), ranging in age from 600 to 36 ka BP (Karner et al. 2001). The volcanic outcrops are widespread throughout Rome and are represented by stratified tuffs, leucititic lavas, pyroclastic, and volcaniclastic deposits. Continental sedimentation continued throughout these depositional cycles controlled by eustatic variations. The stratigraphic relationships between the volcanic and sedimentary units are complex because the effects of erosion during the lowstands coincided with neotectonic processes and volcanic activity (Belisario et al. 1999; Ciotoli et al. 2003; Cattuto et al. 2005). The emplacement of volcanic deposits changed the topography and the hydrography of the area (Heiken et al. 2005); the

Fig. 29.2 Geographical framework of Rome urban area (*source Google Earth, modified; © 2015 Google. Map data: image Landsat, image © 2015 Digital Globe*). The historical centre is included in the *middle panel* (see Fig. 29.3). The city grew rapidly since the end of the nineteenth century, when it became the Capital of the new Italian state. In the 1950s and 1960s, the urban area was included within a ring road (The Great Ring). Today, the urban area is extended from the mouth of the Tiber up to Tivoli town. Some of the main Roman consular roads are represented outside the present-day central area of Rome, according to their current route

main stream of the ancient Tiber (*Paleo-tiber*) moved towards the Monte Mario—Gianicolo ridge, close to the edge of Colli Albani plateau.

During the LGM, at approximately 20 ka BP, the large drop in sea level (Lamb 1995) induced fast erosion processes. In the city of Rome, the Tiber River and its tributaries cut into the Plio-Pleistocene bedrock up to 50 m below the present sea level (Fig. 29.4). The subsequent rising in sea level caused a depositional phase in which the previously incised valleys were filled by up to 60 m of alluvial deposits (Ascani et al. 2008). The rate of deposition over the last 17 ka is related to changes in the rate of sea level rise. In particular, the post-glacial rise of sea level ended between 7 and 5 ka BP. The development of the marine delta at the mouth of the Tiber subsequently began, and the coastal wetlands were filled during the Middle Ages. Over the last 3 ka, human activities everywhere contributed to reshape the topographic surface. The most recent stratigraphic layer overlies the flood deposits: it consists of a mixture of alluvium, colluvium and materials from human activity that have accumulated throughout Roman history. This man-made layer covers the historical centre and ranges in thickness from a few metres on hill tops to tens of metres in the valley bottoms (Del Monte et al. 2013). The landscape of the historical centre of Rome is the result of these complex Plio-Quaternary events.

29.3 Landforms and Landscapes

A fluvial landscape characterizes the urban area of Rome. Three thousand years ago, several tributaries of the Tiber River flowed across the floodplain and marshy lands at the base of Capitolino, Palatino and Aventino hills.

On the Tiber's east side, the "historical" hills have steep slopes and flat tops (Fig. 29.4). The landscape on the west side of the Tiber, in contrast, is dominated by the Monte Mario—Gianicolo ridge, which is higher, more rugged and subjected to severe mass movements. Nowadays, the Rome area is still characterized by landforms derived from the action of surface running waters. Polygenic, structural and gravitational landforms are also widespread; in addition, many landforms were created by human activities.

29.3.1 The Tiber Drainage Network and Its Floodplain

The valleys of the Tiber River and its main tributaries have flat floors (Fig. 29.4), as a result of the Holocene depositional processes described above. The main floodplain (Fig. 29.5) extends eastward up to the base of the volcanic plateau comprising the Seven Hills. On the west side of the Tiber River, the floodplain ends at the foot of the Monte

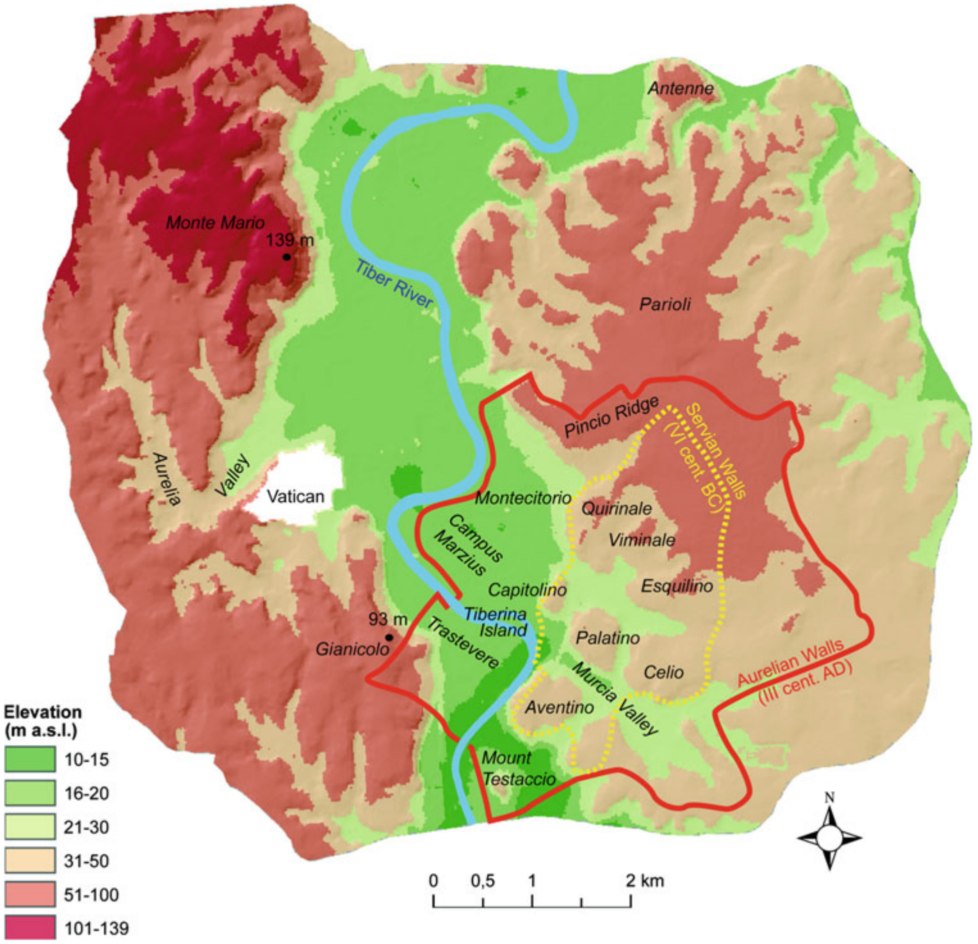

Fig. 29.3 A digital elevation model of the historical centre of Rome. The Tiber River flows southward. The *white area* corresponds to the State of the Vatican City

Mario—Gianicolo ridge. To the west, this ridge is cut by the Aurelia Valley, describing a counterclockwise curve towards the alluvial plain of the Tiber, next to the Vatican City (Fig. 29.3).

The landforms modelled by runoff and channelled water are recognizable throughout the urban area of Rome (Fig. 29.2). Most of the hydrographic networks, particularly the smaller streams, are currently affected by linear erosion. The major streams (including the Tiber River) show the effects of linear or lateral erosion, even though they have been modified for erosion control or drainage management. Consequently, fluvial erosion is now developing many scarps along the valley floors and often affects the embankments too.

The drainage network has peculiar characteristics. The axis of the main valley of the Tiber is oriented north–south (Fig. 29.3), which is similar to the orientation of several other channels, especially on the west side of the main river. The orientation of the Apennines (NW–SE) is also reflected in many landforms. To the east of the Tiber, the Murcia Valley ends with a straight feature that is most likely controlled by the presence of horst and graben structures.

29.3.2 Tiberina Island

A fluvial island is present in the Tiber's urban stretch: the Tiberina Island. It is located in the historical heart of Rome, where the city developed next to the river over 2500 years ago. Its origin is related to a counter-flow confluence (Fig. 29.6), causing a large river bar, that grew to become the only island along the Tiber's urban stream channel (Del Monte et al. 2016).

Several suggestive legends described the island's origin in the past. One explained the accumulation of mud from the Tiber on Tarquin the Proud's crops, which were thrown in the river when the last king of Rome was expelled. Another legend told of a snake that was sacred to Aesculapius, the Pagan god of medicine, which was brought on a boat from Epidaurus (a Hellenic city) to Rome. The city was

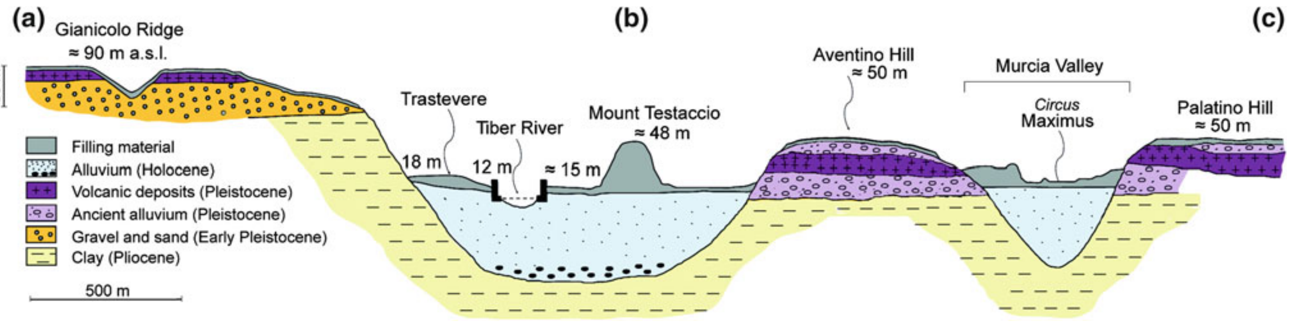

Fig. 29.4 Geological cross section showing some geomorphological characteristics of Rome City centre (see ABC direction in Fig. 29.8d)

Fig. 29.5 The floodplain of the Tiber, between Monte Mario—Gianicolo ridge and the northern ridge (Pincio) of the volcanic plateau, which continues to the south (*right*), including the southernmost Seven Hills (*right*, out of the frame; see Fig. 29.3). The Tiber flows from *left* (north) to the *right* (south); its floodplain narrows crossing the present-day central area of Rome, confined between the Gianicolo and the opposite Pincio. The picture is taken from the top of Gianicolo towards northeast, Hadrian's Mausoleum is in the *middle* of the image

being affected by a pestilence, and the snake appeared to be a solution, but it escaped from the ship and took refuge on the island. This legend influenced all the representations of Tiberina Island over time; even the island's perimeter is made of embankments in the outline of a boat (Fig. 29.6b).

29.3.3 Murcia Valley

The ancient Murcia Valley (Fig. 29.6a) is located in front of the Tiberina Island. The flat-floored valley, approximately 200 m wide, with steep slopes, was the ideal landform for building a large stadium like the Circo Massimo (*Circus Maximus*; Fig. 29.7). The ancient Romans built the Circo Massimo on Holocene alluvial deposits. The valley slope outcrops include ancient fluvial deposits, which are composed of blue clays of the Middle Pleistocene and pyroclastic materials and tuffs of the Latium Volcano (Middle-Upper Pleistocene) (see Fig. 29.4).

Circo Massimo is the greatest stadium ever built; it could hold, depending on the time and the extent of the renovations, between 250,000 and 385,000 spectators (Del Monte et al. 2013). Today, it is often used for shows because it can hold such a large number of people (approximately 700,000). In the Roman period it was the place where the mythical episode of the rape of the Sabines took place, during the games organized by Romulus in honour of the god Consus.

The Romans drained the Murcia Valley and other neighbouring areas (Velabrum) in the sixth century BC, and the stream flow was directed to the Tiber River by an

Fig. 29.6 **a** Nadiral view of the Tiber stream elbow in front of Aventino (see Fig. 29.3). The straight Tiber segment upstream the Tiberina Island is oriented NW–SE and is aligned with the axis of the Murcia Valley. On the *left* (west) of the Tiber the Trastevere quarter lies; on the *right*, the Flavian Amphitheatre (*Colosseum*) is recognizable (*source Google Earth, modified; © 2015 Google. Map data image Landsat, image © 2015 Digital Globe*). **b** Tiberina Island looks like a boat. It housed the temple of the medicine god, on which Christians built the basilica of San Bartolomeo; today it hosts one of the most ancient hospitals in Rome

underground pipe system through the *Cloaca Maxima*, nowadays still operating. It became a trade area (*Forum Boarium*; in Latin, *boarium* = of cattle) and a place of cultural importance. Located between Tiberina Island and Palatino, the *Forum Boarium* corresponded to a large, swampy area, where the legend of Rome's birth began. Romulus and Remus, the twin founders of Rome, were discovered here in a hamper.

In front of *Forum Boarium* there is the church where the famous "Bocca della Verità" (Truth Mouth) is located. It is a representation of a fluvial god that, according to legend, is an oracle (the Romans actually used it as a trap-door for surface water drainage). Here there was a swampy area due to the poor drainage caused by the counter-flow confluence between the Murcia Valley stream and the Tiber.

29.3.4 West of the Tiber: Monte Mario, Gianicolo, Trastevere

On the west side of the Tiber, a series of narrow and deep valleys cuts the western and eastern slopes of Monte Mario —Gianicolo ridge (Fig. 29.3). On the top, many outcrops of the Sabatini Volcano (Fig. 29.4) are present. Pyroclastic deposits (with scoriaceous lava and lava layers), a few metres thick, erupted between 470,000 and 500,000 years

Fig. 29.7 The Circo Massimo was a huge stadium built in the Murcia Valley for chariot races (sixth to second century BC). A view upstream of the former fluvial valley. On the *left* of the valley bottom, the southern slope of Palatino Hill; on the *right*, the northern slope of Aventino. In the middle of the depression, an isolated tree lying on the so-called "spina" (spine), a small ridge around which the chariots turned

ago (Del Monte et al. 2013), alternate with reworked volcaniclastic horizons and marsh deposits. Small trough-shaped valleys are common and indicate geomorphic evolution by both surface running waters and gravitational processes.

Landslides are widespread in this western part of the old town, and particularly common on the slopes of Monte Mario ridge. The crowns of the landslides are located at the edges of substructural surfaces, on the boundaries between the volcanic and the underlying sedimentary rocks, or along scarps bordering flat anthropogenic deposits ("terraces"). Many flows occur in areas of moderate slope gradients, and sometimes within older landslide deposits.

At the bottom of Monte Mario—Gianicolo ridge and close to the Tiber (Figs. 29.4 and 29.6a), Trastevere was a hostile Etruscan area when Rome was founded. Over time, this swampy area became wealthier, and Roman villas, temples, buildings, and churches were built. The entire neighbourhood stands on the Tiber floodplain.

Passing through Trastevere (from the Latin *trans tiberim* = beyond the Tiber), we leave behind the flat Tiber alluvial plain (Fig. 29.4) and walk on hillslope of Gianicolo hill. Several springs are located at the foot of eastern slope: therefore, two thousands years ago, a large and deep stadium was built here for naval battle games (in Latin *Naumachia Augusti*).

On the right bank of the Tiber, the lower Pleistocene sands and gravels occur above the Pliocene clays on the ridge of Monte Mario—Vaticano—Gianicolo (Fig. 29.4). These deposits contain an unconfined aquifer supplying several springs at the contact with the underlying clay. Since these springs did not provide enough water for the needs of citizens, in the 1608 AD Pope Paul V ordered to restore the ancient Traiano aqueduct to supply water from the Bracciano Lake (north of Rome). The aqueduct is today called the "Paolo Aqueduct"; the famous "Fontanone del Gianicolo" (Gianicolo Fountain) celebrates the work. A special viewpoint is located in front of the fountain; a large part of the city centre and its landforms are visible from this location, including the Tiber River floodplain and the eastern hills of Rome (see Fig. 29.3).

29.3.5 East of the Tiber: The Seven Hills

The eastern part of the old town is characterized by a large, flat structural surface. It was formed by the activity of the Alban Volcano during the Quaternary, starting at approximately 600 ka BP (Karner et al. 2001). The volcanic deposits filled many of the old valleys and forced the Tiber's riverbed to move westwards (Heiken et al. 2005). This volcanic plateau was afterwards deeply cut by the Tiber River and its tributaries; after a depositional phase during the Holocene, their valleys acquired their current flat floors (Fig. 29.4). Therefore, the valleys on the east side of the Tiber are similar to the main valley, except for their smaller size. While the present flood plain of the Tiber River can reach 2 km in width (Fig. 29.3), those of its tributaries are a few tens or a couple of hundred metres wide. All these valleys show very steep slopes and display outcrops of volcanic rocks interposed with fluvial deposits of the paleo-Tiber.

It is well known that the Romans built the city starting from the legendary Seven Hills. The first settlements were concentrated on the hills closest to the Tiber and to the Tiberina Island, rising a few tens of metres above the flood plain. The steep slopes and flat tops made them both easy to defend and suitable to hold small villages.

Gravity-induced phenomena are less common on the eastern side of the historical centre than on the western one. Mass movements mainly occur on the steeper slopes of fluvial valleys that cut the volcanic plateau, often at the boundary between the volcanic units and the underlying fluvial–lacustrine deposits. Several small landslides are affecting the artificial embankments or reshaped scarps, but these gravitational deposits are rapidly removed, the embankments reconstructed and the scarps strengthened.

It must be emphasized that the Capitolino and Palatino Hills appear to be isolated from the volcanic plateau described above (Fig. 29.3), but they were once joined to the ridges of the Quirinale and of Esquilino, respectively. The ancient Romans dug the depression between the Capitolino and the Quirinale Hills, in the second century AD, to extend the area of the Roman Forum. In addition, a hill next to the Colosseum (Velia Hill), between Palatino and Esquilino, was erased about one hundred years ago for the construction of a large avenue (Via dei Fori Imperiali; Fig. 29.8). All seven historical hills were therefore shaped as ridges by fluvial erosion processes of the Tiber drainage system in the Late Pleistocene and the Holocene, and then were partially reshaped in the most recent part of the Holocene (Fig. 29.8).

Palatino is close to the Tiber and the Circo Massimo (Fig. 29.7) and reaches a maximum height of 51 m a.s.l. It is an open museum and one of the oldest sites in Rome. A legend tells that the city began as a small village on this hill (*Roma Quadrata*, Squared Rome). The village was surrounded by swamps, from which the Romans could control the course of the Tiber. As said above, the Circo Massimo was built on the Murcia Valley's flat-bottom (Fig. 29.7), at the foot of the Emperor's Villa on the Palatino (in Latin, *Palatium* = palace). The large and straight valley, enclosed by hills, was particularly suitable for hosting a stadium; looking from the Circo Massimo it is easy to imagine its extension upstream, towards the Terme di Caracalla, and downstream, where the Valle Murcia stream flowed into the Tiber (Figs. 29.3, 29.6 and 29.8).

The Capitolino is a very important site of natural and cultural history and the seat of the current city hall of Rome. On its southern slope (*Rupe Tarpea*) the "*Tufo Lionato*", a type of ignimbrite that is particularly representative of Rome's geological history, is visible (Fig. 29.9). The outcrops of Rupe Tarpea show evidence of several phreatomagmatic eruptions; moreover, the Tufo Lionato has a very limited and thin exposure, so this outcrop is very peculiar. The tuff is composed of yellow pumice, black scoria, lava and holocrystalline (leucite and pyroxene) lithic fragments dispersed in the matrix (De Rita and Fabbri 2009). The name "Lionato" comes from the yellow colour of the ashy matrix, which resembles hair on a lion's head.

The Rupe Tarpea is famous in cultural history and is widely considered to be a symbol of Rome. Several legends refer to it. Tarpea was the name of the daughter of Tarpeo, a warrior defending the Capitolino after the kidnapping of the Sabine women, organized by Romulus. She was in love with Tito Tazio, the Sabines' king. When he convinced Tarpea to open the doors of the Capitolino, allowing the Sabine forces to enter the fortress, the Romans immediately executed Tarpea, throwing her from the top of the Capitolino Hill. Since then, the southern slope of the hill has been called Rupe Tarpea, and any traitor has been punished in a similar way. Even today, a well-known proverb keeps alive the moral teaching of this legend. It refers "*Arx tarpeia Capitoli proxima*" (Rupe Tarpea is close to Capitolino), in order to say that everyone after a great honour may know a terrible end, or conversely, that one, even being out of favour, may still rise to great honour.

29.3.6 Man-Made Landforms

Rome has always been affected by a variety of human activities, since the age of the oldest settlements. The signs of these activities are superimposed and juxtaposed with those caused by natural processes.

Rome hosted stable settlements since the Bronze Age and the ancient town is now an area of extraordinary archaeological interest. Mining activities, which are inactive today, started from sixth to fifth century BC and produced numerous caves with straight scarps and step-like slopes. The more recent changes to the topographic surface are due to open-pit mining. Wide areas of Monte Mario ridge and of the northern side of Gianicolo have been heavily modified by excavation and extraction of clay for brick production. Surface modifications due to anthropogenic activities have increased since the end of the nineteenth century. The city's population grew rapidly in the 1950s, generating intense construction activity that led to the development of vast neighbourhoods.

In addition to buildings constructed on almost all sub-horizontal surfaces, human activities have produced a number of flat embankments, stepped slopes and terraces. Intense erosion processes have acted on the man-made deposits, causing mud and debris flows, runoff and piping. Not all the human works have been negative for

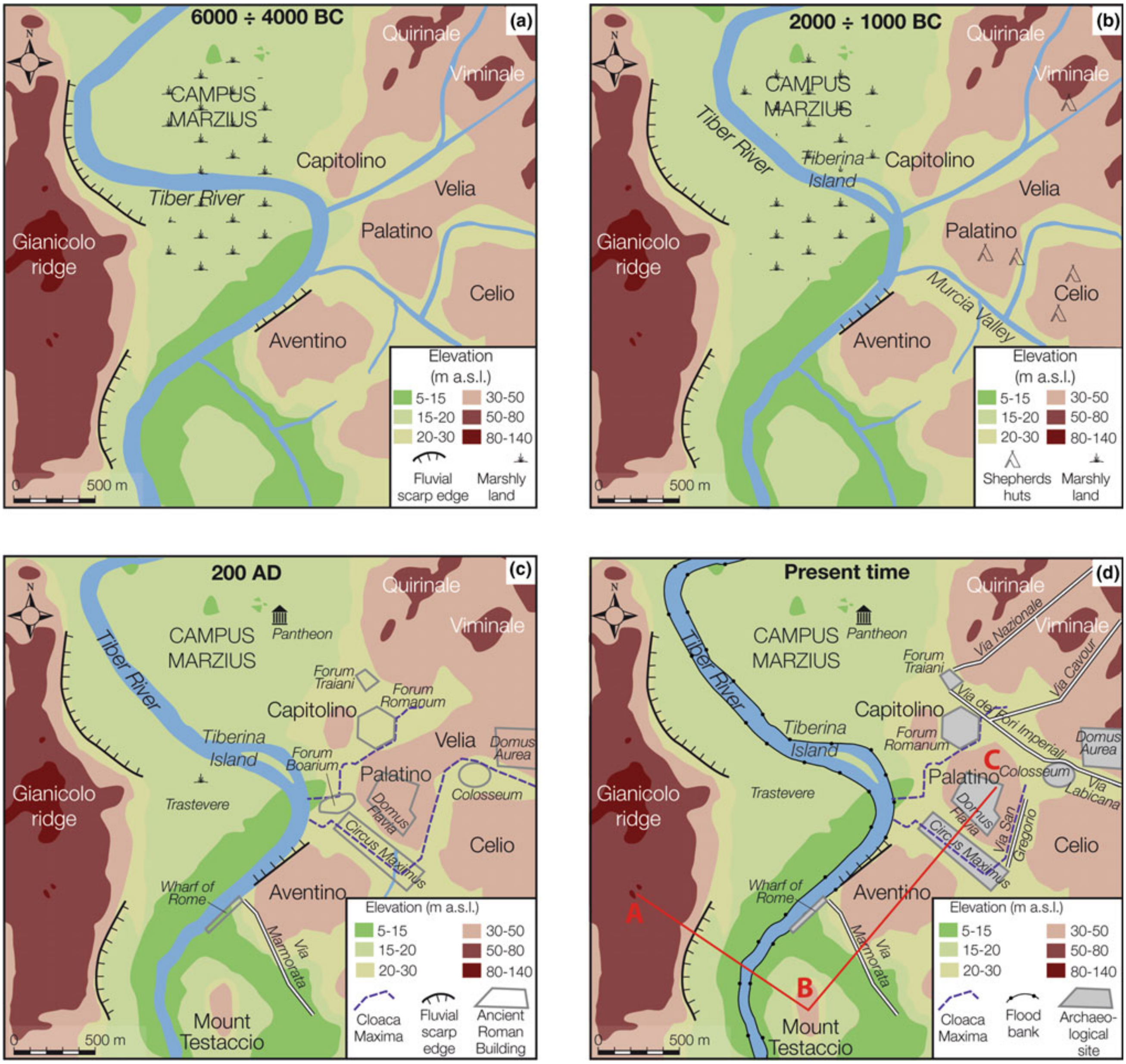

Fig. 29.8 Geomorphological evolution of the Rome City centre (the elevation is referred to the present-day surface). **a** One of the possible scenarios of about 4000 years before its foundation. **b** A few thousand years later, the Tiber Island was formed next to the confluence with the Murcia Valley stream. Meanwhile, the hills on the Tiber left hosted shepherds' huts. **c** 1000 years after the founding of Rome, the area was deeply transformed by man: a depression had been dug, separating the Capitolino Hill and the Quirinale; numerous wetlands disappeared; the Murcia Valley was drained by the *Cloaca Maxima*; different constructions lined the floodplain, including the Wharf of Rome, whose landfill became Mount Testaccio. **d** The old town today is completely urbanized and rich in archaeological sites. The construction of the Via dei Fori Imperiali erased the Velia hill

geomorphological stability: surely useful for flooding prevention is the construction, in the last century, of the Tiber embankments (Fig. 29.8).

Several examples of relief inversion evidence how deeply these human activities have changed the morphology of Rome. Some artificial hills were created and natural hills erased; some ridges were smoothed, and many small valleys were filled up, to promote building of necessary infrastructure. This latter intervention, however, has resulted in particularly unwelcome development. Elimination of the drainage network of the Tiber tributaries, over the past two centuries, not relieved by an adequate sewerage system as

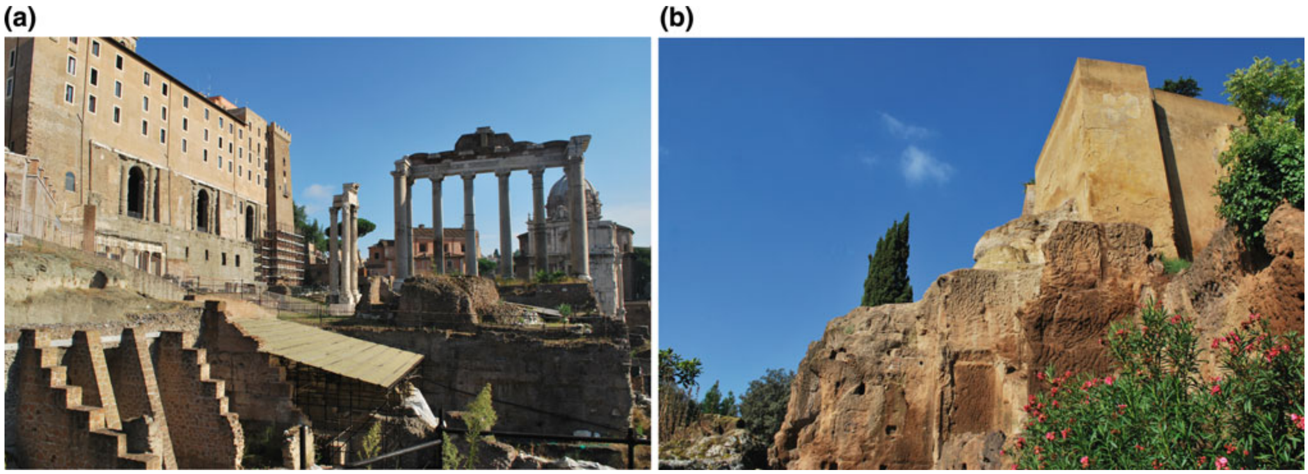

Fig. 29.9 **a** The southern slope of the Capitolino Hill overlooks the Roman Forum and the Tiber. **b** The Rupe Tarpea shows products of several eruptions of Latium Volcano under man-made remains

the ancient Romans used to do, is currently the main cause of overflowing runoff affecting the historical centre, if heavy rains occur.

Among the most significant changes made by man are the excavation of the saddle between the Capitolino and Quirinale and the removal of the Velia hill between the Palatino and Esquilino ridges (Fig. 29.8). Construction activities have covered repeatedly the surface of the historical city centre, producing a continuous layer of materials made up of the remains of collapsed buildings, rubbish, and the ruins of ancient temples, mixed with colluvium and alluvium. The thickness of the filling materials ranges between 0 and 30 m (Fig. 29.4).

A typical example of artificial hill is Mount Testaccio (Fig. 29.10), which reaches 48 m a.s.l. (the height of the nearby Aventino and Palatino hills). On the Tiber alluvial plain, several other man-made mounds appear today as small hills (e.g., Montecitorio, see Fig. 29.3). Mount Testaccio was created by the accumulation of so-called "Cocci" (shards), which are fragments of broken amphorae of the ancient Romans (in Latin: "*testae*", hence the name of the hill, with the addition of the Italian suffix -*accio*, indicating a negative characteristic). The intense trade activity generated the material that was used in the landfill of Testaccio (Fig. 29.10; see detail in the enlargement). As a result, it represents an anthropogenic hill, composed of broken amphorae fragments; in other words, it was a Roman dump. The shards are derived from oil amphorae from the nearby *Emporium* fluvial port (Wharf of Rome; Fig. 29.8), where the *annona publica* (food commodities for the people) were stored. Recent studies indicate that the amphorae fragments were routinely thrown away and accumulated between the Augustan period and the middle of third century AD (Del Monte et al. 2013).

An accumulation of this magnitude and height was made possible by a ramp and two side roads for wagons carrying the shards and amphorae fragments; these materials were placed in terraces (Fig. 29.10) contained by walls made of the same intact amphorae, also filled with shards. The Romans often covered the accumulation with lime, to prevent the decomposition of organics; the lime added cohesion and stability to slopes. Over the centuries, the accumulation became a small mountain, vegetation grew and erosion occurred on slopes. Nowadays, runoff water effects and landslides are present on the hill slopes.

The function of Mount Testaccio has changed several times. After construction of the Aurelian walls (third century AD) (Fig. 29.3), Mount Testaccio was no longer used as a dumping ground. The connections with the port changed greatly, and the sub-Aventino plain was somehow protected from the most destructive Tiber River floods. Originally a port and commercial district, in the Middle Ages, the Testaccio area became an area of vineyards. Several caves were dug on the flanks of the hill and used as wine cellars. "Prati del popolo", meadows of the people, which were used for picnics until the nineteenth century, were located on top of the hill and are still recognizable (Fig. 29.10). Nowadays, Testaccio is protected and the access is granted to researchers and to guided tours. At the foot of the hill a recreational area for cultural activities, music schools and nightlife has been developed.

Finally, it should be remarked that the landscape of Rome preserves signs of the evolution of three different types of hills: the legendary Seven Hills and other natural hills, like the Vatican; several man-made hills, such as Mount Testaccio, the highest one; and disappeared hills, due to man-made erosion, like the removal of Velia hill.

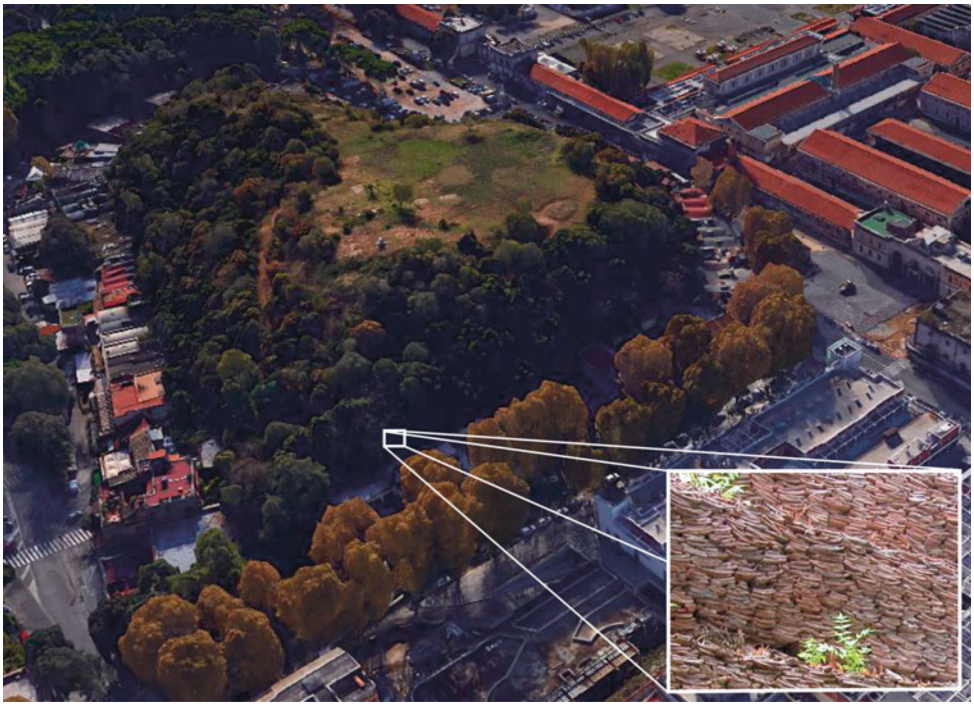

Fig. 29.10 Mount Testaccio is the largest artificial hill of Rome, with a height of 48 m a.s.l. and a circumference of 1 km (*source Google Earth, modified; © 2015 Google. Map data image Landsat, image © 2015 Digital Globe*). At the *lower right corner*, a detail of the geometrical arrangement of the shards

29.4 Conclusion

The geomorphological characteristics and the reconstruction of their variation over time represent just a simplified example of the deep geomorphological complexity of the Roman territory. Some connections between area's history, urban planning and geomorphological characteristics have been highlighted.

Moreover, some examples were discussed to show that the Romans built certain structures in specific places depending on the geomorphic characteristics of the area.

To conclude, the geomorphology of Rome not only represents a topic of geological interest, but also a typical model of a landscape evolution that influenced the development of the ancient *Caput Mundi* (Capital of the World). Rome was not founded accidentally on some small hills in front of the Tiber.

Many natural landforms and landscapes are related to the foundation and to the history of the city. During the last three thousand years, several landforms have been remodelled, created or vanished due to human activity and natural processes. They represent nowadays the morphological consequences that both man and nature have marked in the territory of Rome, creating a stately, majestic open-air museum. For these reasons, the landscape of the *Aeterna Urbs* is unique all over the world.

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Granite Landscapes of Sardinia: Long-Term Evolution of Scenic Landforms

Rita T. Melis, Felice Di Gregorio, and Valeria Panizza

Abstract

Sardinia is characterized by spectacular granite landscapes with superimposed scenic landforms. In the eastern part of the island, the granite reliefs consist of mountain massifs and plateaux separated by metamorphic reliefs and limestone plateaux. Granite landscapes show peculiar landforms such as inselbergs, tors and tafoni and diverse erosion microforms. In the extraordinary landscape of Gallura region, wide flat areas with outcropping rocks, vast extensions of isolated rock blocks and inselberg-type dome-shaped reliefs show evidence of a long period of intense weathering. Scenic landforms characterize the spectacular landscape of Sarrabus region, where differential erosion processes have selected the numerous dikes which have conditioned the orientation of the reliefs and coastal landforms. Many archaeological remnants can be found in most granite regions of Sardinia emphasizing the deep bond between man and the physical environment.

Keywords

Granite • Weathering • Inselberg • Tor • Tafoni • Sardinia

30.1 Introduction

Sardinia is the second largest island in the Mediterranean Sea. Its landscapes are of great geo-diversity and the most spectacular ones are supported by granite bedrock, formed during the uplift of the ancient Variscan chain. Scenic landforms occur in an amazing variety of shapes and settings and are superimposed on splendid granite landscapes.

Throughout the island, the Sardinian granite landscape is characterized by rugged mountains cut by deep gorges, vast uplands scattered with block piles, and large hills covered by Mediterranean scrub. Indented coasts, shaped into promontories, bays and small islands border the ancient granite masses that rise from the sea. Strange landforms carved in granite have inspired the people's imagination.

These spectacular granite landscapes are located almost continuously in the eastern part of the island, from Capo Testa to Capo Carbonara (Fig. 30.1). In this part of Sardinia, granite terrains do not form a high and continuous ridge but a series of mountain massifs and plateaux separated by areas underlain by metamorphic rocks and limestone plateaux. The Limbara massif to the north dominates the Gallura landscape, while to the south the Sette Fratelli (*Seven Brothers*) massif characterizes the Sarrabus landscape.

Similar landforms are present in all granite landscapes of Sardinia, but local structural and lithological conditions allow different morphological features to be distinguished and, as Migoń (2004, p. 30) wrote: "*there are granite landscapes and granite landscapes*".

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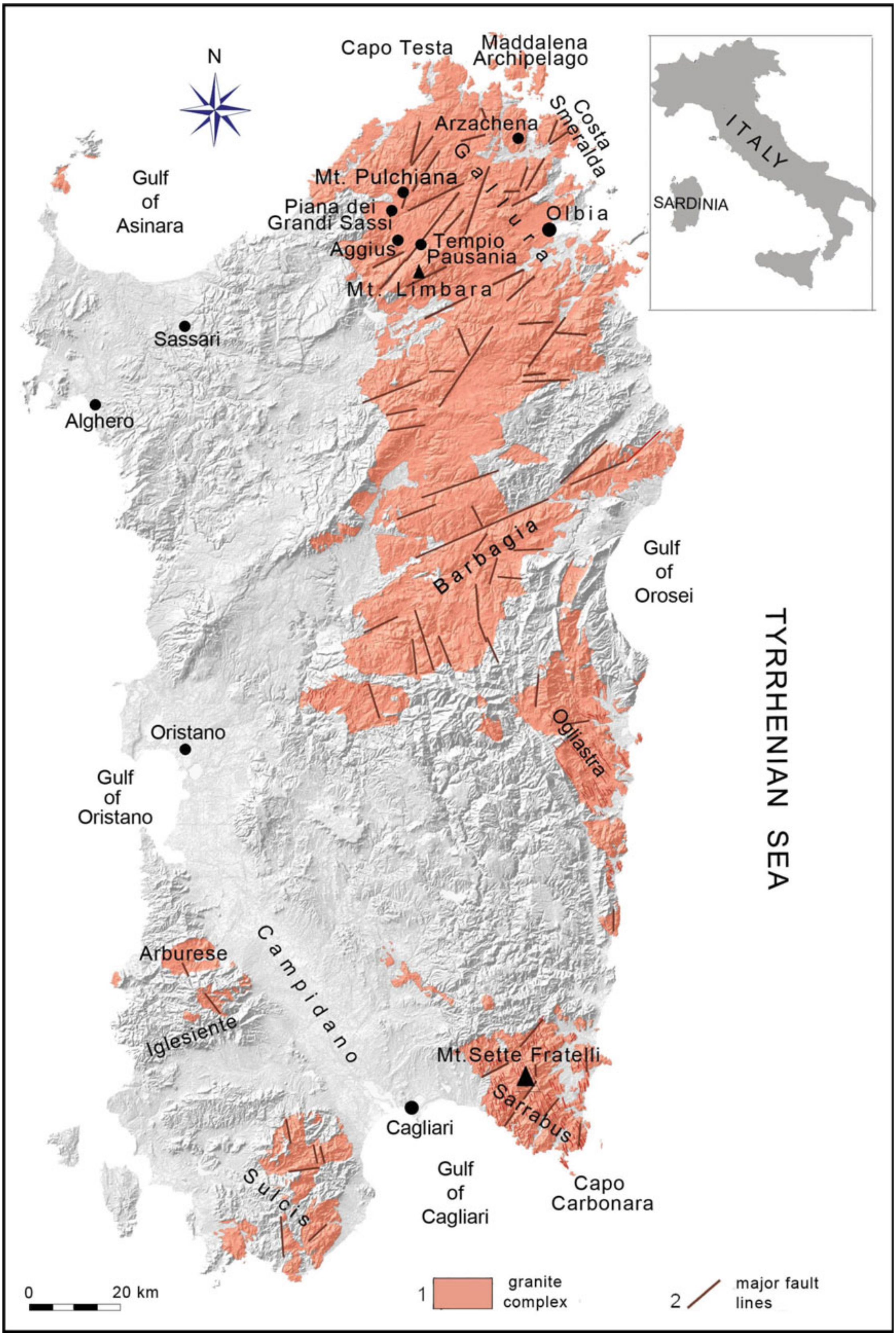

Fig. 30.1 Schematic map of the granite outcrops of Sardinia

30.2 Geographical and Geological Setting

The island of Sardinia is located between 38° 51′ 52″ and 41° 15′ 42″ latitude north. It covers a total area of 23,821 km^2 of which some 6000 km^2 are built by widespread calc-alkalic granitoids intruded in the polydeformed and metamorphosed Palaeozoic basement during Variscan Orogeny, from 350 to 290 Ma BP (Rossi et al. 2009). During this long period of time, changes occurred in the geodynamic framework, influencing the structural and compositional characteristics of various intrusions.

The Sardinian batholith consists of numerous intrusive bodies of variable size and plutons from granodiorites to leucogranites with incidental amounts of tonalite and gabbro (Orsini 1976). Permian hypo-volcanism produced numerous basic and acid dikes crossing the batholith in various directions. At the end of the Carboniferous, the uplifting of the Variscan chain fragmented the granite basement and led to partial erosion of the granite plutons.

The Oligo-Miocene anticlockwise rotation movement of the Corso-Sardinian block and the Alpine collision produced major faulting and tilting in the granite batholith. Its outcrops are mainly found in the Gallura and Barbagia region in the north and in the Sarrabus region in the south (Fig. 30.1). Minor outcrops of granitic rocks are present in the Sulcis-Iglesiente and Arburese districts, in the western portion of the island. In these granite regions, the average altitude is about 300 m a.s.l., with the top peaks of Mt. Limbara (1362 m) to the north and Mt. Sette Fratelli to the south (1023 m).

Typically, the climate is Mediterranean with mean annual precipitation of some 650 mm and mean annual temperature of about 23 °C. In summer maximum values exceeding 40 °C can be attained and in the winter minimum values below 0 °C are recorded at high altitudes. Precipitation often occurs in the form of storms, with very intense but short duration rainfall events in autumn and winter. Winds are frequent and very strong throughout the year, particularly the cold Mistral from the northwest and the hot humid Scirocco from the south. The most important geomorphological control is exerted by the geological-structural setting, but also by the climate, in particular past climate changes. Typical granite landscapes of Sardinia displaying significant landform diversity can be found in the Gallura and Sarrabus areas and these will be described below.

30.3 The Gallura Landscape

The northeastern portion of Sardinia is known as Gallura, a region famous for its rose-coloured beaches and crystal-clear sea, where the famous “Costa Smeralda” and Maddalena Archipelago are found. This area is also known for its extraordinary archaeological heritage, the production of renowned wines, such as Vermentino, and the presence of widespread cork oak (*Quercus suber*) woods.

The landscape is dominated by granitoid rocks, since the Variscan granite batholith crops out extensively with many mineralogical-petrographic variations. Since the mid-nineteenth century, the Gallura landscape has stimulated studies by historians, geographers and geologists who made observations and formulated scientific theories still valid to date and which preceded the more recent geomorphological investigations.

Thanks to the exceptional landforms, numerous protected areas of natural or international importance have been established or are being established. Among these, the Piana dei Grandi Sassi and Mt. Pulchiana are a Natural Reserve and Natural Monument, respectively. They are both located in the municipality of Aggius, in northwestern Gallura. The average altitude, orientation and shape of major landforms generally follow regional tectonic features, with prevalent NE–SW and NNE–SSW alignments, as in the case of the Piana with its saw-toothed crests, locally known as “serre”, towards southeast near the village of Aggius, or the alignments of the relief where the Mt. Pulchiana dome is found. These are the dominant tectonic orientations, especially in the Gallura landscape, which make up, as already observed by Pelletier in 1960 (p. 12), “*the morphological personality of the whole region*”. The imposing granite rock masses, cropping out everywhere with their typical petrographic and mineralogical variations and tectonic alignments, give the landscape its characteristic features, modelled on a small to medium scale by physical and chemical processes.

Out of the Carboniferous-Permian calk-alkaline association characterizing most of Sardinia’s granite, inequigranular monzogranites and equigranular leucogranites prevalently crop out in this area (Carmignani et al. 2001). The former are found in the whole Piana dei Grandi Sassi whereas the latter are widespread in the Mt. Pulchiana and in all the surrounding ridges. Apart from their mineral associations, these granites can be distinguished by the average size of the phenocrysts and the shades of colour, which is typically pinkish in the leucogranites. The whole area is located within a wide belt bounded by two important NE–SW oriented left transcurrent faults, ascribable to Miocene compressive tectonics. Tectonic processes disrupted and displaced the crystalline basement with the formation of the major large-scale physiographic structures and corresponding elevations of the batholith: high-standing structures, wide depressions, horizontal or gently inclined plateaux. Along the dense joint network, intense modelling of relief forms took place in geological times and under diverse climate conditions. Also the hydrographic network follows the main structural alignments almost perfectly.

The granite outcrops with their round-shaped or saw-toothed relief, typical of this region, show sets of regular joints normal to each other. Spectacular forms can be observed where differential erosion has outlined the Permian dikes, such as the porphyritic-microgranite dike disrupted by a fault which characterizes the coastal landscape of Capo Testa.

There has always been a close link between the granite landscape and humans, which has remained strong across the centuries linking many historical, religious, social, etc., vicissitudes. In this part of Sardinia, the availability of resistant building materials, often already available in blocks isolated by the jointed network, was of great importance to the local population. Also the spectacularity and impressiveness of the relief have become part of daily life, socio-economic needs and human imagination, thus producing a constant intrigue between culture and natural landscape. The first evidence of human presence in Gallura dates back to the early Neolithic, in the form of remains of temporary settlements inside wide tafoni. Indeed, these natural cavities have always been a geographic factor accompanying man throughout history, serving as shelters, burial sites or stabling for animals.

Also in recent and even present times, the traditional kind of scattered-habitat settlement, typical of the region, makes use of the many natural morphological features offered by granite to give shelter to farm animals, store tools and create temporary shelters. Some of these landforms show rather curious shapes which in popular imagination have conjured up animal and anthropomorphic figures or even other elements taken from the natural world, such as the Arzachena Toadstool, inside which remains of artefacts were found testifying its use as a shelter in a period ranging from 3500 BC up to the Nuragic age. Also along the Gallura coasts subaerial weathering has created extraordinary forms, among which the famous Palau Bear, which has been declared a regional natural monument (Fig. 30.2).

In this region, archaeological sites such as rock ledge shelters, funerary or cult circles, funerary tafoni and dolmens are extremely important testimonies. Among these, the so-called "Tombs of the Giants" are made up of huge vertical granite slabs (Fig. 30.3). There are many other monuments which witness not only the widespread use of granite rocks in very remote times but also a spiritual relationship with the landscape which in time has created a kind of social organization and adaptation to the environment forming the local identity. The whole of Gallura preserves innumerable sites which can be included in the category of geomorphosites owing to their scientific and often cultural interest (cf. Panizza 2001). Some of these, such as the Palau Bear or Mt. Pulchiana, are protected by specific norms whereas in other cases the introduction of adequate conservation measures and sustainable tourist fruition would be desirable. Indeed, the intrinsic value of the landscape of this region lies in the geohistorical heritage (*sensu* Panizza and Piacente 2009) of its geological-structures and relief forms as well as in the richness of its archaeological and cultural heritage and in the constant functional and cultural links between its

Fig. 30.2 The Palau bear: a spectacular form resulting from subaerial weathering which dominates the coastal landscape of Gallura and the Maddalena Archipelago

Fig. 30.3 Coddu Vecchiu giant tomb: sepulchral Nuragic monument in granite blocks worked by man (Bronze Age, 1800 years BC to 1300 years BC) and, in the *background*, a vineyard of Vermentino di Gallura wine

components. Therefore, it is a cultural landscape where the relief and the geological-structural characteristics are in constant interrelation with the human element (Panizza and Piacente 2009) and convey shareable values and messages.

30.3.1 Piana dei Grandi Sassi

The Piana dei Grandi Sassi is a wide flat area scattered with rock blocks and tors (i.e. free-standing residuals approximately of the size of a small house), surrounded by generally round-shaped reliefs and cut across by the Riu Turrali stream from SW to NE. This spectacular plain is located in the inner part of the wider plateau of Tempio Pausania bordered in the south by the granitic massif of Mt. Limbara. This inner plain has average elevations between 425 and 460 m, whereas the surrounding ridges reach a maximum altitude of 680 m. The lower slopes are connected to the plain at a sharp angle, although in some places the contact surface is gentler owing to the accumulation of residual materials and blocks of various sizes.

This wide area is lower than the surrounding terrains which are arranged according to the prevailing tectonic alignments. Its scenery is spectacular, with wind-bent cork oak trees and grassy tablelands dominated by Mediterranean scrub where flocks of sheep often graze. Everywhere there are chaotically arranged rounded boulders and compact granite outcrops a few metres high (Fig. 30.4). Deposits of residual material partially reworked by pedogenesis fill the plain and the depressions whereas piles of jointed rock blocks stand out in the landscape. A large amount of prevalently round-shaped boulders has been formed by the progressive weathering of the granite blocks and tors.

The boulders are of varying sizes and are scattered practically everywhere across the plain, giving the landscape a very unusual appearance which has made this area particularly well known with the name of “Piana dei Grandi Sassi” (Plain of the Big Blocks). The geological-structural setting and, in particular, the climate changes occurring in the Cainozoic and in the past 2 million years favoured the genesis of numerous landforms now scattered across this particular plain. The erosion of the weathered materials—which originated in past hot and humid periods—carried out by running waters has made the tors and scattered boulders to emerge from the weathering mantle. Exfoliation and disintegration processes occurring during the most arid phases have certainly had an important role in the modelling of these scenic forms.

Everywhere in the plain, the rocky outcrops and blocks have been hollowed out, with cavities varying considerably in width and depth from a few tens of centimetres up to a few metres. They are tafoni (locally known also as “conchi”) which result from granular disintegration of microfissured rock surfaces. This surface weathering is controlled by water penetration into the rock and minerals and is more marked on shaded rock faces where mistiness maintains a high humidity level. The initial phase of the hollowing process can take place under the surface (cf. Twidale 1982), thanks also to subsurface micro-percolation conditions of groundwater inside the granite joint network or underneath the weathering

Fig. 30.4 Panoramic view over Piana dei Grandi Sassi, with wide extensions of large isolated boulders and rock heaps (tors); in the *background* the Serre di Aggius

mantle (cf. Roqué et al. 2013). A more advanced stage of development of tafoni is observed at the base of the blocks.

In these areas, which are more protected from direct sun rays, rock disintegration process has been more intense from the bottom towards the top, thus creating large cavities. Some of these have been used as shelters or burial sites in Prehistory and, up to the 1970s, as sheep shelters during transhumance. In other cases, shepherds have

Fig. 30.5 The Mt. Pulchiana inselberg with its typical dome-shaped profile and the fantastic tors, chaos of blocks and tafoni scattered at the base of steep slopes. In the *foreground* one of the tafoni utilized as a shepherd shelter

transformed the largest tafoni into rustic houses or shelters for their animals by adding walls of small granite blocks (Fig. 30.5).

Most of the tafoni are no longer active. Active disintegration processes can only be observed in particular conditions of dampness and exposure, and are visible on the wettest walls, with the formation of easily detachable weathered material which accumulates on the ground.

30.3.2 Mount Pulchiana

Mt. Pulchiana (673 m), rising just northeast of the Piana dei Grandi Sassi, is an extraordinary landform characterized by a dome-shaped top and may be defined as an inselberg. It rises from the surrounding plain surmounting a ruin-like chaotic landscape rich in tors, rock boulders and tafoni of all sizes (Fig. 30.4). Here the landscape has been controlled by the transcurrent tectonics of this region which has defined crests and reliefs and has conditioned the contrast with the nearby plain. The evolution of this spectacular dome-shaped landform was controlled by the regional fault system and the complex set of joints. Mt. Pulchiana is located inside a vast granite area bounded by NNE–SSW and NE–SW trending faults. Furthermore, the orthogonal joint system characterizing the rock mass has isolated smaller rock portions, one of which hosts this outstanding inselberg. The orientation and spacing of joints have controlled the weathering processes

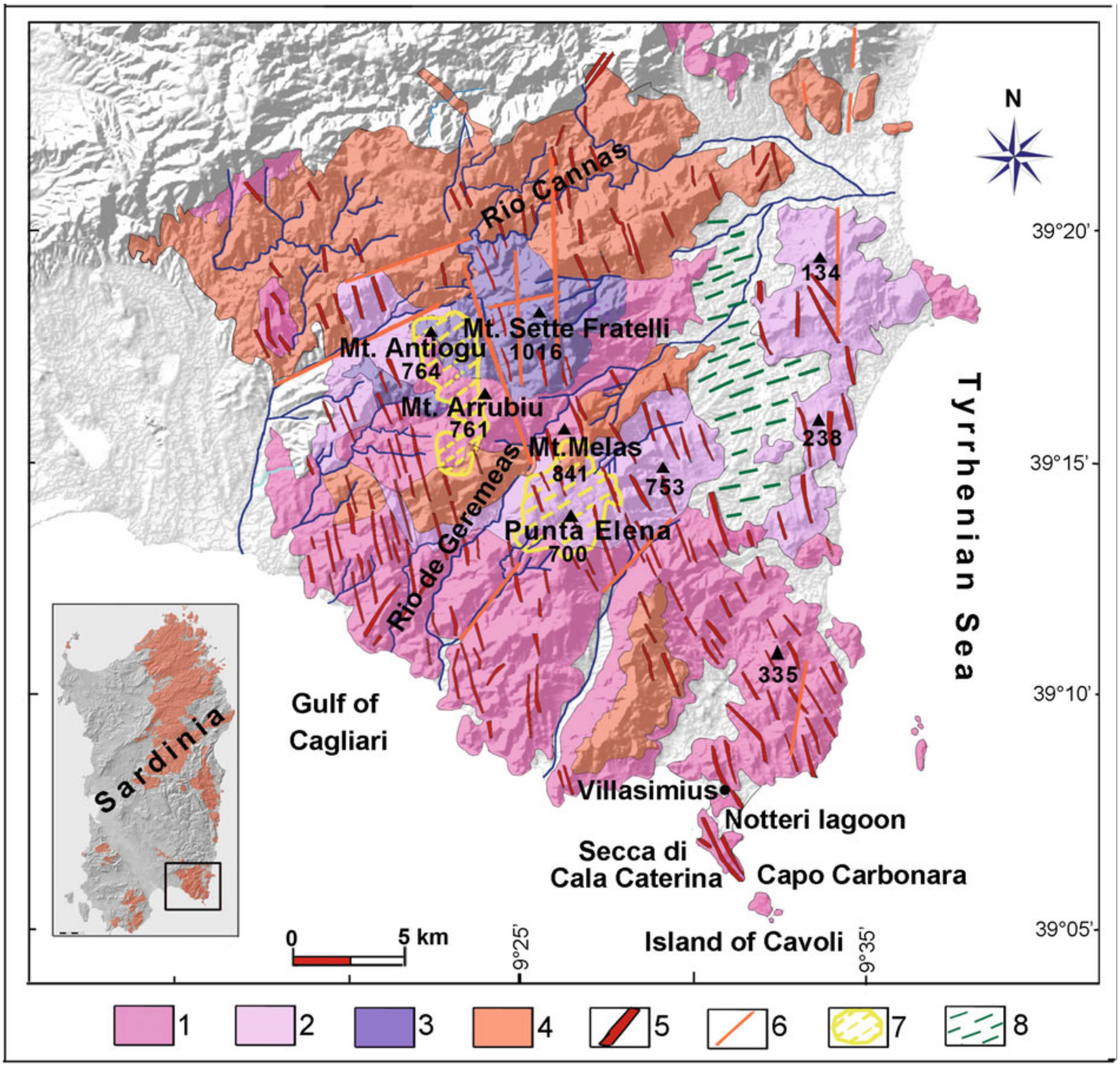

Fig. 30.6 Geological and geomorphological sketch of the Sarrabus granite landscape. *1* Granodiorites, *2* monzogranites, *3* fayalite biotite granites (Mt. Sette Fratelli), *4* leucogranites, *5* dikes, *6* faults, *7* plateau, *8* pediment

and, subsequently, the removal of weathering products carried out by running waters.

In detail, the northwestern slope of Mt. Pulchiana is steeper than the eastern one because of a fault which has favoured the fall of large fractured blocks. Thick Mediterranean scrub covers the abundant boulders and debris accumulated at the foot of the slope. On the other hand, the northeastern slope of this inselberg, which is characterized by sheer convex faces of outcropping rock, is affected in its higher part by mega-exfoliation phenomena due to the opening of sheeting joints. Along the steep southern face numerous joints can be observed in the outcropping rock, which cut across the leucogranites orthogonally. The mountain is separated from other minor ridges to the south by a paleo-valley set along a NW–SE trending fault, with the presence of huge, scattered blocks. The chaotic distribution of rock fragments and rounded blocks, scattered or piled up in heaps, characterizes the footslopes all around the inselberg. This view is very striking, owing also to the presence of many tafoni of various sizes and shapes. Near the top of Mt. Pulchiana the slopes are steeper and ascent can continue only by overcoming narrow and steep passages between rock blocks, within natural cavities and dense thickets of Mediterranean vegetation.

30.4 The Sarrabus Landscape

The Sarrabus granite massif, located at the southeastern extremity of Sardinia (Fig. 30.6), is bounded to the west by the Campidano tectonic trench and to the south and east by the sea. It offers scenic landscapes scattered with spectacular forms. In Sarrabus, as well as in Gallura, the same spectacular granite landforms are found: plateaux, crests, tors and tafoni. In this region, however, the granite bedrock has been, on the whole, more affected by incision. Therefore, deep, narrow gorges are common and the relief energy is higher. This gives the Sarrabus landscape a more rugged, mountain-like and less accessible appearance compared with the Gallura landscape. The Sarrabus massif is shaped into different calk-alkaline bodies which were intruded into the metamorphic basement during Variscan Orogeny and subsequently, in the Cainozoic, were tilted during the east rotation of Sardinia. Numerous acid and basic NW–SE trending dikes intersect the granitoid bodies. To the north, a deep valley separates this massif from the metamorphic terrain of Gerrei. To the south it descends gradually towards the Gulf of Cagliari and the Tyrrhenian Sea. Two different landscapes distinguish this scenic massif. To the west the landscape is characterized by high, rugged relief dissected by deep valleys, whereas to the east the landscape, which was tectonically lowered, becomes gentler, with lower elevations (300 m) and elevations separated by shallower valleys. The contrast between these two landscapes can also be noted by the different trend of the coast, which is high and rocky to the southwest, whereas it is much more irregular with numerous islands, wide bays and rocky promontories to the south and southeast.

In particular, the western landscape is more open than the eastern one and displays spectacular sceneries both in meso- and microscale. Tooth-sawed crests, steep rock faces, wild gorges dug into steep slopes, fluvial valleys enclosed in the

Fig. 30.7 The peaks of Mt. Sette Fratelli with, in the *foreground*, a tor emerging from the remains of the plateau

Fig. 30.8 **a** Bronze Age megalithic structure (Nuraghe) harmoniously blending with the tor blocks; **b** the joint systems in the granite along the Rio Cannas canyon; **c** numerous potholes on the valley floor dug in the granite rock

rock, pinnacles, towers and heaps of rock blocks give the area captivating appearance. In this impressive and striking landscape the Sette Fratelli ridge stands out; it is crowned by rocky crests and bounded by deep winding valleys which are often set along faults.

This area, which is one of the Sardinian Regional Natural Parks, is covered by thick Mediterranean scrub and by a dense forest of holm and cork oaks (*Quercus ilex* and *Quercus suber*). Inside this imposing forest populated by the Sardinian Red Deer (*Cervus elaphus corsicanus*), seven rocky peaks stand out, like still giants watching over this mysterious landscape, giving origin to the place name of “Sette Fratelli” (Fig. 30.7). These mountain tops attain different elevations: from 791 m of “Perd’a Asub’e Pari” to

1016 m of “Punta Sa Ceraxa”, which to the north joins with the peaks of “Casteddu de Su Dinau” (915 m) and “Baccu Malu” (1015 m).

Since very ancient times, their dome-shaped forms and tors have been the subject of myths and legends lost in the mists of time. They stand like towers covered by rocks and appear to be built of a number of loose boulders. These scenic landforms are carved into well-jointed light greyish leucogranite with commonly occurring Fe-amphibole and Fe-biotite minerals, as well as fluorite in accessory amounts and subordinate fayalite (Secchi and Lorrai 2001).

This resistant granite is divided by normal sets of fractures. The evolution of the seven peaks has been influenced by the fracture spacing in each set. Intense runoff erosion has removed weathered material from fractures dissecting the peaks into large rock towers or tors and crumbling boulders. Isolated boulders crown these summits forming picturesque pedestals or rocking stones often of imposing dimensions, such as Punta Sa Ceraxa peak. This peak, whose name means *Point of the Cherry*, is made up of huge isolated blocks which apparently seem to be in precarious equilibrium, piled as they are one on top of the other. Nevertheless, boulder piles at the foot of the crests bear witness to mass wasting in the form of rock block falls.

These scenic landforms are also the result of differential denudation, accomplished mainly by deep weathering during a long period of humid tropical climate. Fairly flat summit surfaces bound the Sette Fratelli relief to the west and south. They bear witness to the remains of a vast denudation area which developed under warm and humid climate conditions at the end of Variscan Orogeny and was later shaped during Oligo-Miocene times. In this period, uplift of the granite rock masses led to an increase of erosion and considerable deepening of the valleys. The deep Rio Geremeas valley separates the two largest flat areas formed in the granodiorites. To NNW there is a very regular 700–800 m high plateau, on which the round-shaped hills of Mt. Antiogu (764 m) and Mt. Arrubiu (761 m) stand out as they were modelled in harder leucogranites. On the opposite side of the Rio Geremeas valley, the plateau is characterized by a surface slightly inclined to the south, from Mt. Melas (841 m) to Punta Elena (700 m). On these two plateaux, elongated depressions bear witness to ancient drainage preceding the Cainozoic uplift, which, in turn, led to the deepening of the valleys. Scattered blocks hollowed with tafoni protrude from dense Mediterranean scrub and characterize the plateau landscape. This gentle morphology, the presence of deep soils, wet areas and piles of rock blocks, could have provided the prehistoric peoples of the Nuragic civilization with favourable conditions for their settlements. Indeed, nestled among the tor blocks, the remains of Nuraghi—megalithic edifices dating from the Bronze Age (Depalmas and Melis 2011)—are hardly visible (Fig. 30.8a).

The deep, narrow valley of Rio Cannas surrounds the Sette Fratelli relief to the north. Striking scenery can be observed by proceeding along the winding canyon meandering in the rose-coloured leucogranites, monzogranites and granodiorites. In the bare walls of the Rio Cannas canyon

Fig. 30.9 Panoramic view of coast of the Capo Carbonara promotory: piles of rock blocks on the beach and, in the *background*, the Sarrabus granite reliefs

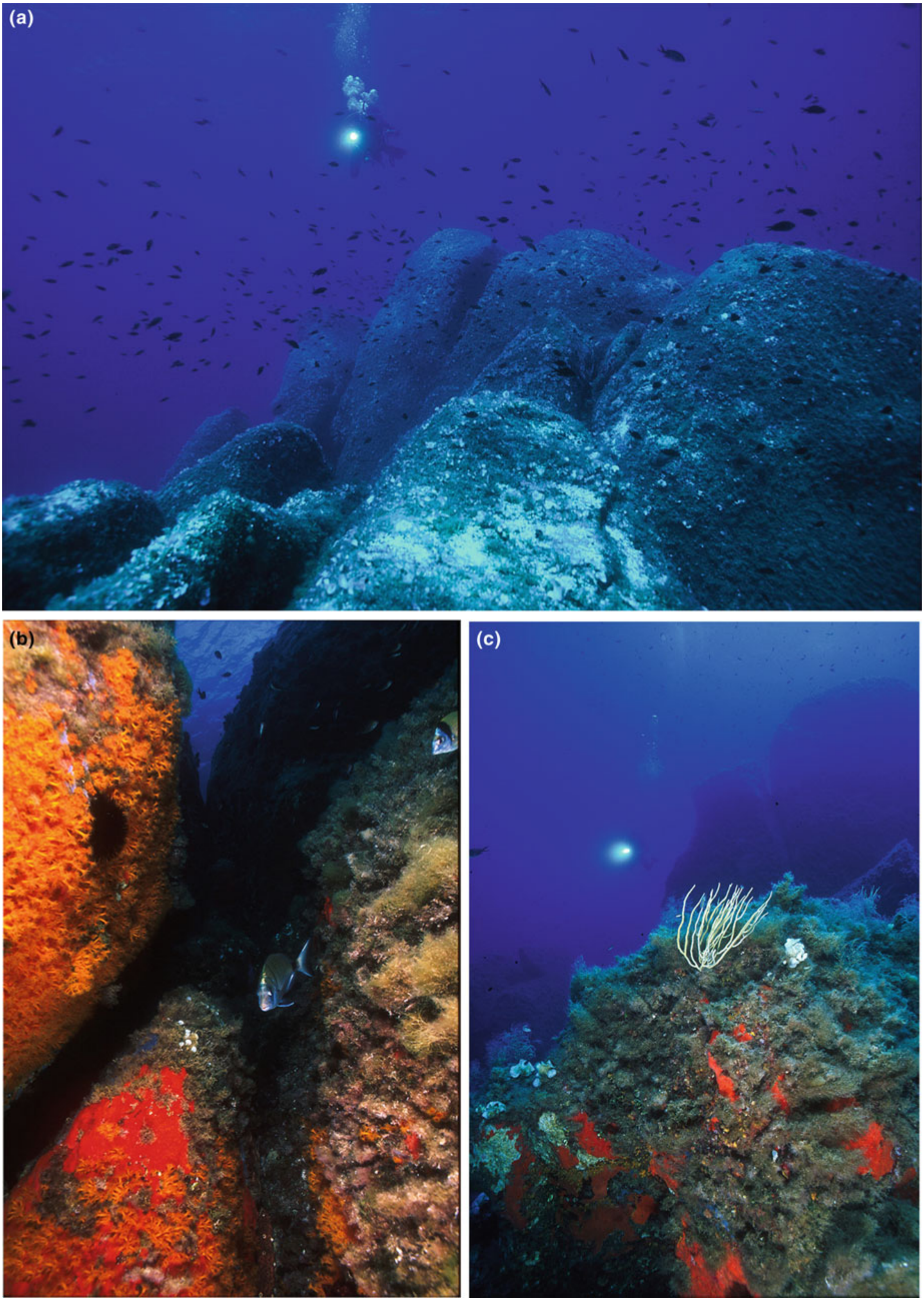

Fig. 30.10 Images of sea floor along the Villasimius coast: **a** granite block piles on the sea floor on the Capo Carbonara coast; **b** habitat for large groupers (Serranidae) and gilt-head breams (*Sparus aurata*) between granite blocks on the shoal of "Santa Caterina"; **c** a granite block coloured by the Yellow Cluster Anemones (*Parazoanthus axinellae*) and by the *red* Gorgonaceae on the Capo Carbonara sea floor (courtesy Area Marina Protetta Capo Carbonara—Comune di Villasimius)

various joint systems can be identified, which separate the outcropping granite units into irregular prismatic blocks (Fig. 30.8b). Fields of porphyry, but also quartz, pegmatite and lamprophyre dikes dissect the granite and arrange the surrounding ridges in the form of crests and inaccessible precipices. In the valley floor fluvial erosion has cut across some rock bars and dug numerous potholes in the riverbed (Fig. 30.8c).

To the south, the Sarrabus granite massif slopes down towards the coast, whereas to the east it is affected by a series of fault scarps. This area is mainly characterized by flat surfaces which almost completely isolate the low ridges to which they are abruptly connected. These flattish areas, identified by Pelletier (1960) as pediments, bear witness to long-term landscape evolution and its advanced stage. On the surface of the pediments the monzogranite and granodiorite bedrock is covered by weathering deposits affected by pedogenesis. It crops out in some parts or is covered by a thin layer of debris and sand. Small residual inselbergs, partly covered by prairie or thick Mediterranean scrub, emerge from the plain.

To the south, in the territory of Villasimius, differential erosion processes have isolated numerous acidic dikes that dissect the granodiorites outcrops. In fact, the crests and parallel valleys are all oriented according to the NW–SE arrangement of the dikes. This marked orientation is found also in the relief of the triangular promontory of Capo Carbonara, linked to the coast by sand bars in which the splendid Notteri lagoon nestles. Various porphyritic-microgranite dikes give the tip of the promontory a particular shape, modelled also by marine erosion (Fig. 30.9). In this sector, the narrow top of the rocky relief suddenly slopes down towards its extremity by means of a fault scarp. The sheer slopes are made up of granite bedrock and scattered blocks. There are also unusual tafoni in the landscape dotted by bushes of Mediterranean scrub. Along the coast, wave-modelled rocks can be seen whereas beneath the crystal-clear waters of the sea fascinating sceneries are revealed by the granite rocks forming pinnacles (Fig. 30.10a), buttresses and depressions, often coloured by the yellow of zoanthid coral or Yellow Cluster Anemones (*Parazoanthus axinellae*) or by the red of the *Gorgonaceae* (Fig. 30.10c). On the sea floor near Secca of Cala Caterina, south-west of the promontory, a fantastic submarine display of rock piles can be admired which makes up the ideal habitat of peaceful populations of large groupers (*Serranidae*) and gilt-head breams (*Sparus aurata*) (Fig. 30.10b).

Opposite the Capo Carbonara point, at a distance of some 700 m, the small island of Cavoli is found which represents the continuation of the promontory into the sea. The joints of the granite bedrock and the dike system have created the beautiful main inlets and alignment of two small elevations (40 m) which give the place its morphological character. Deeply jointed rock blocks characterize the tops of the two ridges which are linked by means of a gentle saddle. Small heaps of blocks emerge from the bushes and adorn the morphology of the island whilst thin sand deposits resulting from weathered granite accumulate in the inner depressions and rock fractures, favouring the development of soil and vegetation.

Along the coast of this wind-swept island, granite surfaces usually remain fresh because of the constant washing effect of the waves. On the other hand, aerosol and high salinity favour weathering processes on the rock surfaces which are not exposed to the direct action of the sea and produce tafoni. These typical subaerial landforms are at present found also in submerged areas and bear witness to sea-level fluctuations in the past 20,000 years.

30.5 Conclusions

The spectacular granitic landscapes of Sardinia result from weathering and long-term denudation occurring under changing climates from the early Cainozoic to the present. The Gallura and Sarrabus landscapes, in particular, offer a range of major and small-scale granite landforms that reflect local structural and lithological conditions. Wide flat areas dominated by inselbergs and covered by rock blocks, shaped in tafoni, characterize the Sardinia northeastern landscape. The island's southeastern landscape offers high relief, surrounded by crests and dissected plateaux framed by scattered tors. The coastal landscape, affected by differential erosion of dikes, shows various scenic features such as spectacular archipelagos, splendid lagoons and promontories. Due to their strong naturalistic interest and their cultural values, these landforms represent an important geoheritage of the Italian landscape. Palau Bear and the Mt. Pulchiana landforms are protected by regional laws as natural monuments, while two protected areas are set up, respectively the National Park of the La Maddalena Archipelago and the Protected Marine Area of Capo Carbonara promontory.

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31 The Coastal Dunes of Sardinia: Landscape Response to Climate and Sea Level Changes

Rita T. Melis, Felice Di Gregorio, and Valeria Panizza

Abstract

The Sardinian coasts are characterized by spectacular aeolian landscapes. These are concentrated in areas where the morphology of the coast, the age-long wind action on the wide sandy beaches and the past availability of sand from the continental shelf—during the low sea level during Pleistocene glacial phases—permitted remarkable volumes of sands to accumulate and to dominate above other forms of the coastal landscape. In the western coast of the island, hit by strong northwestern winds, vast dune fields, adorned by the Mediterranean bush and white flowers of sea, show a spectacular variety of landforms such as small nebkhas, loose dunes, cobblestone floors and deflation furrows. Lithified fossil dunes (aeolianites) occur along most Sardinian coasts, providing important information on past climate and sea level changes. These attractive wind landscapes offer researchers and visitors many and various opportunities of study, recreation and tourism, in a context unique due to the high value of the present and past landscapes.

Keywords

Aeolian processes • Coastal dune • Aeolianite • Sardinia

31.1 Introduction

The island of Sardinia, located in the centre of the western Mediterranean Sea (38°51′52″–41°15′42″N lat. and 8°8′–9° 50′E long), is exposed to strong winds, especially from the north and west, which favours transport and accumulation of aeolian sand along the coast, resulting in widespread deposition. Furthermore, eustatic fluctuations in response to Quaternary climate changes, when vast portions of the continental shelf emerged, favoured these processes (Fig. 31.1). Along the western coast of Sardinia, from the Asinara Gulf to the north, to the Oristano Gulf in the centre and the Iglesiente-Sulcis coast to the south, vast extensions of pearly white sand spread inland from the coastline, covering coastal plains and rugged reliefs. Aeolian processes have created fragile, dynamic landscapes which are very sensitive to environmental and climate changes. These ever-changing wild sceneries are characterized by spectacular erosion and accumulation aeolian landforms. Here, one can observe with fascination an intact and evocative natural landscape, in which the rhythm of life is still marked by strong blowing of the wind. Vast dune fields adorned by the dark green of the Mediterranean bush and, near the sea, by white flowers of sea daffodils (*Pancratium maritimum* L.) and the slender stems of the European marram grass (*Ammophila arenaria*) are mainly located along the northern and western coast, frequently hit by the strong Mistral wind.

The golden dune fields at Pistis, along the centre-western coast, and the Piscinas (Arburese) dunes, more to the south, are spectacular dynamic aeolian landscapes combining a great variety of micro- and macroforms. In Nurra (northwestern coast), in the Sinis peninsula and along the southwestern coast (Porto Paglia) thick reddish dune fossil

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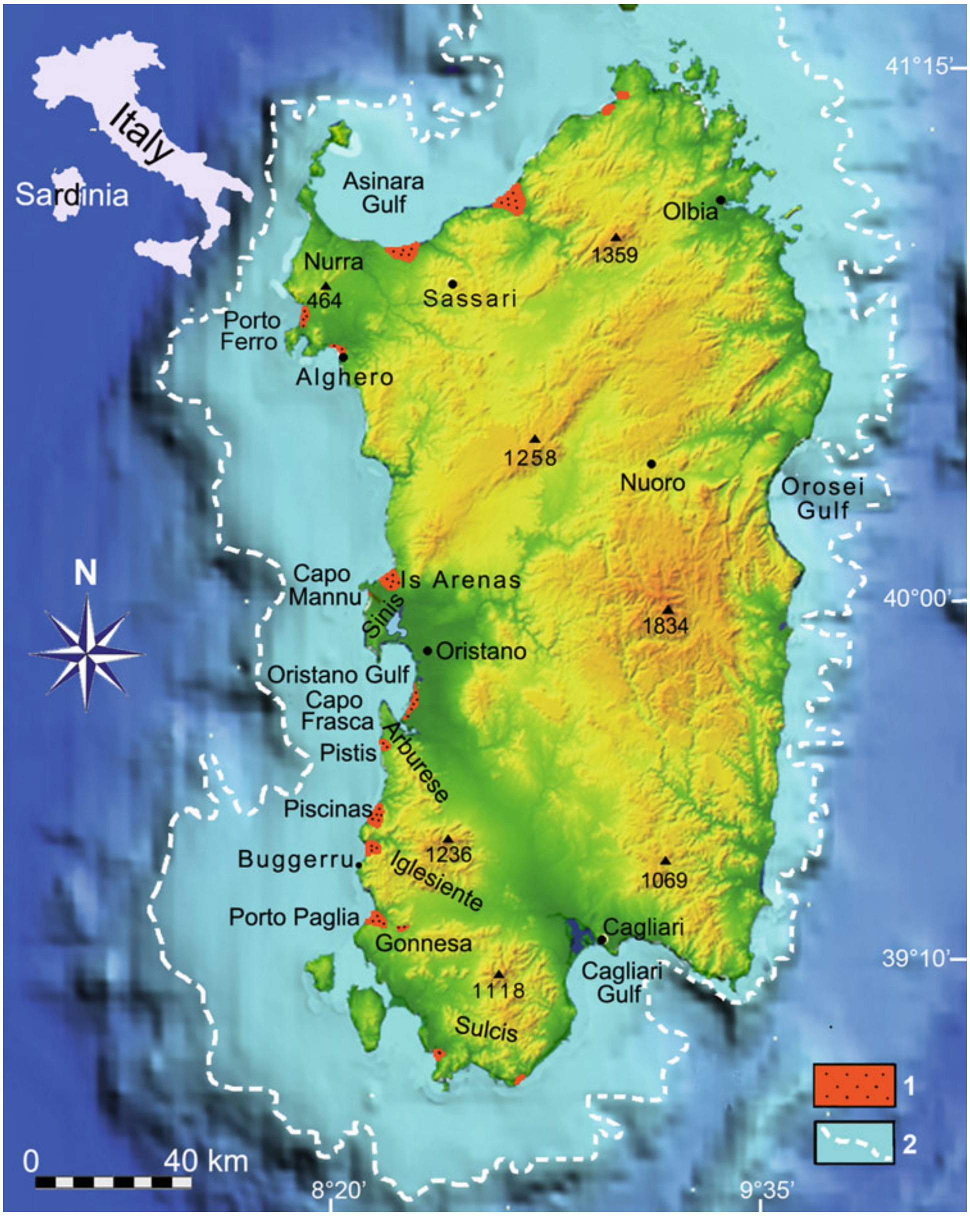

Fig. 31.1 Location of the Sardinia coastal dune fields: *1* dune fields; *2* approximate boundary of the continental shelf that extends to a depth of *ca.* −120 m. Elevations are in metres a.s.l.

sequences crop out, forming the legacy of ancient aeolian landscapes linked to Pleistocene climate changes. They form brittle cliffs exposed to the action of waves and winds.

31.2 Geographical Setting

Sardinia is the second largest island (24,090 km^2) of the Mediterranean Sea. It is located 120 km away from the Italian peninsula and 185 km from the North African coast. Its coastline stretches for about 1849 km and is prevalently made up of rocky and jagged coasts alternating with long sandy beaches, where vast dune fields are found. The latter can mainly be observed along the western coast, which is characterized by a wide continental shelf with sandy seafloor, which has allowed the growth of a thick and extended sea prairie of Mediterranean tapeweed (*Posidonia oceanica*). To the contrary, the eastern coast is narrow and the shelf is incised by deep canyons.

The present-day position of Sardinia is the result of complex geological history that records some of the greatest geodynamic events occurring in the last 400 Ma (Variscan, Thetys and Alpine s.l. evolution). Its geological features are among the most varied in the world. The island is mainly known for Palaeozoic metamorphic and igneous successions and Jurassic–Cretaceous carbonate successions, which occupy most of its territory (Melis et al. 2017). The coast is nearly all characterized by prevalently silicoclastic

Quaternary deposits linked to marine processes and wind action following climate and eustatic changes.

Sardinia is characterized by a warm temperate maritime climate with an average temperature ranging from 7 °C in winter to about 25 °C in summer. It shows a wet season (October to April) accounting for 80% of the yearly precipitation (300 mm during 2008), and a dry one (May to September) (Delitala et al. 2000). The most frequent winds blow from the northwest and southwest, without appreciable variations from one year to the other. Data show that 60–70% of the winds have a speed of less than 10 m/s, although speeds up to 25 m/s are not rare (ARPA, Servizio Agrometeorologico Regione Sardegna, http://www.sar.sardegna.it/). Indeed, high wind speeds cause the main morphological changes in the dune fields and their progradation.

The winds from the western quadrant prevail on the island for most of the year, except in summer, when a breeze regime is established. The western coasts are windier than the eastern coasts. The latter are sheltered from the westerly winds, thanks to the natural protection offered by a mountain range stretching in northsouth direction near the eastern coast.

In these spectacular landscapes dune movements occur, causing damage to farming and infrastructure. The Buggerru dunes (Iglesiente) and the large Is Arenas dunes in the Sinis peninsula were once mobile dunes but in the second half of the twentieth century they were subject to large-scale afforestation which has transformed the landscape: where there used to be a vast sand desert, now is a thick wood of stone pine (*Pinus pinea*) and Aleppo pine (*Pinus halepensis*).

Cross-bedding cemented dunes (aeolianites), testifying to the evolution of these landscapes during the Middle/Upper Pleistocene glacial periods, are present along the Sardinia coasts, buried underneath younger aeolian deposits, nearly all recent.

31.3 Wind Landscapes

The coastal dune systems found along the coasts of Sardinia make up striking and particularly dynamic landscapes in relation to wind frequency and intensity. At the same time, they are areas which are very sensitive and vulnerable to natural or man-induced changes. The origin and evolution of these fragile but fascinating aeolian landscapes located in the rear-beach areas largely depend upon geomorphological features of the beach to which they are connected and also upon sea level fluctuations and sedimentary balance.

Thus, where the action of wind coming from the sea is not particularly strong and frequent, dunes have developed in an arrangement parallel to the beach, as observed along many shores of the island's eastern coastline. To the contrary, on the northern and western shores, lashed by the dominant Mistral wind, nearly all aeolian deposits show a marked longitudinal development, according to the wind direction and the width of deflation areas.

Within the same dune field, it is possible to observe mobile areas subject to progressive stabilization as well as areas subject to erosion with furrows, channels and deflation hollows. In particular, the dune systems of Pistis and Piscinas (Arburese) are very spectacular and of great scientific interest.

These "wind landscapes" present considerable variety of morphological and vegetation aspects which provide researchers and visitors a high value of diversity from the landscape, scientific and tourist–recreational viewpoint.

31.3.1 Pistis Dunes

The Pistis dunes are found on the centre-western coast of Sardinia, south of the Capo Frasca peninsula (Fig. 31.2). The area occupied by the dune field diverges from a coastal curvature with a 2 km wide arch and stretches inland up to an altitude of about 70 m.

Aeolian deposits, varying in thickness from some decimetres up to some tens of metres, are made up of middle-fine, whitish-yellowish quartz–feldspar sands. Owing to their particular ochre or golden colour, which is more evident when they are wet, these dunes are known as *Sabbie d'oro* (Golden Sands). The succession of aeolian sediments lies on both the Palaeozoic bedrock, made up of metamorphic rocks (quartzites, sericite sandstones and filladic schists), and on the edge of ancient terraced alluvial deposits and cemented aeolian deposits from the Pleistocene. The latter crop out occasionally in the inner areas—where deflation is more intense—and at the southernmost tip of the beach.

The Pistis dune field consists mainly of free dunes (Fig. 31.3a) stretching inland with a NW–SE oriented axis. The entire dune system constitutes a particularly attractive landscape, with erosional and accumulation macro- and microforms present in the southern sector. A detailed observation from the upper beach towards the hinterland allows the following erosional features to be identified: (i) outcrops of aeolianized Palaeozoic bedrock (Fig. 31.4a), (ii) wide stretches of pebble floors with well-sorted and rounded quartz grains, (iii) deflation furrows with desert pavements made up of sharp, tiny fragments of metamorphic rocks (Fig. 31.4b). Depositional landforms are characterized by embryonic dunes or nebkas (Fig. 31.3b), dunes fixed by shrubs and trees, and free dunes. Spectacular ripples shape the surfaces of the latter (Arisci et al. 2003) (Fig. 31.4c).

Fig. 31.2 Satellite image of the Pistis (Arburese) dune field (*source* Google Earth, modified; © 2015 Google. Map data: image Landsat, image © 2015 Digital Globe)

Notwithstanding evident signs of tourism expansion in the peripheral northern and southern areas, this landscape still possesses marked natural integrity and considerable scenic impact. Also for this reason, the Pistis dunes have been declared of high natural interest and worthy of conservation measures. Furthermore, this area has now been registered in the list of Sites of Community Importance (SCI) of the European Union.

31.3.2 Piscinas Dune Field

The Piscinas dune field originated from the wide beach between Punta Fenu Struvu to the north, and the northern root of the Capo Pecora promontory to the south (Fig. 31.5a). These dunes stretch into the hinterland for more than 5 km, over a surface of about 20 km^2, attaining considerable height of 100 m. Therefore, together with the Pilat dunes in the French southwestern coast of Landes (Costa and Suanez 2013), they are among the highest in Europe. This fascinating landscape is one of the most significant and interesting dune systems of Sardinia and the Mediterranean from the natural, educational, scientific and geotourism standpoint.

The Piscinas aeolian landscape is a vast stretch of undulated sand gently descending towards the sea and abruptly interrupted near the coastline by a high erosional bluff, turning in some points into a proper cliff, developed in the Pleistocene aeolianites.

Most of this dune field have been fixed by vegetation. However, the northern sector is characterized by a narrow and elongated three-belt system of free quartz–feldspar sand, which makes up the most spectacular and scenic area of the whole aeolian complex (Fig. 31.5b). This sand results from the weathering cover of the underlying aeolianites and the sandy alluvial deposits of Rio Piscinas and Rio Naracauli watercourses. Deposition was more consistent during last century owing to the great amount of stream sediments coming from the tailings dams of the Montevecchio and Ingurtosu mines which are located in the elevated area behind the Piscinas field dunes.

These three long belts of aeolian sediments are different in size, according to the geomorphological features of the coastal sector where they originated. Their axial

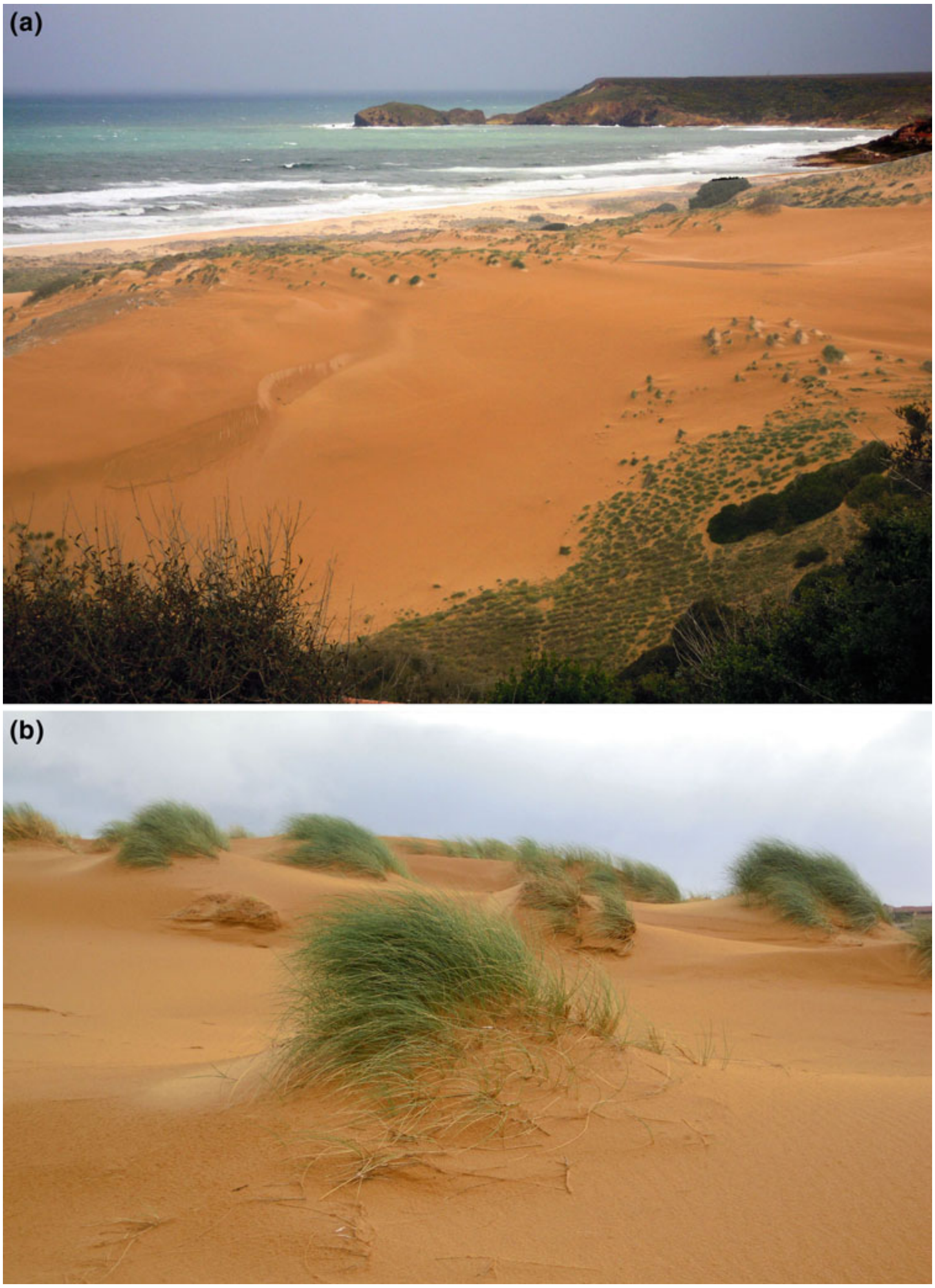

Fig. 31.3 The Pistis aeolian landscape: **a** view of the Pistis ochre-coloured dune field; **b** embryonic dunes (*nebkas*) fixed by vegetation (*Ammophila arenaria*)

development, starting from the beach is about 400 m in a WNW–ESE direction for the *northern belt*, placed north of Rio Piscinas; *ca.* 1 km in a NW–SE direction for the *central belt*, stretching between Rio Piscinas and Rio Naracauli; *ca.* 2 km still in a NW–SE direction for the *southern belt*, the largest and most striking one, located south of Rio Naracauli (Fig. 31.5b).

The diverse extent of the front beach influences the availability of sediments for wind transport towards the inland from north to south. The different development of the three belts is influenced by the morphological context of the surrounding area that controls the actions of the wind. The more advanced development of the large *southern belt* is due to the wider extent of the front beach, thanks to the supply of sediments from the Rio Piscinas and Rio Naracauli and to the littoral drift current with a prevalent N-S direction.

The large *southern belt*, which in its terminal portion attains the height of 98 m, makes up the most interesting and striking part of the mobile dune complex. Its total length, of about 300 m, remains practically constant for a long stretch, as shown by two lateral parallel crests which border the inner part where typical and striking erosional and depositional

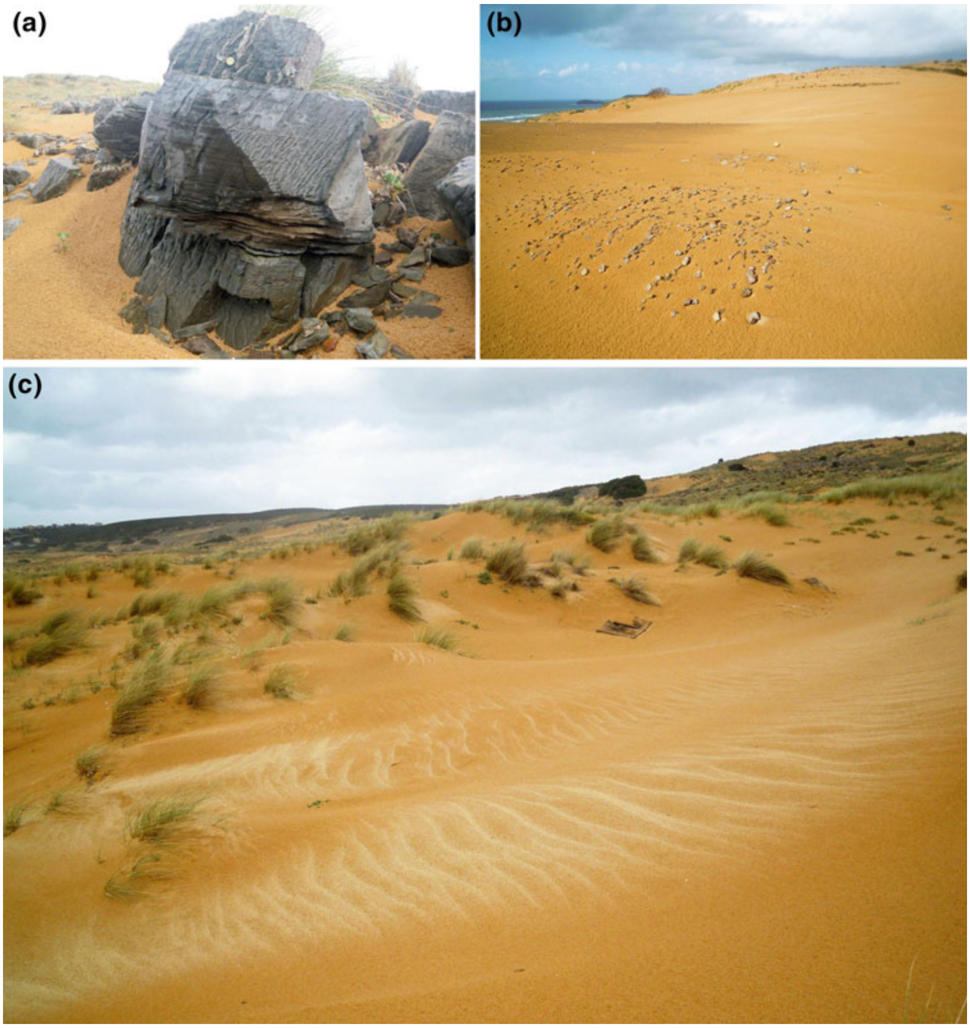

Fig. 31.4 The Pistis dune field: **a** aeolianized outcrops of the Palaeozoic bedrock; **b** desert pavements; **c** deflation hollows with spectacular ripples

landforms can be seen (Fig. 31.6a). Its initial portion, in proximity to the front–rear beach, is characterized by a wide area of embryonic dunes (nebka), less than 1 m in height, with their typical sandy tail on the leeward side (Fig. 31.6b). In this sector wide deflation surfaces are found with widespread fine or more or less coarse debris resulting from disintegration of metamorphic basement rocks, subject to intense aeolian processes (Fig. 31.6c). Proceeding to the hinterland, the embryonic dunes give way to more complex and stable dune formations, made up of less evident, half-stabilized sand accumulations, which in some cases have been fixed by shrub and arboreal vegetation. Nevertheless, between the dunes numerous deflation furrows are visible, which testify to the efficacy of transport process. Further along, the vegetation cover becomes more scanty with the presence of a mobile dunes, made up of donkey-back deposits which seem to be an early advancement front, consisting of material accumulated from the deflation areas. A second dune advancement front can be observed at the elevation of about 60 m a.s.l. It is made up of crescent-shaped dunes which border small deflation hollows, within which interesting aeolianized outcrops of the lithic bedrock are present (Fig. 31.5a). Finally, the terminal portion of the entire dune belt is characterized by a slightly undulating and inland–inclined wide accumulation area which ends abruptly with a cliff. The whitish surface of this area is modelled by innumerable, constantly changing aeolian ripples.

The diachronic comparison of photographs taken in the past 50 years shows that this belt is subject to 1 m/year advancement and is progressively covering a previous advancement front dating probably from historical times. The surface of the latter is stabilized by thick Mediterranean bush, prevalently mastic (*Pistacia lentiscus*) and Phoenician juniper (*Juniperus phoenicea*).

The *central belt*, comprised between the estuaries of Rio Piscinas and Rio Naracauli (Fig. 31.5a), has, on the whole, a structure similar to the previously described one but both its length and width are smaller. It starts on the wide beach with a wide field of less than 1 m high, nebka-like embryonic

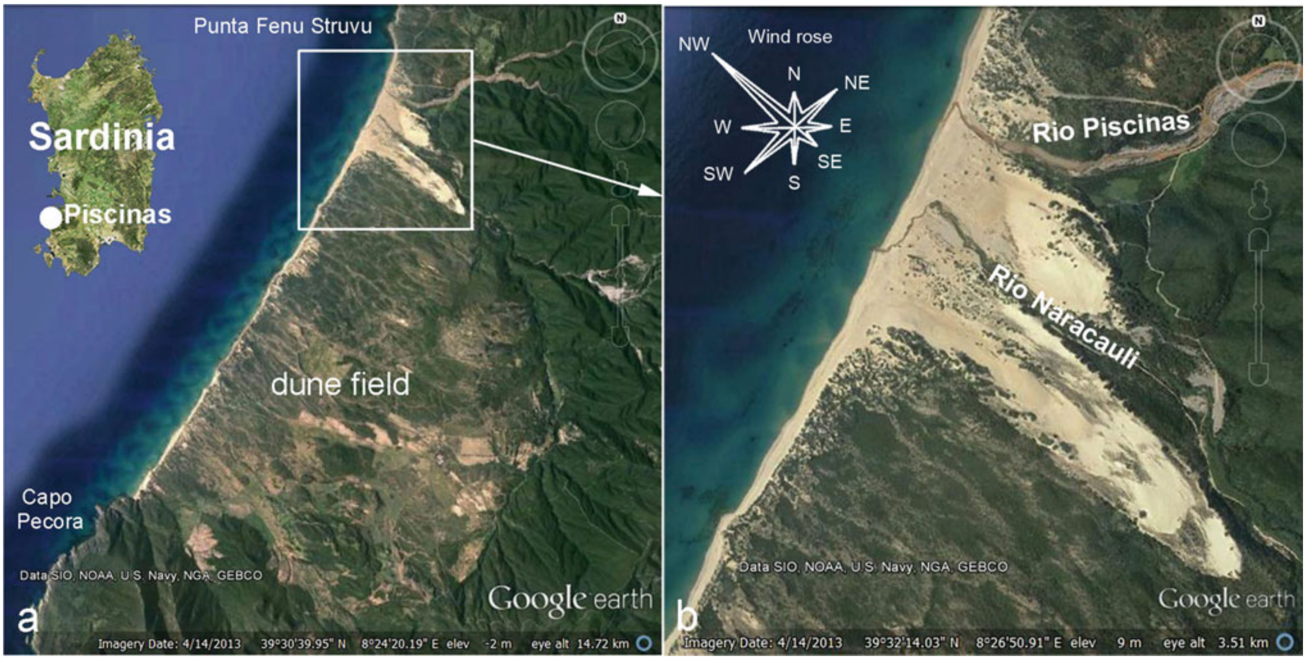

Fig. 31.5 Satellite images of the Piscinas aeolian landscape: **a** satellite image of the three belts of mobile dunes in the northern sector of the Piscinas dune field; **b** satellite image of the Piscinas dune field (*source* Google Earth, modified; © 2015 Google. Map data: image Landsat, image © 2015 Digital Globe)

dunes showing the typical leeward tail. This structure is then characterized by a vast deflation area stretching inland for a few hundred metres, in which there are wide stretches of more or less aeolianized, fine-grained desert pavements. Less pronounced sand deposits are present on this surface, colonized by European marram grass (*Ammophila arenaria*), *Tamarix* sp. shrubs and rare arborescent junipers. In the most inland area, mammillary aeolian deposits rest on the gentle arenaceous-schist slopes of the Palaeozoic bedrock.

The *northern belt*, north of Rio Piscinas, is smaller than the other ones, due to the narrow beach and the presence of slopes closer to the coast. This belt is characterized by deflation furrows and small longitudinal dunes oriented NW–SE.

31.4 The Aeolian Landscapes of the Past

Partially lithified ancient aeolianites are present along most Sardinian coasts, providing important information on Pleistocene sea level changes. Their lithological composition is strictly linked to the local environment and lithology and they present continuous outcrops along many coastal stretches, as is possible to observe in the Sinis Peninsula (central western Sardinia). These outcrops, in particular, have been studied and dated, and represent a fundamental reference series in studies about coastal landscape evolution during periods of sea level and climate changes, for this part of Mediterranean Sea.

Biogenic dunes, defined as aeolianites by Sayles (1931), are present along the coasts of Sardinia from Nurra to the Sulcis region (Fig. 31.7a). These aeolianites are partially lithified, cemented by carbonates and composed of fine- to medium-grained, well-sorted sand. The characteristics of sand grains largely depend on the local environmental setting but the dominant constituents of the aeolianites are quartz and feldspar, as well as marine carbonate particles.

Above all, during the Last Glacial Maximum (LGM), when the sea level was 120 m lower than the present one, the western Sardinian coasts were strongly affected by aeolian processes, generating a system of dunes and associated facies, locally extending several kilometres inland from the coast. These aeolian deposits alternate with palaeosols and more or less marked erosional surfaces, associated with colluvial/alluvial and fluvial deposits (Ulzega and Hearty 1986; Andreucci et al. 2010).

In Nurra (northwestern Sardinia), along the southern coast and north of the town of Alghero, continental and marine deposits can be observed with a certain continuity, witnessing sea level and climate changes occurring in the last 200,000 years. Along this suggestive coastline, Quaternary sediments unconformably overlie Tertiary volcanic

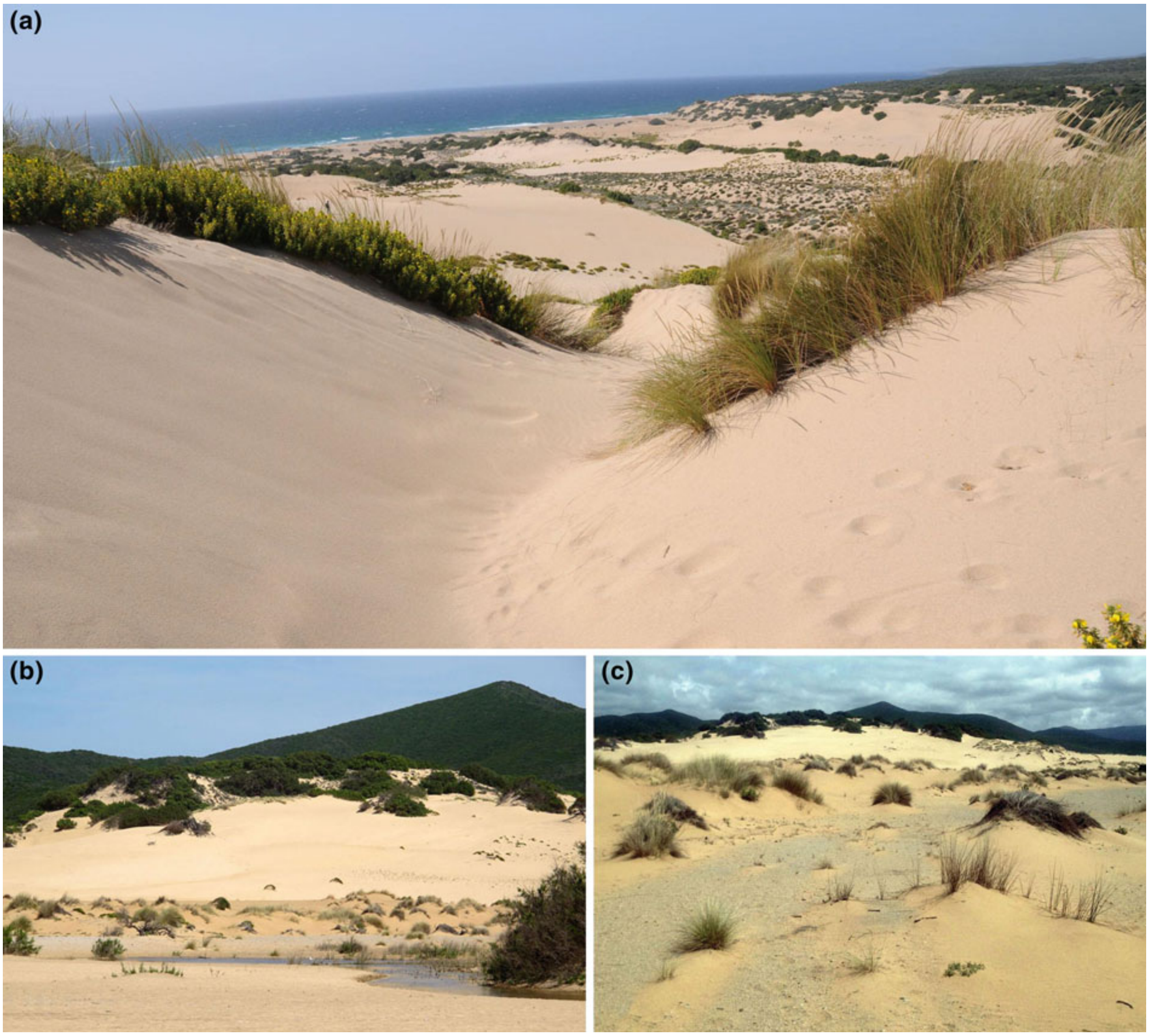

Fig. 31.6 The Piscinas mobile dunes in the large belt of aeolian sediments (**a**); wide fields of embryonic dunes (*nebkas*) at the back of the beach and in proximity of Rio Naracauli, in the *foreground* (**b**); deflation hollows with pebble floors in-between sand dunes (**c**)

rocks and Mesozoic carbonate formations. Continental deposits are represented by cemented aeolian sediments (aeolianites) with intercalations of alluvial, slope and palaeosol deposits. The limited areal extent of last interglacial (Upper Pleistocene) beach sand deposits (Tyrrhenian Stage, Marine Isotope Substage 5e), points to coastal morphology very similar to the present one, with small pocket beaches set between the rocky cliffs (Andreucci et al. 2006). The presence of aeolianites overlying the Upper Pleistocene beach deposits (Tyrrhenian Stage) shows a retreating sea level, with great availability of sand from the continental shelf and a progressively cooling climate (Andreucci et al. 2010). The formation of these dune systems was possible during the LGM, at *ca.* 20 ka BP, when the sea level dropped more than 100 m below the present-day position, favouring accumulation, on the continental topography, of great amounts of sand coming from the shelf. The phases of greatest accumulation took place during the driest periods, whereas the presence of intensely bioturbated aeolian layers and reddish palaeosols (Fig. 31.7b) bear witness to more humid climate phases. In the bioturbated layers, vertebrate bones and footprints were found, in particular the remains of *Praemegaceros cazioti*, an endemic species of deer, which became extinct in the Middle-Upper Pleistocene. Orientation of lamination shows prevailing wind from west and northwest, similar to the present-day wind direction, although wind intensity was certainly higher (Fig. 31.7c). In this part of Sardinia, dune fields are found nowadays only in correspondence with wide bays characterized by sandy beaches, as in the case of Porto Ferro.

Remarkable evidence of aeolian landscapes resulting from Pleistocene climate and sea level changes are

Fig. 31.7 Cemented dunes (aeolianites) cropping out along the cliffs of the southwestern coast of Sardinia (**a**); bioturbations and palaeosols in the aeolianites along the Nurra coast (**b**), laminated texture in the aeolianites near Cave del Cantaro, south of Alghero (**c**)

observable in the Sinis peninsula, north of the Oristano Gulf. Thick dune successions are exposed in the form of cliffs along the northwestern side of Capo Mannu promontory, where various dune generations can be observed, intercalated with palaeosols in the high cliff overhanging the sea (Fig. 31.8a). These dunes were deposited during the Pliocene and Lower Pleistocene (Carboni and Lecca 1995). They are made up of carbonate sandy bodies with a maximum thickness of 50 m, resulting from the overlapping of four main dune units which show lateral continuity, while another three units are discontinuous, since they are separated by palaeosols, with a lenticular trend and occasional mammal remains (Bovidae and Suidae) (Abbazzi et al. 2008). Within the main dune units, which in some cases attain an average thickness of 6–9 m, at least 19 dune subunits can be observed (Carboni and Lecca 1995). These striking dunes were affected by marine erosion during the rising of the sea level in the Tyrrhenian Stage (Marine Isotope Substage 5e), as witnessed by the palaeocliff buried underneath the aeolian sediments of the LGM (MIS 2) (Carboni and Lecca 1995) (Fig. 31.8b).

Aeolianites ascribed to this latter period (MIS 2) (Lecca and Carboni 2007) crop out at Capo San Marco and San Giovanni in the southern portion of the Sinis peninsula. They were excellent building materials for the construction of the Punic-Roman town of Tharros (Fig. 31.9a) and also suitable bedrock for the excavation of necropolises of pre-historic and historic populations (Fig. 31.9b).

More to the south, along the coast of the Gonnesa Gulf (Sulcis-Iglesiente), vast complexes of well-cemented, cross bedding dunes, ascribable to the Middle Pleistocene, have developed from the coast to the inland (Fig. 31.9c). In these spectacular aeolianites, the remains of a Sardinian dwarf elephant (*Mammuthus lamarmorae*) were found at Morimenta (Palombo et al. 2012). In addition, traces and fossil tracks attributed to the *Praemegaceros cazioti* Megaloceros

Fig. 31.8 Dune succession with intercalations of palaeosols exposed in a cliff at Capo Mannu (Sinis) promontory (**a**); fossil cliff in the cemented dune complex of Capo Mannu, partially buried by aeolian and slope deposits of the LGM (MIS 2) (**b**)

species (Fanelli et al. 2007) are visible in the aeolianites cropping out along the Porto Paglia sea cliff.

31.5 Conclusions

The spectacular fields of mobile dunes which characterize the coastal landscapes of Sardinia are the result of age-long wind action on the wide sandy beaches. Their evolution is linked to sea level fluctuations and climate changes during the Quaternary, as witnessed by the underlying thick lithified dunes. The geomorphological interest in these gentle and wild dune landscapes and aeolianites, which form long cliffs along the shores exposed to the actions of sea and wind, is also enhanced by their relatively easy accessibility. Most of these fascinating aeolian landscapes, such as the Piscinas and Pistis dune fields and the aeolianites making up the high Sinis cliffs, have been enrolled among the sites of

Fig. 31.9 View of the Punic-Roman town of Tharros (Sinis), built with blocks of aeolian sandstone (**a**); detail of the Punic necropolis of San Giovanni (Sinis) dug out in aeolianites (**b**); aeolianite cross-bedding at Morimenta (Gonnesa, Sulcis) (**c**)

community importance (SCI) owing to their considerable natural interest.

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The Terrestrial and Submarine Landscape of the Tremiti Archipelago, Adriatic Sea

32

Enrico Miccadei, Tommaso Piacentini, and Francesco Mascioli

Abstract

The archipelago of the Tremiti Islands, situated in the centre of the Adriatic Sea, is considered, nationally and internationally, a very important geological and geomorphological laboratory, rich in Cenozoic stratigraphic, tectonic and, recently, geomorphological studies. Despite the small size of the islands, the present landscape of the Tremiti Islands and of the inner continental shelf shows an outstanding wealth of ancient and present terrestrial and marine landforms. They provide the islands with their intrinsic and distinctive value and beauty and that can be discovered walking on the islands, sailing around them or diving into the turquoise to blue sea.

Keywords

Coastal landforms • Paleodrainage • Karst landforms • Landslides • Tremiti Islands • Adriatic Sea

32.1 Introduction

The Tremiti Islands are an archipelago in the central part of the Adriatic Sea, north of the Gargano Peninsula (Fig. 32.1). They are a marine protected area included in the Gargano National Park. The archipelago is made up of the San Domino, San Nicola, Capraia, Cretaccio and Pianosa islands, and of the La Vecchia rock.

For a long time, the name of the archipelago was linked with the Greek hero *Diomedes*—their ancient name was indeed Diomede's Islands (*Insulae Diomedeae* in Latin and *Διομηδιες* in ancient Greek). The myth has it that the islands were made by Diomede by throwing into the sea three huge rocks, taken from Troy, which then arose from the sea as islands (San Domino, San Nicola and Capraia). According to another myth Aphrodite, the Goddess of Love, turned Diomede's companions into *diomedeae*, rare sea birds nesting on the limestone coastal cliffs of San Domino.

The name *Tremitis* appears for the first time in medieval manuscripts and relates to historical earthquakes and seismic hazard in the area, since the word *tremiti* means "tremors".

The islands and the surrounding underwater landscape are characterised by landforms originated from marine and continental geomorphological processes, such as marine erosion, gravity-induced processes, surficial running water and karst processes. These landforms, located below and above the present sea level, preserve the record of a long Quaternary landscape evolution connected to geomorphological processes driven by the interaction between climate, tectonics and sea level changes.

In pre-historical and historical times, the location and the landscape—characterised by steep cliffs and flat summits—made the archipelago a good place to live and fish and to emplace military and naval stations. The most ancient human records are findings of cabin villages on San Domino dating back to the Neolithic age (eighth–seventh millennium BC), while on San Nicola pole holes of an Iron Age cabin and sepulchral graves of Archaic, Classic and Hellenistic age

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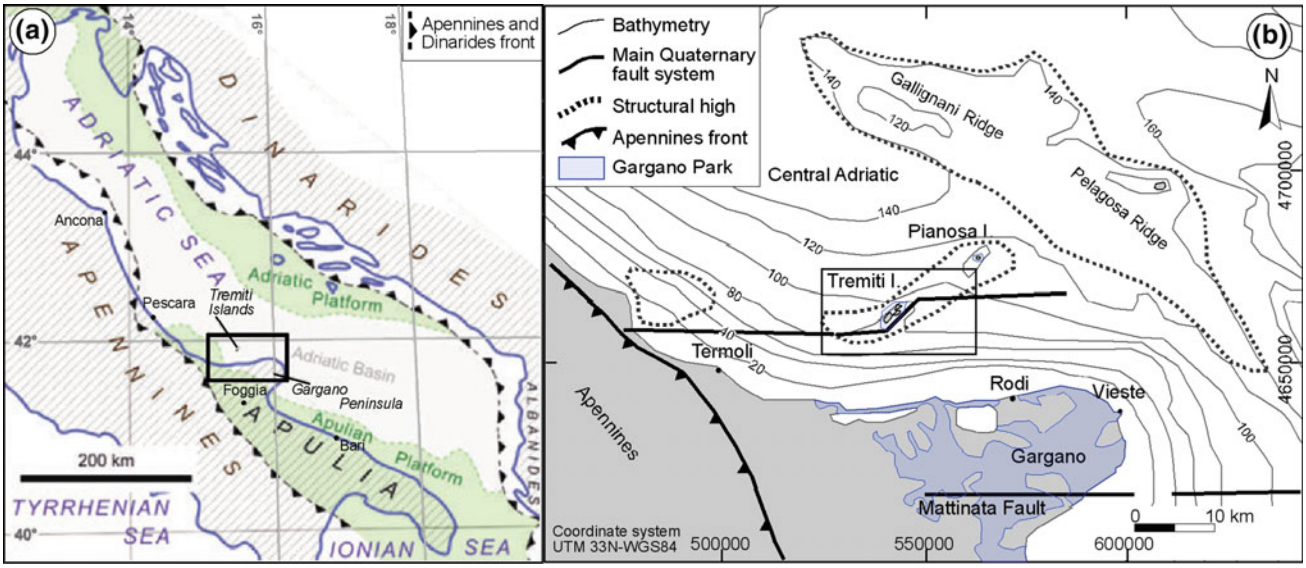

Fig. 32.1 Tremiti Islands. **a** Location map (modified after Tropeano et al. 2013). **b** Regional geological scheme of the Central Adriatic Sea and the Gargano area

(sixth–first century BC) have been found. The Roman presence is documented by a second century BC *domus*.

Since the first century BC, the islands were used for the exile, deportation and internment of prisoners. Roman Emperor Tiberius exiled here his granddaughter Giulia, guilty of adultery. Much later, political prisoners were interned here by Benito Mussolini's Fascist regime.

However, the strongest anthropic impact on the landscape of the Tremiti Islands, and particularly on the island of San Nicola, is due to the settlement of Benedictine monks (1016 AD), who built a church and a monastery-fortress (Santa Maria). The impact on the landscape was both positive, as the cliffs were protected from erosional processes, and negative, due to the quarrying of large amounts of rocks in the island. In the following centuries the protection of the monumental part of the island was improved with huge digs, such as the so-called "La Tagliata"—an artificial incision of a natural bottleneck on the top surface of the island.

Therefore, the Tremiti Archipelago's islands and submerged landforms provide a fascinating key to improve the reading and understanding of the landscape and the natural and human history of the southern Adriatic Sea.

32.2 Geographical and Geological Setting

The Tremiti Islands, the only Adriatic Italian ones, are located about 20 km off the Italian coast, in northern Apulia, close to the Gargano Peninsula (Fig. 32.1), and have a 3 km^2 surface; they can be reached by ferry from Vieste and Rodi Garganico in the Gargano area and from Termoli, on the Molise coast, and by helicopter from Foggia airport.

The islands are aligned in a SW–NE orientation and rise from a gentle underwater slope characterised by a pronounced asymmetry with a wide NW continental shelf extension and a smaller SE one. The islands show a tabular landscape, with summit gentle surfaces between 116 m (San Domino) and 55 m a.s.l. (Capraia), bounded by very steep or vertical cliffs (Fig. 32.2).

Geoscientists have carried out studies in the archipelago since the late 1800s, when Tellini (1890) published a first paper with a geological map. Then scientists focused mostly on palaeontology and only few of them on Quaternary continental deposits and landscape and lithic industries (Pasa 1953; Zorzi 1958).

The archipelago of the Tremiti Islands is composed of a sequence of limestone marine rocks, with interbedded dolomites and marls, dating from the Cenozoic (Paleocene—Middle Pliocene), which constitute the carbonate bedrock of the archipelago (Selli 1971). Despite their small size, the islands are characterised by widespread Quaternary continental deposits (Middle Pleistocene—Holocene), indicative of slope, alluvial fan and aeolian environments. They overlie marine rocks from the sea level and up to the summit, more than 100 m a.s.l., have a maximum thickness of about 40 m, and are well exposed along the cliffs of San Nicola, part of San Domino (Cala degli Inglesi, Cala Tramontana, Cala delle Roselle) and north of Capraia. These deposits are made up of sand and gravel clastic deposits, paleosoils, calcretes, aeolian sands and loess (Selli 1971; Cresta et al. 1999; Miccadei et al. 2011a), with Middle Pleistocene mammal vertebrates in clastic deposits (Pasa 1953) and Holocene lithic industries in eluvium–colluvium (Zorzi 1958) (Fig. 32.3).

Fig. 32.2 Panoramic view of the Tremiti Islands from San Domino

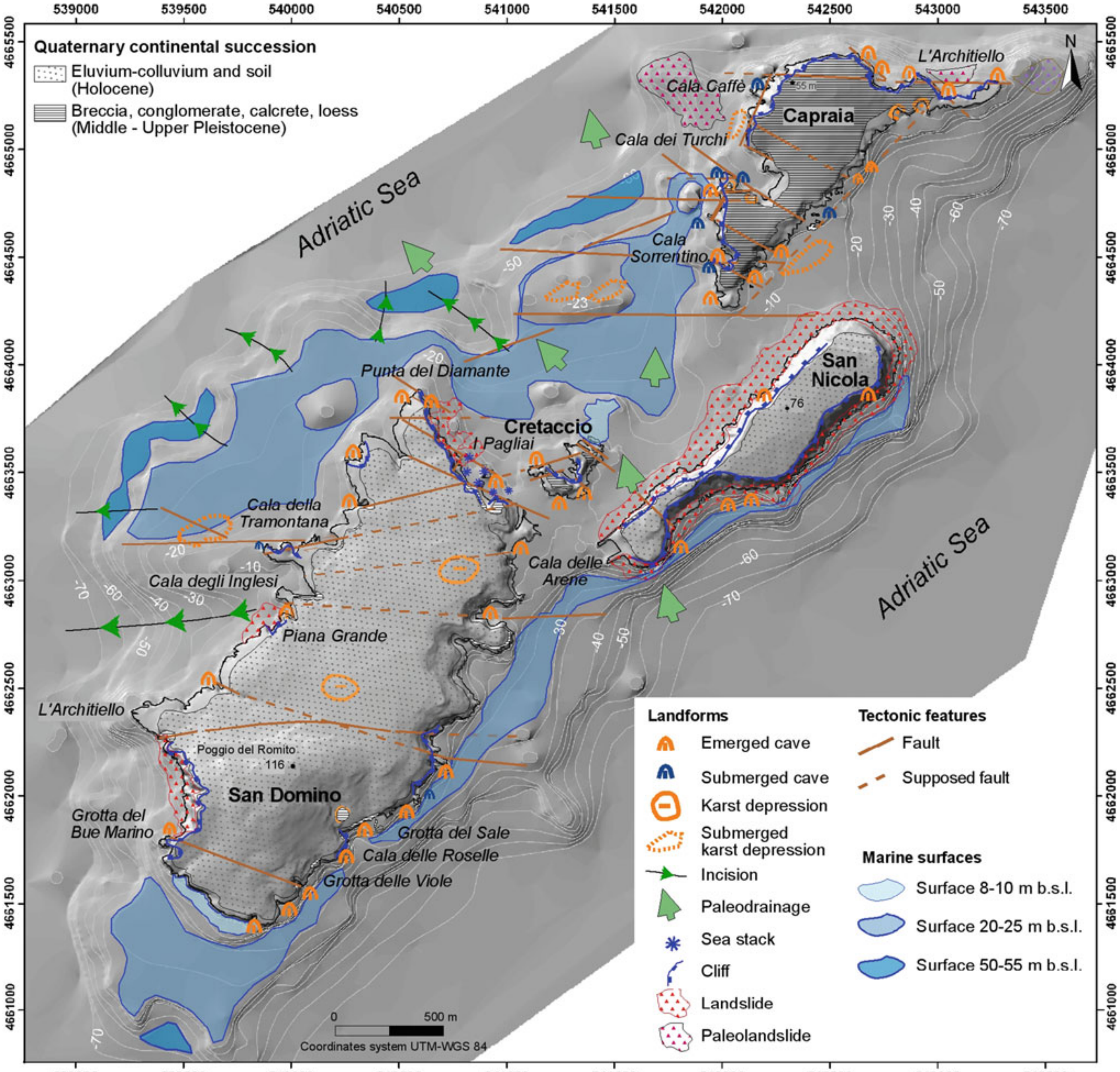

Fig. 32.3 Geomorphological scheme of the Tremiti Islands (modified after Miccadei et al. 2011a, 2012)

The oldest deposits (Middle Pleistocene) consist of breccias (with intercalated paleosoils) related to slope processes and, in some places, aeolian sands. These lay on an erosive surface on carbonate bedrock and in some cases fill pre-existent karst depressions (San Domino, Cala degli Inglesi, Cala delle Roselle and Capraia, Fig. 32.4). San Nicola is characterised by a second sequence of clastic deposits (Br$_1$, Ps$_1$, Cg$_1$), consisting of breccias and paleosoils (Fig. 32.5a). Above the breccia units, subrounded conglomerate levels (Cg, Cg$_1$, Figs. 32.4 and 32.5a; more evident in the southern side of San Nicola and in the SE side of San Domino, Cala delle Roselle area, and including remains af a fossil rabbit, *Oryctolagus cuniculusI*; Pasa 1953) possibly outline alluvial fans and streams which developed on the islands during the sea level low stand of the late Middle Pleistocene. The clastic units are covered by loess and calcretes (Cr) (dating from the initial part of the Upper Pleistocene, Miccadei et al. 2011a)—which are widespread on all the islands (Figs. 32.4 and 32.5b)—consisting of limestones formed by the cementation of soil, sand, gravel, shells, by calcium carbonate deposited due to evaporation or the escape of carbon dioxide from vadose water. The top of the calcretes is characterised by clear evidence of karst landforms. Scattered on the calcretes, aeolian sandy deposits (AS) are present (San Domino), dating back to the Upper Pleistocene (Miccadei et al. 2011a).

The most recent part of the Quaternary continental succession is constituted by soils and eluvial–colluvial deposits (S, Fig. 32.4) (San Domino, at Cala degli Inglesi, and San Nicola), dating back to the Early–Middle Holocene on the base of Neolithic siliceous and ceramic industries (Zorzi 1958).

The carbonate Cenozoic succession is in a general 10–20° SE-dipping homocline setting. This is regionally coherent with a limb of a NE–SW anticline, faulted several times during the various tectonics stages that involved the uplifted Adriatic-Apulian foreland of the Apennine orogenesis during the Pliocene and Lower Pleistocene (Argnani et al. 1993); this is also possibly related to diapirism of buried salt sequences (Festa et al. 2014). The main tectonic discontinuities have E–W, WSW–ENE and NE–SW directions (Fig. 32.3); they are characterised by strike-slip kinematics (Argnani et al. 1993; Miccadei et al. 2011a) and by strong seismicity, with earthquakes along E–W to SW–NE tectonic discontinuities.

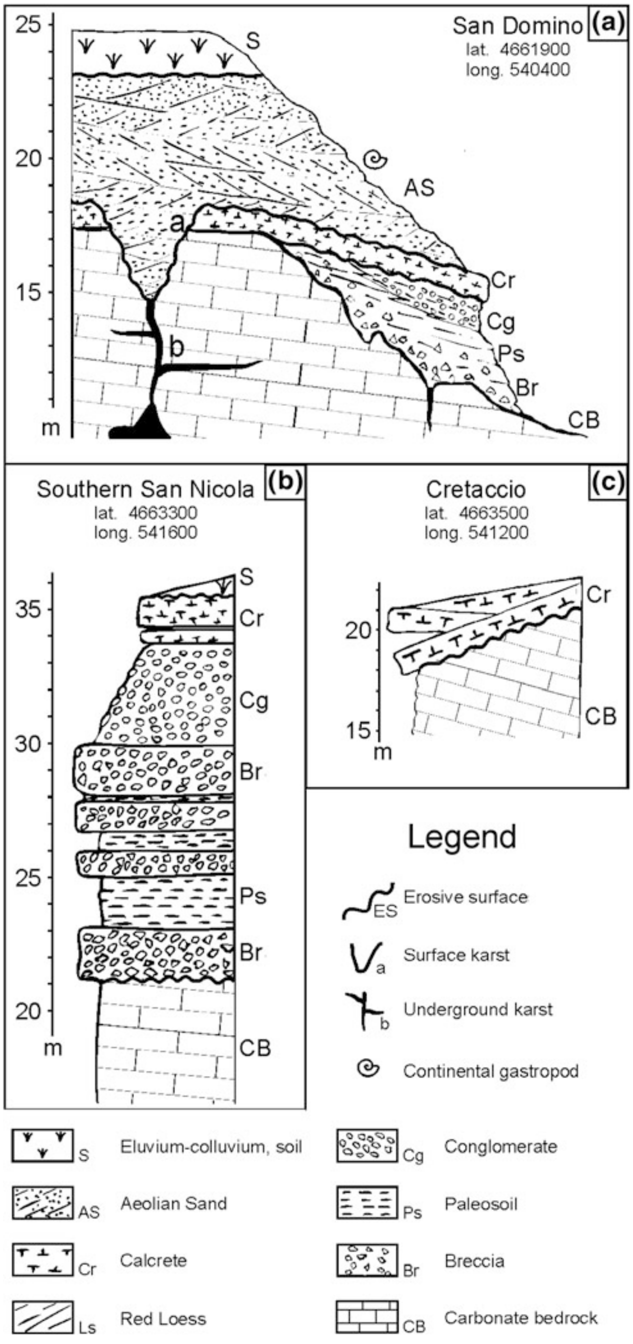

Fig. 32.4 Quaternary continental succession for San Domino (**a**), southern San Nicola (**b**) and Cretaccio (**c**). Elevations a.s.l. are shown along the y axis; the coordinates, in the UTM-WG84 system, indicate the location of typical outcrops (modified after Miccadei et al. 2011a)

The geomorphological features of the islands, as well as of the inner continental shelf, are characterised by different types of landforms (i.e. gravity-induced, fluvial, karst, coastal and marine) which outline a complex long-term evolution resulting from the superimposition of marine, costal and subaerial processes over time. Coastal morphology is the result of coastal and subaerial processes, strongly related to lithologic and tectonic features (Andriani et al. 2005). Remains of superficial running water and alluvial fan landforms are scattered on the islands and preserved in submerged areas. The karst landforms have been known since the beginning of the 1900s (Pasa 1953; Cresta et al. 1999) and are related to processes contributing to the Quaternary morphogenesis of the islands at least since the Middle Pleistocene; evidence of karst processes is

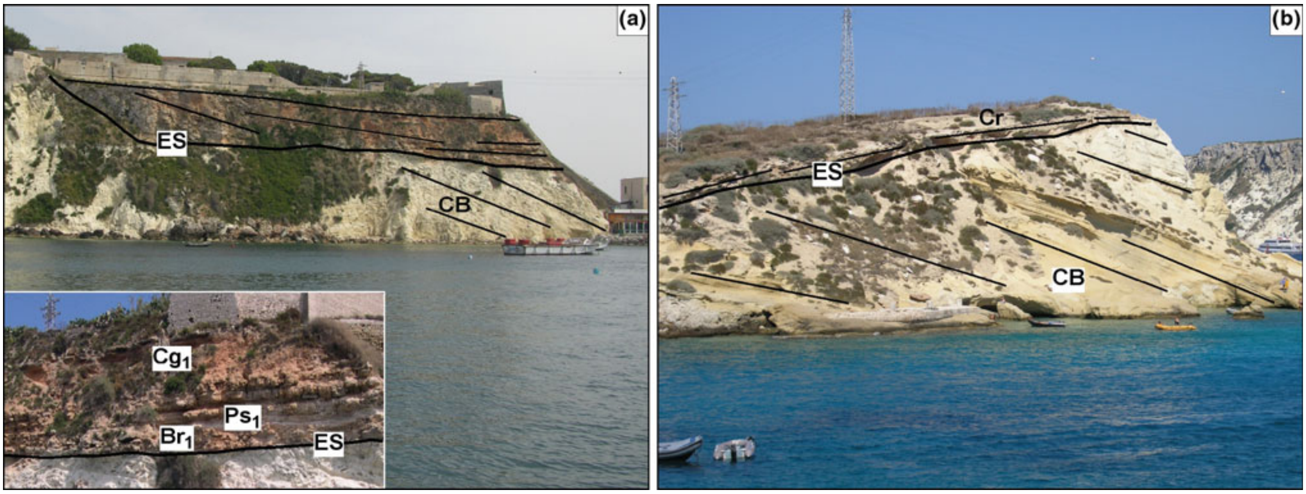

Fig. 32.5 Cliffs and rocky coasts on Cenozoic limestone, dolomites and marls rocks and Quaternary continental deposits of the islands (after Miccadei et al. 2011a). **a** San Nicola, cliff >30 m high on an outcrop of breccias (*Br*), paleosols (*Ps*) and conglomerates (*Cg*), on an erosional surface (*ES*) over calcareous marine bedrock (*CB*), rock falls are scattered at the cliff's base; in the lower left part a close-up of the deposits is included; **b** Cretaccio, cliff on calcrete (*Cr*) deposits on an erosional surface (*ES*) over carbonate bedrock (*CB*); the calcrete's age is 121 ± 21 ka (U/Th dating; Miccadei et al. 2011a); rocks fallen from the cliff are scattered at the cliff's base

documented also within the bedrock marine succession since the Eocene (Cresta et al. 1999). The present-day morphodynamics of the islands is characterised by the complex interaction of gravitational and marine processes that induce the instability, retreat and evolution of the marine cliffs (Cotecchia et al. 1996).

The geomorphological features of the archipelago highlight the relationships between Quaternary tectonics, regional uplift, possibly diapirism (Mastronuzzi and Sansò 2002; Tropeano et al. 2013; Festa et al. 2014), and eustatic sea-level changes (Ridente and Trincardi 2002; Parlagreco et al. 2011); this has led to alternate periods of emersion and submersion of the area between the islands and the Italian coast (now at a depth of up to 80 m b.s.l.), driving the long-term geomorphological evolution (Miccadei et al. 2011a, b, 2012).

32.3 Landforms

Despite the small size of the islands, the present landscape of the Tremiti Islands and of the inner continental shelf shows an outstanding wealth of active, inactive and relict landforms, that give the islands its intrinsic and distinctive value and beauty. Present and relict landforms of the islands can be easily observed walking and sailing around them or diving into the sea. Such landforms are due to different kinds of continental, coastal and marine geomorphological processes (Fig. 32.3) that developed in response to the varied geology, tectonics, climate conditions, and history of alternated periods of emersion and submersion of the area between the islands and the Italian coast. Tectonic features control the overall islands' morphology. The most peculiar landforms of the islands are marine ones; moreover alluvial fans, superficial running water-related landforms and karst landforms (visible both above and below sea level) are well preserved and highlight the complex landscape evolution. Other landforms are gravity-induced ones, affecting all the cliffs with several rock falls, translational and complex landslides, and locally lateral spreads, as well as anthropogenic landforms which outline the most recent changes in the landscape of the Tremiti Islands (Andriani et al. 2005; Miccadei et al. 2011a, b, 2012).

32.3.1 Tectonic Landforms

The elongated SW–NE morphology of the islands and several of the coastal indentations, bays and inlets—oriented mostly NW–SE, EW and SW–NE and bounded by straight walls—are clearly related to the orientations of faults, joints and associated fracturation zones (e.g. Architiello, Cala degli Inglesi and Cala Tramontana area on the NW sides of San Domino and on the NE and N side of Capraia; Figs. 32.3 and 32.6a). Locally, the location and shape of karst features (dolines) are also controlled by tectonic features (Fig. 32.6b). Submerged tectonic landforms are also present, mostly sub-vertical scarps and bedrock outcrop alignments, related to the main fault systems, for example in the area between the San Domino and Capraia or San Nicola islands and in the northern and southern sectors of San Domino.

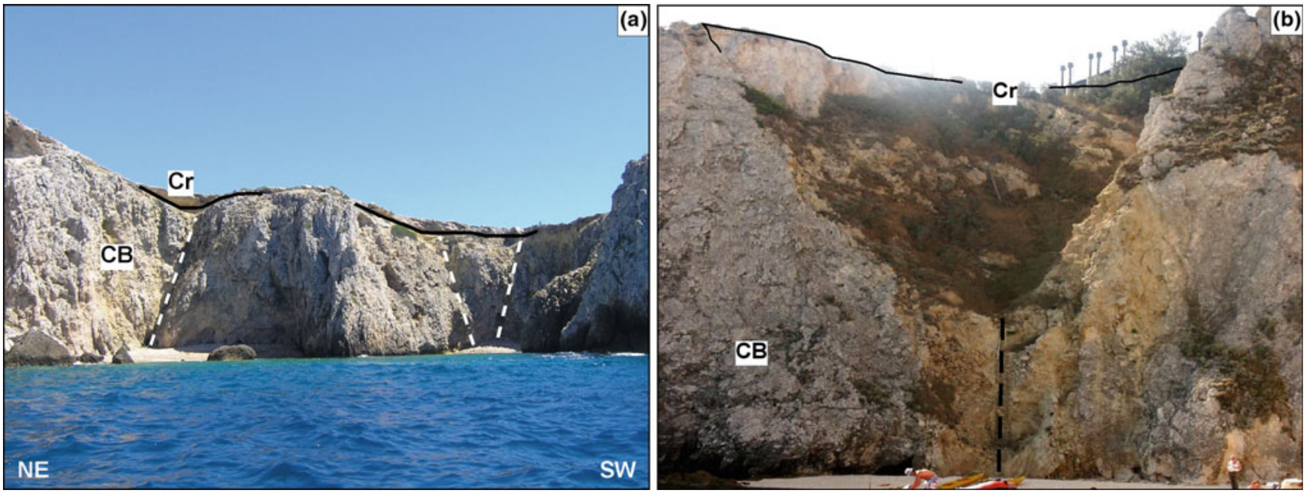

Fig. 32.6 Cliffs and rocky coasts on Cenozoic limestone, dolomites and marls rocks and tectonic features (after Miccadei et al. 2011a). **a** Capraia, Cala Sorrentino, cliff up to 30 m high, with two inlets characterised by small pocket beaches; the inlets corresponds to NW–SE-oriented faults affecting the calcareous bedrock (*CB*) with high fracturation which induced their development; on the upper part of the island they correspond to saddles and karstic depressions filled by calcretes; **b** San Domino, northeast coast of the island, karst depression on the calcareous bedrock of the cliff (*CB*), with calcretes (*cr*) on *top*; the karst landform is controlled by a tectonic discontinuity (*black dashed line*), characterised by a vertical fault plane and cataclastic rocks

32.3.2 Marine Landforms

Almost the entire length of the Tremiti coast consists of a well indented (except for San Nicola) rocky coast on carbonate rocks and, locally, on Quaternary continental clastic and calcrete deposits. Much of the coast of San Nicola, Capraia and Cretaccio and part of the coast of San Domino are characterised by steep, vertical, >80 m high cliffs descending precipitously into the sea (Fig. 32.3). In most cases, they are affected by rock falls, characterised by marked undercut notches and several caves, and associated with sea stacks and rocks in front of them (e.g. I Pagliai) (Figs. 32.7 and 32.8). The morphology and indentation of coastal cliffs are in most cases controlled by faults and related fracturation zones; within indentations and coastal inlets, small pocket beaches bound the cliffs (Fig. 32.6a). More than 40 caves are either located at the present sea level (Fig. 32.8) or they are completely submerged (Fig. 32.9a). About 30 of them are half-submerged (Fig. 32.8b), with bottoms at a 3–7 m b.s.l. depth, covered by centimetre and decimetre-size sub-rounded pebbles. Other submerged caves are located along the main sub-vertical rocky scarps between the main flat surfaces, at depths of 8–18 m and 25–45 m b.s.l. (Fig. 32.9a). Most of them have a small entrance and are mostly <25 m long, without wide halls. In the northwestern side of Capraia (Cala Caffè), at 25–30 m b.s.l., a large submerged cave called Il Grottone is present, in which lithic industries of the Neolithic age were found (Cresta et al. 1999). The pace of marine erosion shaping the caves is controlled by tectonic features and fracturation, but in many cases the marked circular shape and morphological features suggest a karst origin.

Below the sea level, the bathymetry allows to outline three main flat surfaces at 8–10 m b.s.l., at 20–25 m b.s.l., and at 50–55 m b.s.l., more evident on the northwestern side of the archipelago, which are to be explored by expert divers (Fig. 32.3). They are marine erosion surfaces related to different past sea levels, lower than the present one. They are bounded by scarps and sub-vertical slopes, and provide the inner continental shelf with a step-like morphology. The most elevated flat surface shows slightly variable edge depths, between 8 and 10 m b.s.l., with good inner margin bathymetric correlation, and it is externally bounded by sharp or irregular-rounded scarps. The flat surface at 20–25 m b.s.l. (the largest and most continuous one) is covered by gravelly and sandy marine deposits and by gravelly alluvial fan deposits, with scattered carbonate bedrock outcrops (Miccadei et al. 2011b). The inner margin is defined by a sub-vertical or steep rocky scarps. Locally, it is characterised by reefs sub-parallel to the bathymetric trend, morphologically similar to beach-rocks, characterised by a thick seaweed cover. The deepest surface (50–55 m b.s.l.) is covered by sand and gravel deposits; it is mostly bounded by rounded edges and carved by slight incisions and small valleys, which possibly originated as subaerial drainage incisions (Miccadei et al. 2011b).

The marine erosion surfaces appear to be rich in small erosional landforms, circular coastal rock pools, with

Fig. 32.7 San Domino, I Pagliai, cliff and sea stacks affected by rock falls

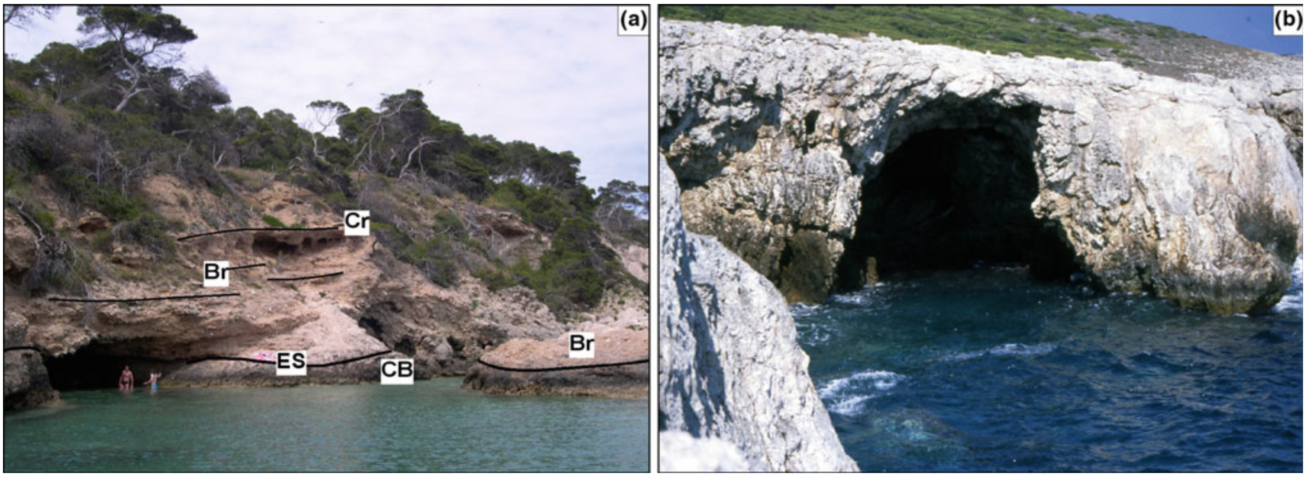

Fig. 32.8 **a** San Domino, Cala delle Roselle, cliffs with a small cave, developed on calcretes (*Cr*) stratified breccia (*Br*) with sub-angular centimetric clasts, laying on carbonate bedrock (*CB*) (for labels see Fig. 32.4; after Miccadei et al. 2011a); **b** San Domino island, cave at the sea level extending down to 8 m b.s.l. (after Miccadei et al. 2011b)

diameters varying from some decimetres to over one metre, often open towards deeper areas and connected to drainage channels and coastal erosion landforms (Fig. 32.9b).

32.3.3 Paleodrainage-Related Landforms

While alluvial fan conglomerate deposits are present on the emerged part of the islands, landforms related to superficial running water are mostly present on the inner continental shelf areas; both provide important evidence of alternating terrestrial and marine geomorphological processes due to sea-level fluctuations since the Middle Pleistocene (>200,000 years ago). Submerged landforms, related to subaerial paleodrainage, consist of several gullies arranged in two main systems. The deepest one is composed of SE–NW incisions that developed between 35 m and over 60 m b.s.l. in limestone bedrock, showing sub-vertical side scarps (NW

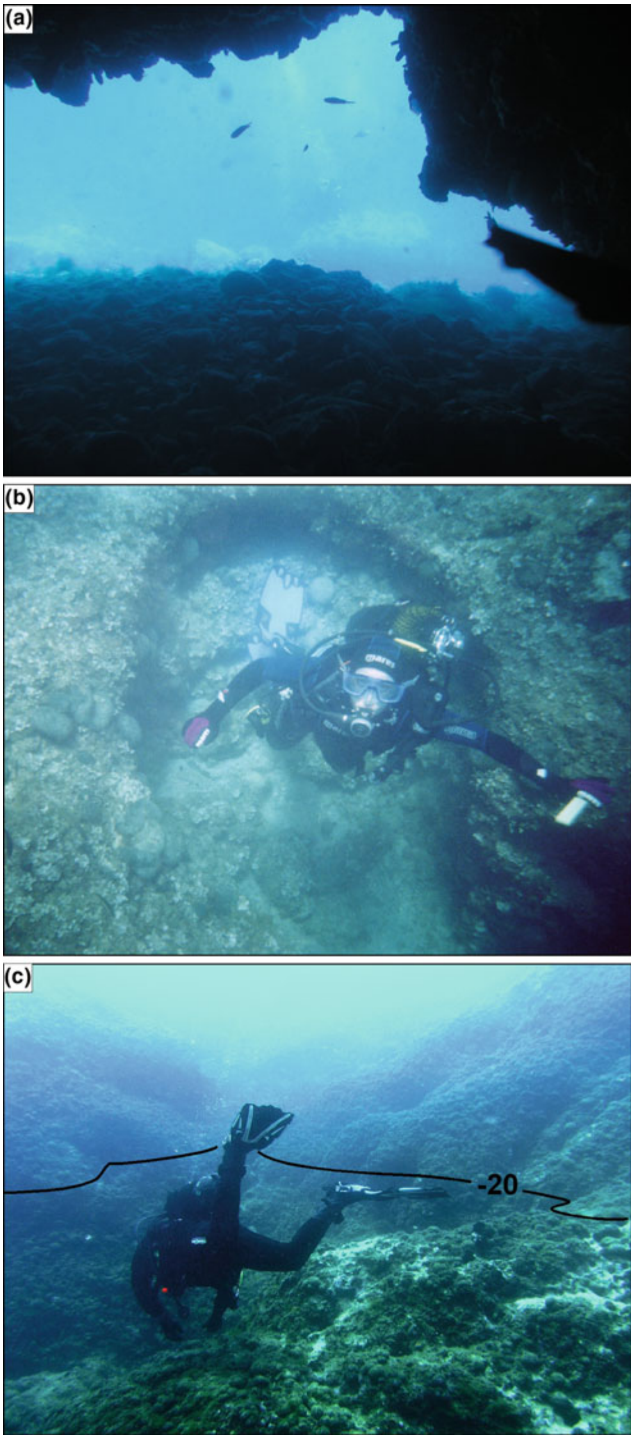

Fig. 32.9 Submerged landforms on the inner continental shelf (numbers indicate depth) (after Miccadei et al. 2011b); **a** San Domino island, submerged cave at 10 m b.s.l.; **b** Metric sub-rounded coastal rockpools, at 8 m b.s.l.; **c** Capraia island, paleo drainage incision between the sea-level and about 20 m b.s.l.

side of San Domino, Cretaccio and San Nicola). The shallowest one shows deep incisions and erosion channels, extending from the sea level down to about −25 m (Fig. 32.9c). They are V-shaped and characterised by steep valley sides in carbonate bedrock, and are partially filled by gravel to sand deposits, suggesting a possible origin due to stream or river incision. Alluvial fans with decimetric sub-angular clasts, usually stabilized and covered by algal cover, are located on the 20–25 m b.s.l. surface at the outlet of the shallower incisions. Alluvial fans lie on the inner part of the surface at 20–25 m b.s.l. Superficial running water-related incisions also affect the slopes and scarps between 20–25 m and 50–55 m b.s.l. and those below 50–55 m b.s.l.

32.3.4 Karst Landforms

Walking on the islands or sailing around them, the effects of karst action are clearly evident and the landforms tell about the history of landscape evolution in the archipelago related to climate variations. Wide sub-circular depressions (particularly on San Domino and, locally, Capraia), dolines and solution pans (on Capraia, San Domino and San Nicola) are well present at heights ranging from 40 m a.s.l. down to the sea level (Figs. 32.6a, b and 32.9). The surface karst landforms also shape the erosional surface at the top of the calcretes. Significant examples can be found on San Domino, I Pagliai (Fig. 32.6b) and Cala delle Roselle, where karst depressions are relict landforms carved in calcretes and filled by aeolian sand deposits. The underground karst is represented by about 50 caves scattered throughout the archipelago, at heights from 0 to about 50 m a.s.l. Moreover, several sub-circular coastal indentations (San Domino) are a possible inheritance of ancient karst (large dolines), later affected and partially eroded by marine processes (Fig. 32.10).

Terrestrial karst processes on the inner continental shelf during sea-level low stands are testified by relict karst landforms present at different bathymetric ranges, affecting the rocky sea floor on carbonate rocks, in some cases covered by marine deposits. On the southern coast of the Capraia island dolines are present at 9–15 m b.s.l., partly filled by gravel deposits; dolines and solution pans are also located at the sea level and are intensely reshaped by marine erosion. Between the islands of San Domino and Capraia, north of San Domino, dolines over 100 m wide, filled by sandy and gravelly deposits, are present at 25–35 m b.s.l. (Fig. 32.3). Also, the submerged caves, located between the sea level and 50 m b.s.l., are in many cases relict karst landforms, mostly reshaped by marine processes.

32.3.5 Landforms Due to Mass Movement

Gravity-induced landforms are widespread on the Tremiti Islands. Inactive and relict landforms are outlined by Middle Pleistocene—Holocene talus slopes and paleolandslides,

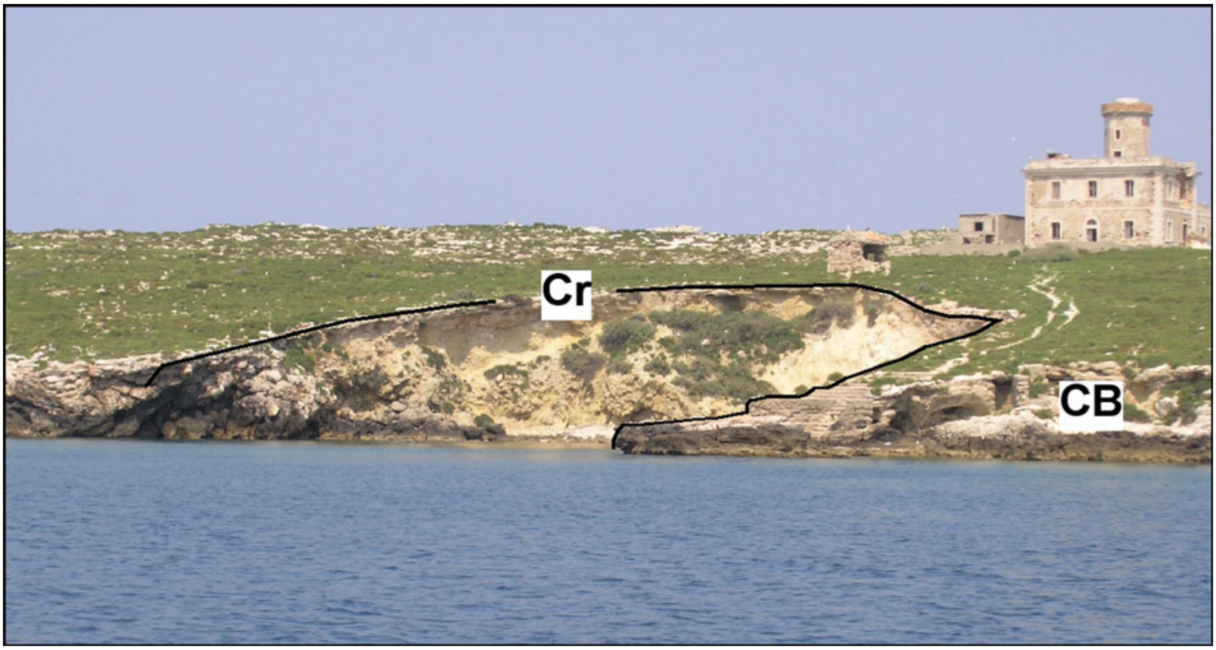

Fig. 32.10 Capraia, southern coast of the island, partially submerged relict karst landform on calcareous bedrock (*CB*) covered by calcretes (*Cr*) (after Miccadei et al. 2011a)

both on the islands and below sea level (see Sect. 32.2, Fig. 32.3); active landslides significantly affect the whole present-day coastline (Figs. 32.5, 32.11 and 32.12). Due to the lithological setting, bedrock faulting and fracturation, and continuous marine erosion at the base of the cliffs, most of the present cliffs are characterised by different types of mass movements such as lateral spreads, secondary topples, rock falls and slides. They involve almost the whole coast of San Nicola and locally the coast of Capraia and San Domino (Fig. 32.10a, b). In San Nicola, along the summit edges of the cliffs, tension cracks are present, related to tectonic fracturation and relaxation along the free face of the steep slopes; trenches are also locally present along the cliffs' edge, outlining possible new landslides to occur. This setting induces rock falls from the top of the cliffs and locally translational slides and lateral spreads affecting the whole cliff. The control of tectonic features on landslides is evident in several locations, such as at La Tagliata, where landslide development on highly jointed rocks induced a narrowing of the top surface of the island of San Nicola, which was then anthropically deepened. At the base of the slopes, rock falls, translational and complex landslide deposits, made up of large rock blocks, become a natural defence from marine erosion. Landslides are mostly controlled by the contrast in competence, shear strength and stiffness between the Pliocene re-crystallised dolomitic calcarenites and calcisiltites and the Miocene marly calcilutites and calcisiltites (Fig. 32.11) (Cotecchia et al. 1996; Andriani et al. 2005).

In the islands of San Domino and Capraia, coastal rock falls mostly occur in well fractured Paleogene limestones. Large and frequent rock falls occur, for example, from the up to 100 m high cliffs of the Architiello area (the highest of the Tremiti in San Domino) and in the I Pagliai area. They consist of small- to medium-size block falls due to undercutting at the base of the cliffs, locally, at the notch level. They are rather instantaneous events related to sea storms, rainfall or seismic shaking. In some cases they affect caves and induce a "cave-arch-stack" evolution (Andriani et al. 2005).

Below the sea level, landforms due to mass movement are also present, well represented in the northwestern sector of Capraia, such as paleolandslides located between 30 and 40 m b.s.l. and made of decametric calcareous blocks (Fig. 32.3).

32.3.6 Human Modifications of the Landscape

Anthropogenic landforms affect mostly the channel between San Domino and San Nicola, the best protected from the wind and the waves, where ancient and recent ports, settlements and villages have been established. Several human modifications affect the natural morphology of the channel such as piers, massive walls, cliff excavations and/or cliff protections. An ancient Roman dock is present, submerged at ~15 m b.s.l. between Cretaccio and San Nicola. Urban settlements are present in San Nicola (mostly the inheritance of the ancient Benedictine settlement, Fig. 32.12a) and in the upper part of San Domino, where only one small village is located, showing, so far, a limited impact on the natural

Fig. 32.11 Gravity-induced landforms: San Nicola, rock fall at the base of the cliff, mostly controlled by the contrast in competence between the Pliocene dolomitic calcarenites and calcisiltites (*Pl*) and the Miocene marly calcilutites and calcisiltites (*Mi*)

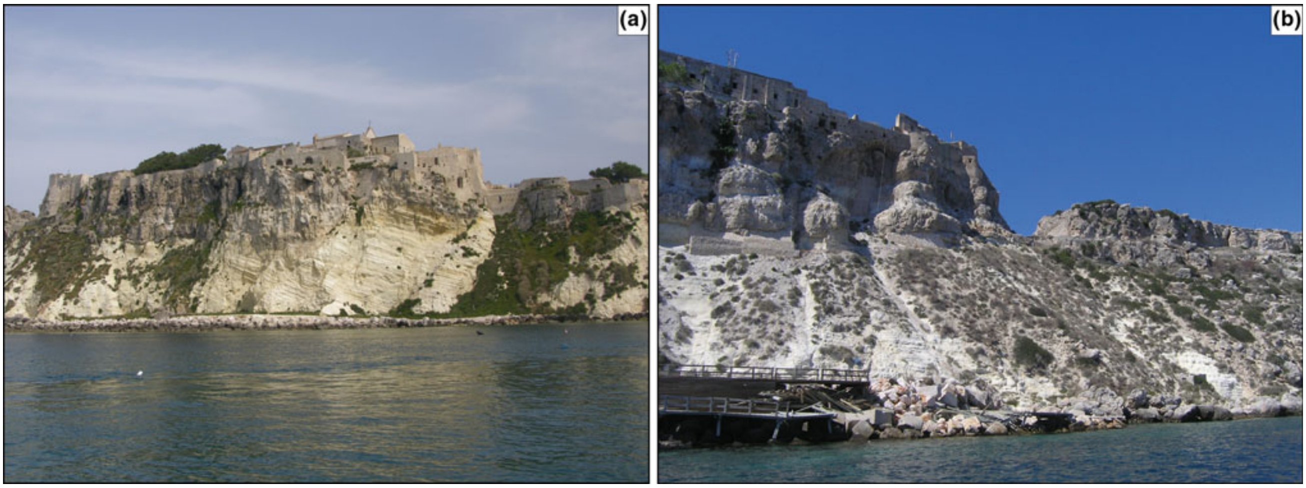

Fig. 32.12 Urban settlement and anthropogenic landforms: **a** San Nicola, cliff topped by walls of the Santa Maria abbey-fortress; at the *bottom* a concrete block cover is set up as an erosion/protection measure; **b** San Nicola, La Tagliata, cliff affected by rock falls and incision on the top of the island between the abbey area and the northeastern part of the island, erosional feature artificially deepened by Benedictine monks for a better defence of the Santa Maria abbey-fortress

landscape of the island. One of the most impressive landforms is La Tagliata (San Nicola, Fig. 32.12b), between the Benedictine abbey area and the northeastern part of the island; it is an erosional landform due to landslides controlled by tectonic features, artificially deepened by the monks to enhance defence of the Santa Maria abbey-fortress.

32.4 Conclusions

Spectacular features of—and intriguing relationships between—active, inactive and relict landforms have sculpted the outstanding terrestrial, coastal and submerged landscapes of the Tremiti Islands, which can be easily walked on, sailed around and dived into. Additionally, the geomorphological significance of the Tremiti Archipelago is enhanced by their considerable ease of access and by their protection within the Gargano National Park and the Tremiti Island Marine Protected Area.

Such a small archipelago holds an incredible wealth of landforms, mostly due to marine, slope and karst processes, but also to superficial running water and alluvial fan deposition; moreover, the overall setting of these landforms is related to tectonic and lithological control. The outstanding and intriguing geomorphological setting reflects alternating stages of marine and variable terrestrial processes related to Quaternary paleolandscapes different from the present one, whose evolution is recorded by continental deposits and by the superimposition of terrestrial and underwater landforms (Miccadei et al. 2011a, b).

The dramatic changes in landscape and drainage that occurred in the Tremiti area have been induced, at least since the Middle Pleistocene, by tectonic activity (and salt diapirism) and the effects of eustatic and hydroisostatic sea-level changes, while climate fluctuations induced stages of intense karst processes. This has resulted in alternating wide gentle hilly terrestrial landscapes, with slope, karst, alluvial fan and superficial running water-related processes (Tremiti Islands connected to the Italian coasts during sea-level low stands), and marine landscapes submerged by sea-level rises (outlining the islands' morphology during sea-level high stands).

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Vesuvius and Campi Flegrei: Volcanic History, Landforms and Impact on Settlements

33

Pietro P.C. Aucelli, Ludovico Brancaccio, and Aldo Cinque

Abstract

Vesuvius and Campi Flegrei are among the best known active volcanoes in the world because of their well-documented activity in historical times (witnessed also in the archaeological sites) and due to the risk they create in the surrounding densely populated area. Vesuvius is a composite stratovolcano including an older cone cut by a large caldera (Mt. Somma, 1131 m) and a younger cone called Vesuvius Gran Cono (1256 m). The Campi Flegrei are composed by a large caldera (12 km wide) occupied by about 30 younger monogenic edifices, mainly tuff rings and tuff cones, created by explosive eruptions due to the interaction between trachytic magma and underground water. Very famous is also the vertical ground deformation (bradyseism) affecting Pozzuoli in the Campi Flegrei. This phenomenon has been recorded for the last 2000 years by sea level marks on the columns of the Roman temple Serapeo.

Keywords

Volcanic landforms • Bradyseism • Volcanic risk • Campi Flegrei • Vesuvius

33.1 Introduction

Mt. Vesuvius and Campi Flegrei are located along the Tyrrhenian coast, at the margin of an area of recent extensional tectonics (Cinque et al. 1997). The fame of these volcanic areas is due to their location and interactions with human settlements in an area of continuous inhabitation since the Bronze Age. The best known example is the Vesuvius eruption of 79 AD that destroyed and buried the Roman towns of Pompeii and Herculaneum. Very famous is also the bradyseism (see Sect. 33.3.5) affecting Pozzuoli in the Campi Flegrei.

33.2 Geological Setting and Volcanic History

Mt. Vesuvius, with a height of 1281 m a.s.l. and a basal radius of 11 km, rises from the wide Piana Campana (Campania Plain) and is bounded to the SW by the water of the Naples Gulf (Fig. 33.1). Its magma chamber is located 4–5 km deep in Mesozoic limestones and is covered by about 2 km of Quaternary sediments. It is classified as a stratovolcano because the edifice is composed of alternating strata of lava and pyroclastic deposits, due to effusive and explosive eruptions, respectively.

Moreover, the edifice reveals composite morphology which includes: (i) remnants of an older stratovolcano called Mt. Somma; (ii) a vaguely elliptical summit caldera, whose rim is higher and therefore still prominent to the N and NE; (iii) a younger cone called Vesuvius Gran Cono, with a deep crater on its summit. Due to this composite architecture, the

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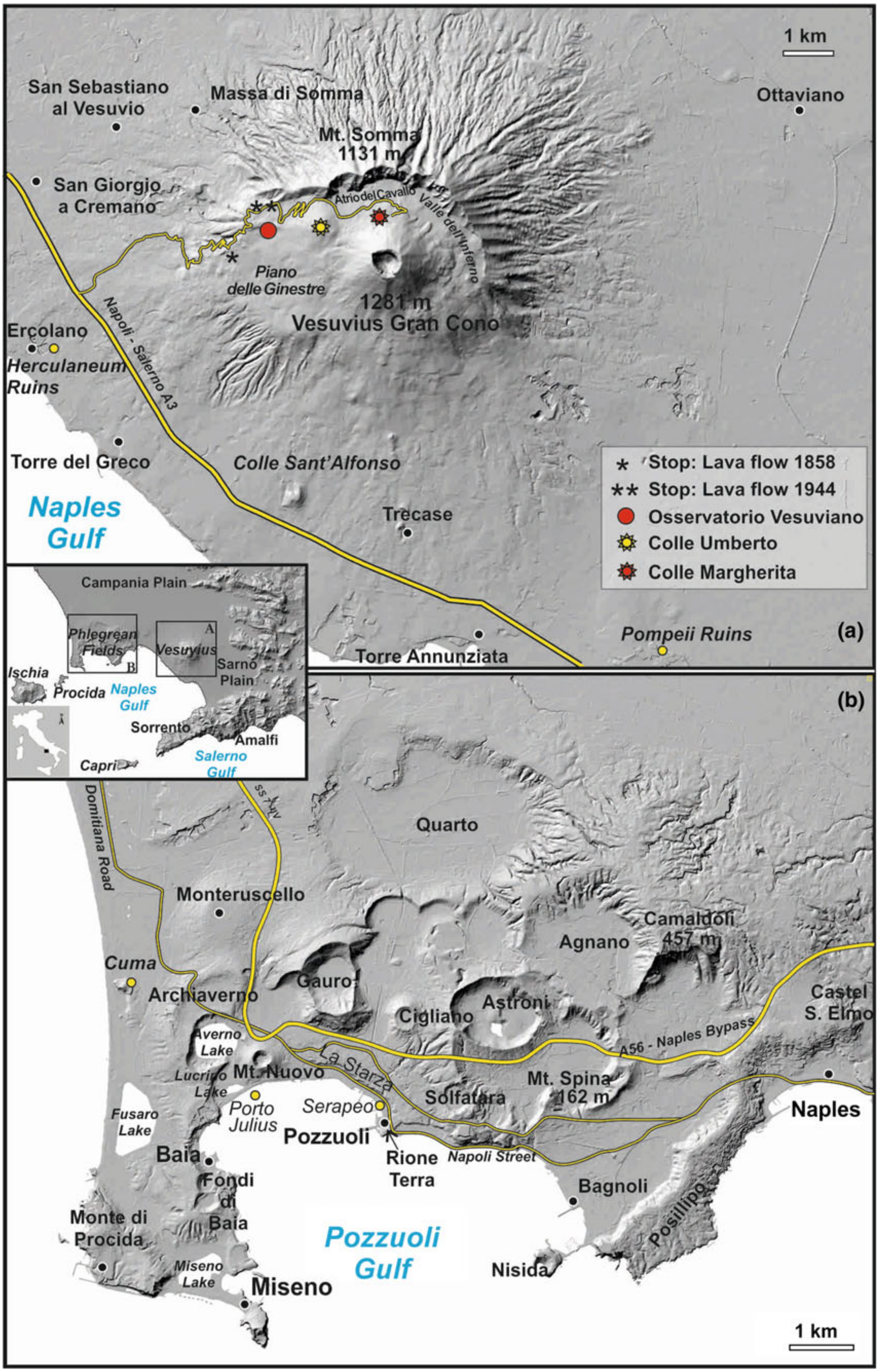

Fig. 33.1 Shadow relief of the Somma-Vesuvio volcano (**a**), the Campi Flegrei (Phlegrean Fields) (**b**) and their position in the Piana Campana (Campania Plain)

most appropriate name of this volcano is Somma-Vesuvius (Fig. 33.2).

Prior to the origin of the caldera, the Somma volcano reached probably 1600–1800 m a.s.l. Presently the highest point along the caldera rim is 1131 m (Mt. Somma). In the northwestern sector of the volcanic complex, the younger cone has not completely filled up the caldera and a residual depression called Valle dell'Inferno remains between the caldera wall and the Vesuvius Gran Cono. Conversely, in the southwestern sector the caldera was completely filled because the rim was less elevated (from about 800 m to the E to about 400 m to the SW) and the Vesuvius products formed the terrace of Piano delle Ginestre (Fig. 33.1a).

The Valle dell'Inferno depression opens up on the Vesuvius external slope through the so-called Atrio del Cavallo: a narrow and steep valley dissecting the caldera rim and descending towards the town of San Sebastiano al Vesuvio.

Even though Mt. Vesuvius is an active volcano, its piedmont belt hosts an almost uninterrupted series of towns totalling over 600,000 inhabitants. Most of the population is concentrated in the SW sector, which is also the most exposed to potential lava and pyroclastic flows, as the caldera wall is missing on this side. In response to this high risk, largely due to unplanned and uncontrolled urban development during the second half of twentieth century, Vesuvius is now the most monitored volcano in the world thanks to the activity of Osservatorio Vesuviano, part of the Italian National Institute of Geophysics and Volcanology.

The present edifice of Somma-Vesuvius began to form around 25 ka ago but an ancestor volcano can be documented with its earliest lavas dating back to about 400 ka ago (cf. De Vivo et al. 2010).

Throughout time the activity of Somma-Vesuvius has occurred in cycles, each composed of (a) a very strong explosive eruption consisting of the so-called 'Plinian' and 'Subplinian' events, whose strength was increased by water–magma interactions at depth (phreatomagmatic eruptions); (b) a period of less intense 'Strombolian' and 'Vulcanian' eruptions with lava flows emission, jetting off clots of fluid lava (fountains) and pyroclastic material emissions; (c) period of variable time of repose.

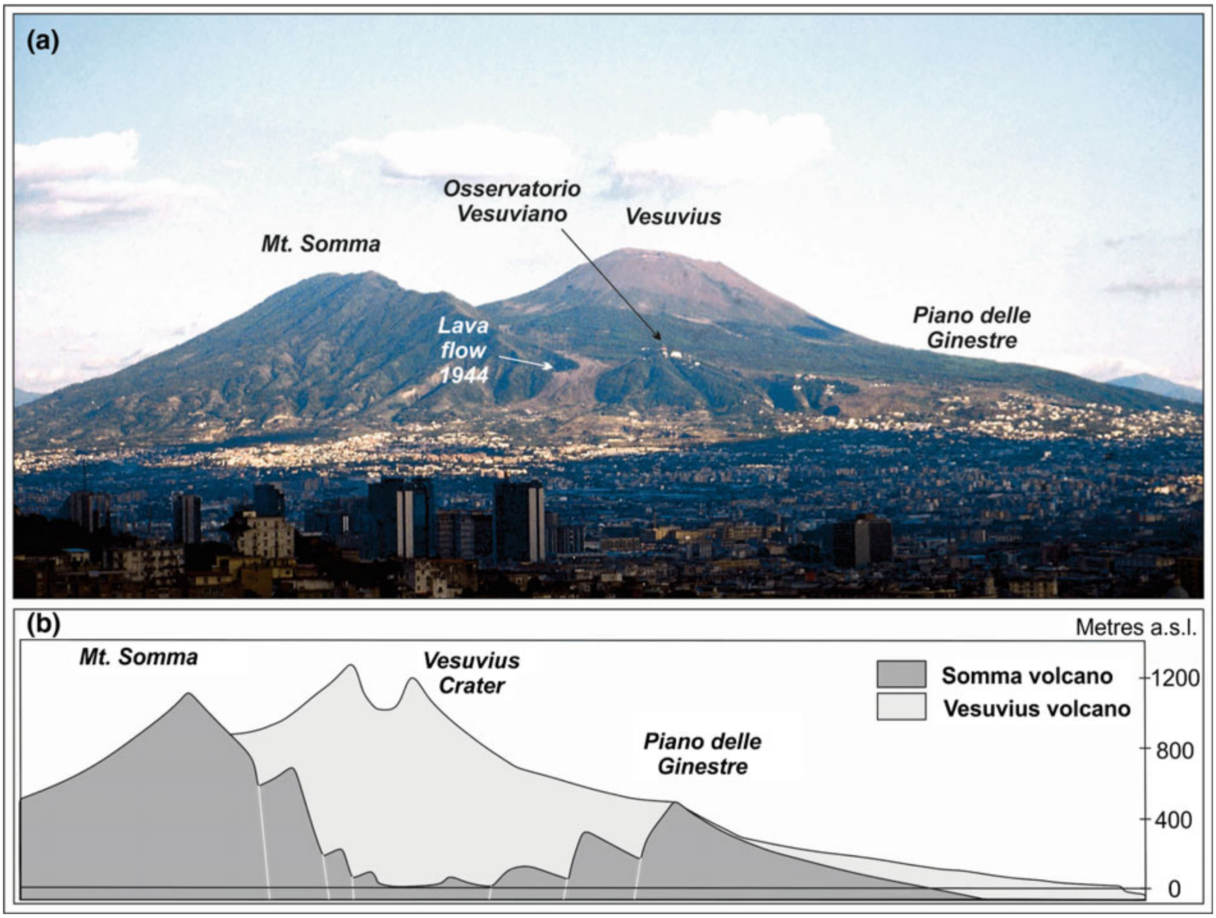

Fig. 33.2 **a** View of Somma-Vesuvius from Castel Sant'Elmo in Naples (*photo* M. Di Vito); note the densely populated piedmont. **b** Scheme of the composite volcano structure

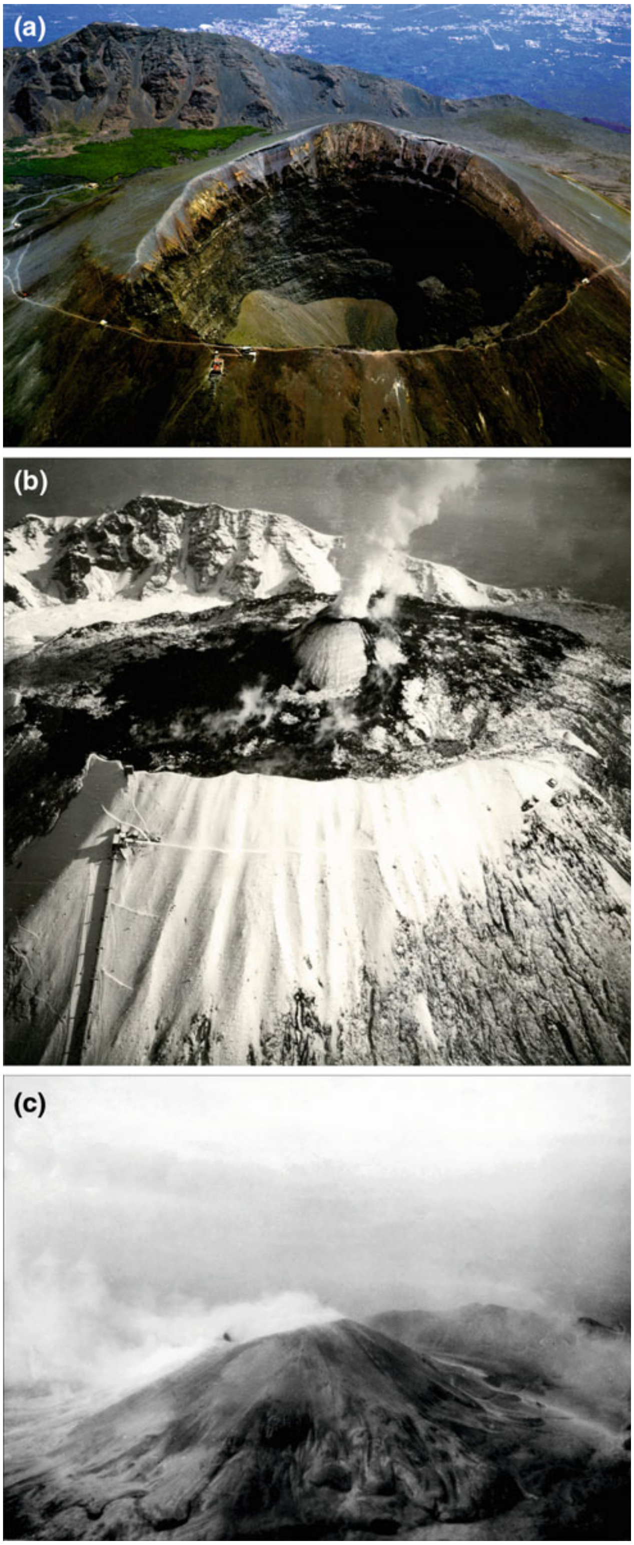

Fig. 33.3 Detail of the crater rim of Vesuvius Gran Cono. **a** The cone as it is today; note the deposits of the last eruption of 1944 along the upper part of the rim (*photo* M. Di Vito); **b** The crater during the eruption of 1944 from a photograph taken by an American military aircraft (Liberator—B24, *photo* Archivio fotografico dell'Osservatorio Vesuviano). Clearly visible are the lava fills of the crater and the new small cone above it; **c** aerial view of the cone during the 1944 eruption with scoriae flow lobes (*photo* Archivio fotografico dell'Osservatorio Vesuviano)

The attribute 'Plinian' originates from the name of the Roman naturalist Plinius the Elder who witnessed and documented the Vesuvius eruption of 79 AD. Therefore, the modern volcanologists call 'Plinian' an explosive eruption, able to launch a column of gas and pyroclastic material up to the stratosphere, forming a very tall pine-shaped cloud, the so-called Plinian cloud feeding both distal fall out and proximal pyroclastic flows.

The depressurising of the magma chamber, related to the 79 AD eruption, is responsible for the final "reshape" of the caldera, which had already been formed due to previous Plinian eruptions. The growth of the Vesuvius cone post-dates the 79 AD eruption (Santacroce et al. 2003) and probably started after the last explosive eruption of Mt. Somma at 472 AD (Rolandi et al. 2004).

The last eruption of Mt. Vesuvius occurred in March 1944 when the lava appeared within the crater rim and significant outflows occurred towards south and then north, reaching and inflicting serious damages to the towns of San Sebastiano al Vesuvio and of San Giorgio a Cremano. That eruption ended with an explosion on March 18, 1944, creating the large and deep empty crater which is still visible today (Fig. 33.3).

Shifting attention to the Campi Flegrei (literally 'burning fields'), it should be remarked that this appellative refers to a large caldera (12 km wide) located immediately north of Naples and occupied by a number of younger volcanoes. The pre-caldera volcanic edifice is morphologically well preserved only in the N–NE sector, where it appears as a gentle slope in radial descent from the Camaldoli hill (457 m), as it was disrupted also by some regional faults and partly drowned by the Tyrrhenian Sea (Fig. 33.1). The Campi Flegrei area is also densely inhabited. Its largest town is Pozzuoli (80,000 inhabitants) built above the ruins of the Roman Puteoli.

The trachytic magma of the Campi Flegrei chamber, interacting with underground water, produced mainly explosive eruptions, most of which were characterized by magma degassing at shallow depth. For this reason, and also for the frequent migrations of the vents facilitated by the highly fractured bedrock, volcanic landforms are remarkably different from those of Somma-Vesuvius. The landscape of Campi Flegrei consists of about 30 monogenic edifices, mainly tuff rings and tuff cones, never exceeding 310 m of height and having external slope rarely exceeding 20°.

The oldest volcanic rocks exposed in the Campi Flegrei area date back from 60 to 40 ka. Some authors proposed a correlation between the last phase of this activity and the emplacement of the Campanian Ignimbrite (CI), an ignimbrite tuff occurring all over the Campania region related to a huge phreatomagmatic eruption. Most probably the CI eruption, which emitted about 300 km^3 of magma, occurred

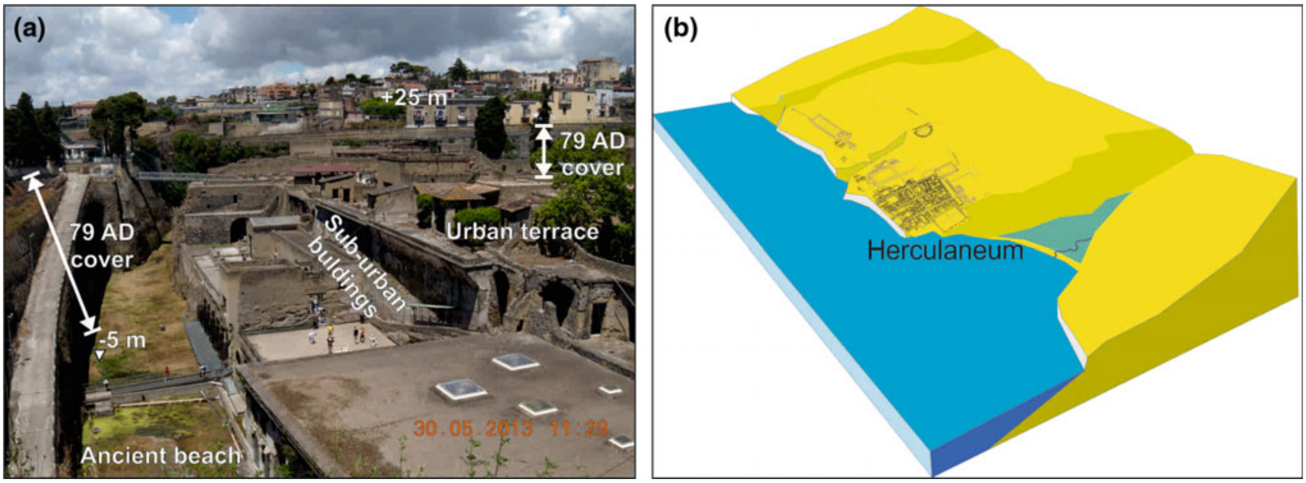

Fig. 33.4 **a** The SW portion of Herculaneum excavation, exposing an ancient beach area at the bottom (*photo* E. Cubellis). Note the down-stepping Sub-urban buildings covering the pre-existing sea cliff and the smooth modern topography at the horizon. **b** Reconstruction of the landscape before the 79 AD eruption

not only through vents in the Campi Flegrei, likely promoting a first phase of calderization (Rosi et al. 1983), but also through faults located elsewhere in the Campania Plain graben (De Vivo et al. 2001; Rolandi et al. 2003).

Another important phreatomagmatic eruption (40 km^3 of emitted magma) in the Campi Flegrei was associated with the Neapolitan Yellow Tuff (NYT) dating to about 15.3 ka ago (Deino et al. 2004). This eruption was responsible for the formation of the present caldera. The NYT deposit is over 100 m thick and forms, among others, the hills on which the city of Naples was built. After the big eruption of the NYT, a new phase of explosive activity can be recorded between 15 and 9.5 ka, with the Gauro, Agnano and Archiaverno eruptions followed by minor explosive episodes (Fondi di Baia) between 8.6 and 8.4 ka.

Most of the well preserved crater morphology, however, can be ascribed to the last eruptive phase that occurred between 4.2 and 3.7 ka, when the Astroni (4.1–3.8 ka), Averno (3.7 ka) and Solfatara (4.1–3.8 ka) craters were formed, among others. The last eruption of Campi Flegrei occurred in 1538 AD, when the 110 m high scoria cone of Monte Nuovo was formed in only 1 week. Eruptions are not the only morphogenetic forces that shaped the Campi Flegrei landscape throughout time, because very influent were also vertical ground deformations (bradyseism).

33.3 Landforms

33.3.1 Somma-Vesuvius Volcano

The best view of the Somma-Vesuvius is from the city of Naples; good observation points being the A3 highway in the direction of Salerno, the hill of Castel Sant'Elmo and the city sea shore (Fig. 33.2).

Within the Vesuvius profile one can identify, from left to right: (i) Mt. Somma with its dissected external slope and the cliffed inner one, i.e. the caldera wall, (ii) the Atrio del Cavallo valley with the 1944 lava flow, (iii) the Vesuvius Gran Cono and (iv) the inclined terrace of Piano delle Ginestre. The old Osservatorio Vesuviano is also visible on a prominence that constitutes another remnant of the caldera from the Somma volcano times.

Considering that Piano delle Ginestre terrace formed due to the damming of Vesuvius lava flows by the caldera wall, we may fully appreciate the remarkable inclination of the ancient caldera rim to the SW. It was in the early eleventh century that this side of the caldera circle was filled up. The progressive growth of the Vesuvius cone also caused that the lavas emitted in the northern direction converged in the Valle dell'Inferno depression and left the caldera through the gap called Atrio del Cavallo.

With regard to landforms due to erosion by running water, it should be noted that only the external slope of the ancient Somma volcano is densely and deeply cut by gullies and valleys. The difference with the scarcely dissected SW sector is certainly due to the fact that the Somma edifice is older than the Vesuvius by millennia.

To visit the volcano from Naples, one should drive to Ercolano and then take the paved road SP19 and SP140 ending in parking area at 1000 m a.s.l. (Fig. 33.1). From there, a path leading up to the Vesuvius crater rim begins. After Piano delle Ginestre, the steep road crosses the ropy surface of the lava flow of 1858 emitted by a fissure at the base of the Vesuvius cone vent. Further upslope, after reaching the valley called Atrio del Cavallo, the road approaches the 1944 lava flow. Such flow was emitted from the summit crater towards the north; after sliding down on the steep flank of the Vesuvius cone, the lava thickened in the Valle dell'Inferno depression and flowed slowly towards the Atrio del Cavallo gap. As the lava surface cooled down and became rigid while the mass beneath was still hot and moving, the lava flow developed a blocky surface.

Carrying on the ascent to the summit, one comes across the Colle Umberto and Colle Margherita lava domes formed in the late nineteenth century; after that, the tall wall of the caldera becomes visible. The caldera wall exposes alternations of lavas and scoria, crossed by dikes and sills that appear to be slightly protruding because they are better crystallized and therefore more resistant to weathering and erosion.

33.3.2 The Vesuvius Summit Crater

The path going from the parking lot to the volcano summit runs along the steep flank (up to 42°) of the Vesuvius cone. It is mostly made of scoria, sometimes welded and compacted, that began forming in the late Roman period or in the early Middle Ages and underwent several phases of construction and explosive dismantling. Its present shape and size are mostly due to deposition that occurred after the sub-Plinian eruption of 1631, when the previous cone lost about 450 m of its height.

The summit crater has an elliptical shape (480 × 580 m) and a depth of about 300 m (Fig. 33.3). It was formed after the last explosive phase of the 1944 eruption, responsible for the accumulation of 20 m of scoria and lapilli that can be seen on the top of the crater rim. Prior to that event, the crater, left empty after the 1906 eruption, underwent a phase of aggradation (1913–1944) that completely filled it up leaving a small, smoking spatter cone in the centre (Ricciardi 2009).

Inside the crater an almost continuous belt of steeply stratified and unwelded debris at the base of the caldera wall is noticeable (Fig. 33.3a), related to mass wasting and run off processes. The main predisposing factors of this debris production are the cooling cracks affecting the rock and the tensile joints created by stress release after the emptying of the crater in 1944 (Fig. 33.3b). The outer slope of the Gran Cono is also affected by water erosion and mass movements. The latter include mainly debris avalanches and debris flows that can even reach the piedmont coastal cities of Torre del Greco and Torre Annunziata. Some lobes of small-scale scoriae flows were formed during the last eruption of 1944 and were photographed by American military aircrafts (Fig. 33.3c).

33.3.3 Herculaneum, Pompeii and the Surrounding Landscape Before the 79 AD Eruption

33.3.3.1 Herculaneum

The ruins of Herculaneum (third century BC–79 AD) are enclosed within a vast area, with only about one-fourth of the ancient town excavated (Fig. 33.4a). The archaeological area is located about 0.5 km from the shore, in an almost planar landscape that is gently inclined (6°–7°) towards the sea. This topography is largely due to flattening effect imposed by pyroclastic deposition during the 79 AD eruption, which also produced an advance of the coastline by several hundred metres. An image of the landscape prior to the 79 AD eruption can be evinced from the Latin writer Sisenna (Hist., 53) who described Herculaneum as a walled town built on a high ground very close to the sea (a coastal terrace) delimited on the sides by two streams descending from Mt. Vesuvius (Fig. 33.4b). The coastal cliff bounding the ancient terrace to the SW remains largely buried under the 79 AD pyroclastic cover but part of it is still visible in the so-called Sub-urban sector of the excavation (Fig. 33.4a). This is a 12–14 m high cliff disguised beneath a building dating to the time when the Roman city of Herculaneum expanded beyond the boundaries of its walls (Sub-urban buildings).

The sands of the ancient beach were also found between 2 and 4 m below the present sea level, as a proof that the area subsided by about 3 m after the 79 AD eruption. However, a drilling campaign recently carried out by the Herculaneum Conservation Project (funded by the Packard Humanities Institute) revealed that strong subsidence (4–7 m) also occurred during the first century BC (Cinque et al. 2009). This subsidence caused local rise of the sea level and it was necessary to relocate the Herculaneum harbour piers (as it happened in Pozzuoli during the year 1983) and to protect the Sub-urban Thermal Bath from the sea by means a robust and prominent cornice.

Returning to the time of the 79 AD eruption, the fact that Herculaneum was buried beneath many metres of hot pyroclastic flow deposits (absent in the fall out sequence covering Pompeii) suggests that the Vesuvius caldera depression was more pronounced than today. Therefore, most of the hot and degassing fragments falling down from the pyroclastic column (stage of collapse) engulfed it exiting where the caldera rim was the lowest (nowadays it corresponds to Piano delle Ginestre).

33.3.3.2 Pompeii

More famed than the ruins of Herculaneum are those of Pompeii, a Roman town situated 10 km to the SE of

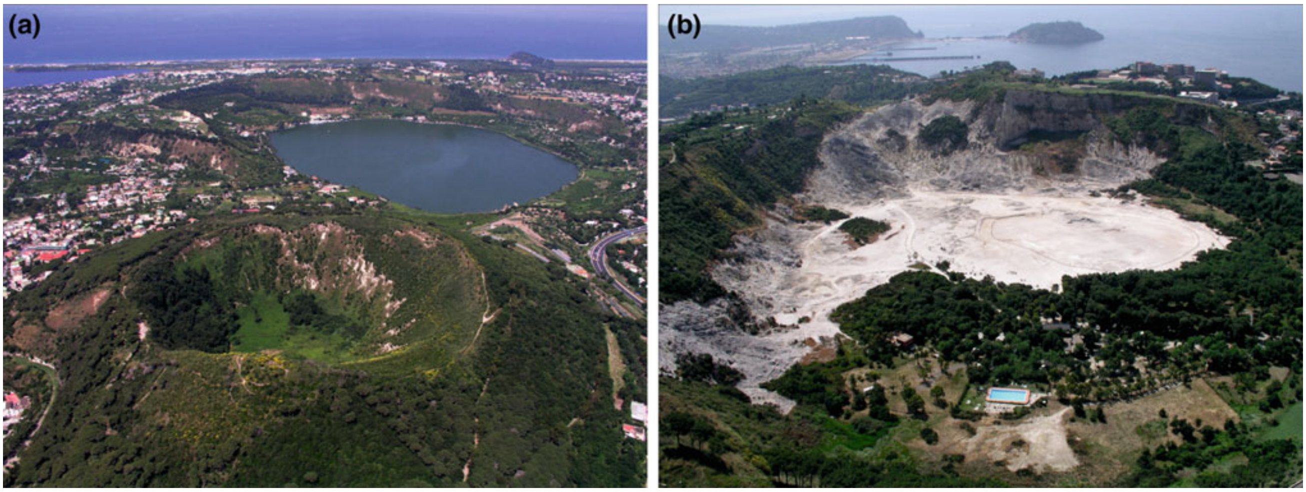

Fig. 33.5 Aerial views of the Averno, with Monte Nuovo in *foreground* (**a**), and Solfatara (**b**) craters (*photo* R. Scandone). A number of recent buildings appear on the western part of the Solfatara crater rim; they are exposed to very high risk since the phreatomagmatic eruption of this type of volcano could be sudden and destructive

Vesuvius crater that was buried by air-fall and surge deposits of AD 79 Plinian eruption.

The eruption lasted 18 h and at Pompeii it produced a 5 m cover made mostly of pumice fall deposits plus thin ash layers due to surge propagation. The weight of the fall deposits caused the sudden collapse of roofs of the buildings. Whilst the push of the surges, related to the collapse of eruption column occurred in the last part of the eruption, locally broke down those part of walls that were still emerging from the pumice cover. At that time, Pompeii had no less than 12,000 inhabitants.

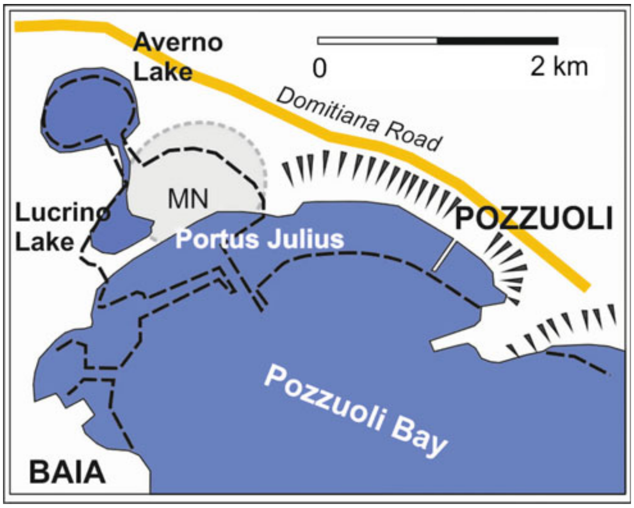

Fig. 33.6 The sketch represents the current morphology of the Pozzuoli coast. The first century BC palaeogeography is indicated by a cross hatched line; the *light grey spot* marks the position of Monte Nuovo (MN)

Ancient Pompeii was built on top of a low hill (about 50 m a.s.l.) that was touched by the Sarno River to the south. The western foot slope of the hill was bordered by coastal environments (marshes and sand ridges) related to a coastline that was about 1.5 km less advanced than today.

This hilly ground represents the faulted and eroded remnants of a pre-historical parasitic cone of Mt. Vesuvius (Cinque and Irollo 2004). Prior to the 79 AD eruption, the landscape around Pompeii was remarkably different from the present one. The Sarno River was meandering (now it appears straight due to reclamation works of the nineteenth century) and its mouth, with a port inside, was much closer to the town, because the ancient shoreline was about 1 km less advanced than the contemporary coastline. The correlative beach sands are buried under the modern plain, proving post-eruption subsidence of about 4 m. This phenomenon anyway did not provoke the regression of the shore, because the volcanoclastic supply balanced the subsidence, actually causing the progradation of the coast (Cinque et al. 1997).

33.3.4 Three Volcanoes of the Campi Flegrei Area

Solfatara, Averno and Monte Nuovo are among the most interesting and best preserved volcanoes of Campi Flegrei; being easily accessible to visitors are briefly described below.

33.3.4.1 Averno

The tuff ring of Averno (Fig. 33.5a) is a wide volcano hosting a dark phreatic lake (Averno Lake) which formed during one of the most recent intra-caldera phreatomagmatic explosive eruptions (3700 years BP). Averno presents an elliptical crater rim (about 1450 and 1000 m wide) reaching its maximum elevation of about 100 m a.s.l. along the southwestern edge; on the SE only a saddle caused by marine erosion of the volcanic edifice remains.

From an overlook at the Domitiana road running along the northern edge of the crater rim it is possible to look down into the roughly circular crater lake measuring 2 km in circumference and 60 m in depth. The Romans thought that a cave located next to the lake *Avernus* was the entrance to the Hades or the underworld of death. The name derives from the Greek word αορνος (read aornos), meaning "birdless", probably referring to the fact that poisonous gases emanating from the area before Roman times may have kept away the birds.

In 37 BC, the Roman general Marcus Vipsanius Agrippa converted the lake into a shipyard for a military naval base located near the present day Lucrino Lake, to which Averno was connected by an artificial canal (Fig. 33.6). The large harbour of the naval base at Lucrino Lake was named *Portus Julius* after Julius Caesar.

33.3.4.2 The Solfatara

This volcano (Fig. 33.5b) takes its name from the Latin word 'Sulphur' because the gases it emanates smell like Sulphur anhydride. It can be easily reached by Domitiana road going from Naples to Pozzuoli.

The Solfatara is an elliptical tuff cone 180 m high, with the crater floor located at 90 m a.s.l. The tuff cone is made mostly of hydrothermally altered breccias, dune-bedded ashes and lapilli (Rosi and Sbrana 1987); it was formed between 4.1 and 3.8 ka ago (Di Vito et al. 1999) through a classical phreatomagmatic explosive eruption and a historical chronicle also reports a phreatic event in the twelfth century. Currently, the Solfatara is affected by intense diffuse degassing and fumarolic activity determined by both magmatic and underground waters. These gases are constantly monitored by the Osservatorio Vesuviano, as the increase of magmatic component, e.g. carbon dioxide, is supposed to have a relevant role in triggering the unrest of the volcanic system that can affect the area. Ground temperature on the crater floor is 40 °C on average and, in some areas, it can exceed 100 °C (about 160 °C at Bocca Grande). The water table forms ephemeral lakes in the central part of the crater and water gases gurgling in them simulate a boiling effect. Most of the crater floor is whitish in colour and lacks soil as well as vegetation cover. In contrast, the inner southern and western slopes are covered by Mediterranean maquis.

33.3.4.3 Monte Nuovo Crater

Along the road to Baia there is a 110 m high volcanic cone called Monte Nuovo (Fig. 33.5a); it is the youngest among 30 monogenic volcanic centres identifiable within the Campi Flegrei. This small volcano has a diameter of about 1.2 km at the base and 375 m at the crater rim. The name Monte Nuovo, meaning 'New Mountain', is related to its rapid construction due to 1538 AD eruption.

This event was characterized by two eruption phases with contrasting eruptive styles. The first stage of phreatomagmatic activity produced a tuff cone and was followed by a second, explosive phase that deposited Strombolian-type tephra on top of the tuff cone (Di Vito et al. 1987).

It was a very short-lived and dramatic event as most of the cone was formed in only 2 days, between September 29 and 30, 1538. It caused the destruction of the village of Tripergole and killed 24 people. The event was preceded some months ahead by ground uplift which was so intense during the eruption that it caused a sudden retreat of the sea leaving the fish trapped on the newly emerging seashore without enough time to swim away. The eruption strongly modified the coastal physiography of the Pozzuoli Gulf transforming a sea branch, Averno Bay, into a lake, Averno Lake (Fig. 33.6).

33.3.5 Coastal Change Due to Bradyseismic Movements

The Campi Flegrei caldera is famous for the bradyseism. This term was coined by Arturo Issel, an important Italian geologist of the nineteenth century, to designate vertical ground movements in volcanic areas; it derives from two ancient Greek terms meaning 'slow movement of the landmass'. Such movements are said to be 'slow' because they are not detectable by human eye, ranging from mm to dm per year. The cause of negative (i.e. rising) and positive (i.e. descending) bradyseism can be either the intrusion of new magma and its degassing or fluctuations of hydrothermal activity, causing expansion and contraction of rocks and sediments due to variations in pore pressure in relationship with heat flux variations. In coastal areas, ancient bradyseismic movements are recorded as changes in relative sea level but in the Campi Flegrei they are also documented archaeologically. To this regard, two important sites in the bay of Pozzuoli should be considered: Portus Julius and Serapeo.

33.3.5.1 Portus Julius

This large port was built in 37 BC to host the military fleet of Rome and its ruins are today submerged off the beach of Lucrino (Fig. 33.7a). When the sea is calm and clear, these ruins can be seen from the top of Monte Nuovo. The Portus Julius did not have a long life. Soon after its foundation it became unusable due to the phase of negative bradyseism that reduced the water depth and in 12 BC the Roman fleet abandoned it in favour of the nearby port of Miseno. From

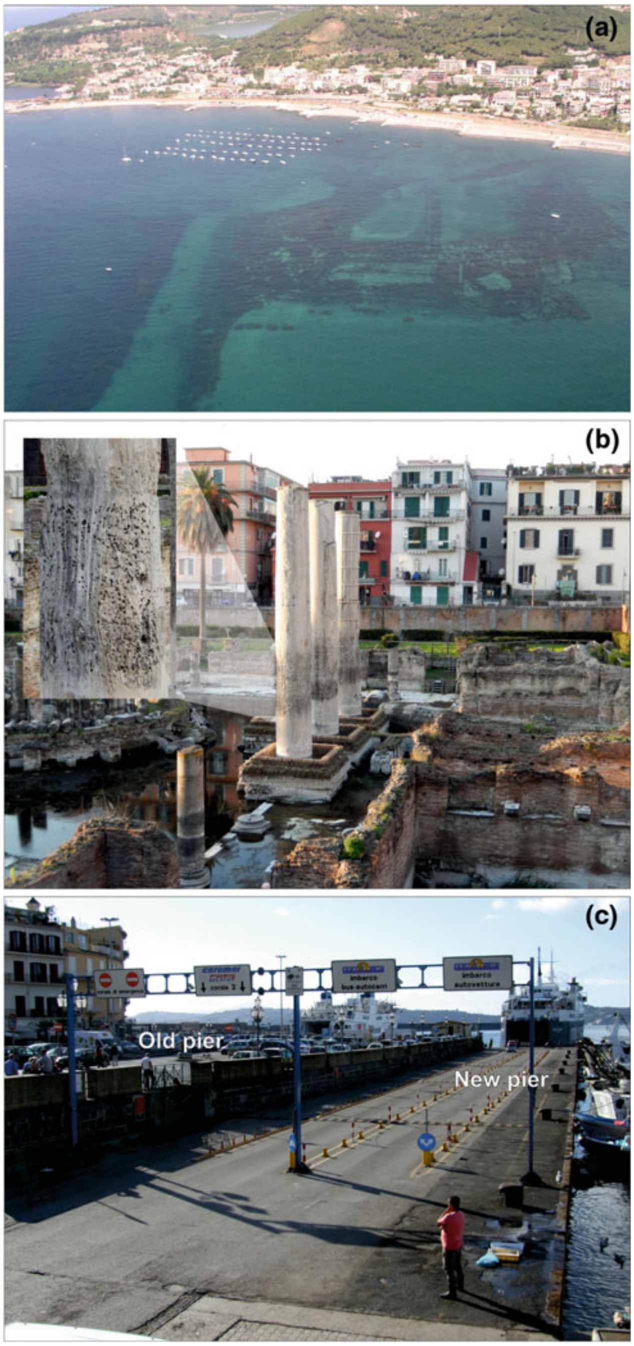

Fig. 33.7 **a** Aerial view of Portus Julius submerged ruins (*photo* M. Di Vito); **b** The Serapeo in Pozzuoli (see detail of the column with the Lithodomus Litofagus holes); **c** View of the modern Pozzuoli Port (note the piers located at two different levels, *photo* M. Di Vito)

the fourth century AD, there has been a period of stronger bradyseismic movements alternating between positive and negative, with the prevalence of subsidence. Today the structures of Portus Julius are located at about 5 m below sea level (Fig. 33.6).

33.3.5.2 Serapeo

The so-called Serapeo has helped Earth scientists to unravel the history of the Phlegrean bradyseisms from Roman times onwards (Fig. 33.7b). Its ruins are located near the Pozzuoli port, at the base of the abandoned sea cliff bounding La Starza marine terrace. This large Roman edifice was built in the late first century BC and modified in the third century AD; initially believed to be a temple for the Egyptian god Serapis, it was actually a market place or *macellum*. The Serapeo gained international fame among geologists when Charles Lyell displayed an engraving of the ruins on the frontispiece of his famous book "Principles of Geology" printed in 1830.

The Serapeo consisted of a pillared court with tall marble columns supporting a roof, three of which are still standing. Due to bradyseism, the monument has recorded variable levels of flooding by the sea evidenced by the whitish marks left on its walls (Fig. 33.7b). In addition, the relative sea level rises of the Middle Ages are also documented by the presence of littoral sediments on its floor (now removed) and holes on the columns caused by a marine mollusc called *Lithodomus lithofagus*. These perforations found as high as 7 m a.s.l., along with the ^{14}C dating of some shells, reveal that this sea level rise happened between the third and fifteenth century AD (Morhange et al. 2006). At that time the former coastal plain was submerged and the sea returned to touch the base of the cliff below La Starza terrace. From the sixteenth century onward, negative bradyseismic movements prevailed. They were particularly strong in the first years of the sixteenth century, before the Monte Nuovo eruption. This is the reason why strong negative bradyseism is now assumed to be one of the precursor of eruptions.

33.3.5.3 Recent Events

From 1538 to 1969 the coast of Pozzuoli experienced gradual lowering at a documented mean rate of 14 mm/year from 1822 onwards. During summer 1969 the area of Pozzuoli was affected again by uplift that reached a maximum of 1.70 m by December 1971. This uplift was accompanied by moderate seismicity. Between mid-1972 and the end of 1974, the ground subsided by 0.22 m while in the following eight years no significant change was recorded. In 1982, a new intense uplift phase began, with low seismicity lasting until the end of the year. By the end of 1984, the maximum uplift was 180 cm. Combined with the 1.5 m of uplift recorded between 1969 and 1974, this new uplift caused the abandonment and replacement of the harbour pier in Pozzuoli (Fig. 33.7c). From 1983 to the end of 1984 the seismicity was very intense (magnitude up to 4), with hypocentres located at shallow depth (4–5 km) in the northern part of Pozzuoli Bay. This seismicity caused severe damages to the town and 40,000 inhabitants had to be evacuated. As the chance of an eruption was seriously considered, based on the events of 1538 AD, most of these people were relocated to a new residential area built outside the caldera rim (Monteruscello Village). However, since the end of 1984 the ground has generally subsided (with scattered minor uplift episodes), but now the instruments are recording a new uplift phase.

The subsidence has never been accompanied by earthquakes, while seismicity did accompany the uplifts. The geometry of the movements has a circular pattern centred in Pozzuoli. The null uplift can be verified at a radial distance of about 10 km from Pozzuoli.

33.4 Conclusions

The volcanic district of Campania is an example of continued interaction between man and volcanoes since the Greek times (fifth century BC). Such interaction has always been associated with high risk to the dense population living on the Vesuvius piedmont and in the Campi Flegrei Caldera, as the two volcanoes have eruptive histories characterized by high-energy explosive events. Bradeyseism in the Campi Flegrei constitutes an additional problem to people. It affects building and infrastructure safety, and negative bradeyseism is supposed to be the precursor of an eruption.

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34

Sorrento Peninsula and Amalfi Coast: The Long-Term History of an Enchanting Promontory

Aldo Cinque

Abstract

The mountain ridge forming the Sorrento Peninsula and the Amalfi Coast is of great physical beauty and plenty of tourist attractions. Moreover, it has an interesting geomorphological history that this chapter illustrates in the form of a 7-stops visit tour. The local landscape was influenced by extensional tectonics that divided the western coastal belt of southern Italy in horsts and grabens. While creating impressive fault scarps with truncated landscapes suspended above them, tectonics promoted, among others, cutting of steep canyons and opening up of ancient karstic conduits. Around the end of Middle Pleistocene the area attained tectonic stability and the following climatic and eustatic changes are geomorphologically recorded at stream mouths and in some coastal caves.

Keywords

Limestone geomorphology • Morphotectonics • Eustasy • Ignimbrite terrace • Sorrento Peninsula • Amalfi Coast

34.1 Introduction

The area presented in this chapter is a famous tourist destination since the eighteenth century. Sorrento and Amalfi were major stops along the *Grand Tour* that brought to Italy visitors from the European elites who wanted to be immersed in Classical culture. The beauty of the natural landscape and the rich artistic and historical heritage contribute to the longstanding appeal of the Amalfi coast. UNESCO has included the Amalfi Coast among its World Heritage Sites because of its "great physical beauty and natural diversity… (and of) towns such as Amalfi and Ravello with architectural and artistic works of great significance". However, while a number of existing guidebooks provide information on the towns and the historical monuments, no source focuses on the surrounding natural context; the goal of the present chapter is to fill this gap and to offer explanations on the origin and evolution of landforms to those who are interested in going beyond the aesthetic appreciation of landscape.

34.2 Geographical and Geological Setting

The area, lying along the west coast of southern Italy, is a well-defined physiographic unit consisting of a WNW trending calcareous ridge (Lattari Mts.) abruptly rising between two large gulfs and coastal plains (Fig. 34.1). The Amalfi Coast is the south flank of the eastern part of the ridge, whose peaks are 900 to over 1400 m high. The Sorrento Peninsula is the western part of the same ridge, whose elevation rarely exceeds 500 m a.s.l.

The area has a climate of the Mediterranean type (mesothermal with summer drought) with average annual temperatures of 21–28 °C at the sea level and 12–14 °C at the highest peaks. Correspondingly, the annual rainfall varies from 850 to 1800 mm. Differently from other calcareous massifs of the Mediterranean zone, the Lattari Mts. are very

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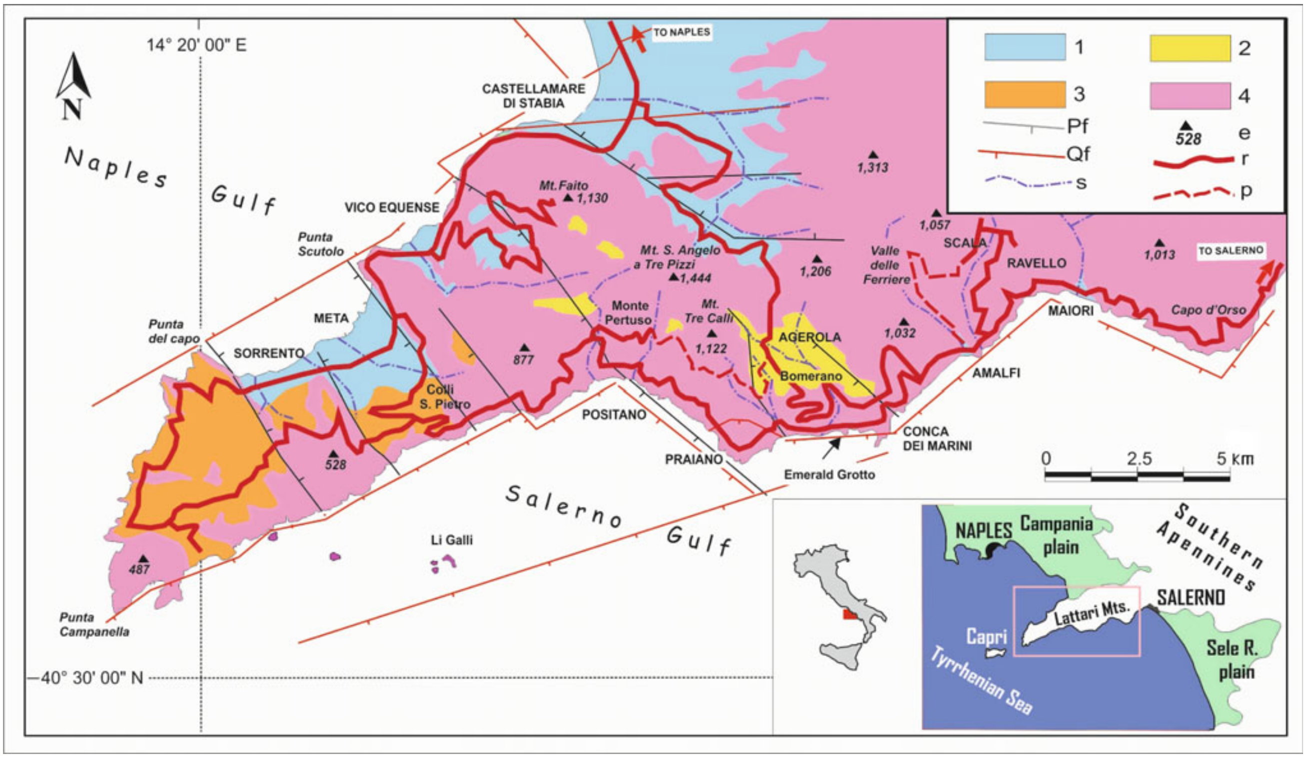

Fig. 34.1 Simplified geological map of the Sorrento Peninsula. *Legend 1* Quaternary deposits (mostly continental sediments and volcanics); *2* Pliocene continental deposits; *3* Miocene marine sediments (mostly sandstones and shales); *4* Cretaceous to Triassic marine carbonate rocks (limestones and dolostones); *Pf* main faults of Pliocene age; *Qf* main faults of Quaternary age; *s* main water courses; *e* main summits and their elevation in m a.s.l.; *r* main roads; *p* pathways mentioned in the text (Bomerano—Positano and Scala—Valle delle Ferriere—Amalfi)

green because they are mantled by pyroclastic material coming from Mt. Vesuvius and other Neapolitan volcanoes. The natural vegetation cover (often replaced by cultivations of lemons, grapes, olives and chestnuts) includes *maquis* up to 300–500 m a.s.l. and mixed deciduous forests as well as birch dominated woodlands above 800–1000 m.

Geologically speaking, the Lattari Mts. belong to the Southern Apennines; a chain segment that formed in Late Tertiary—Early Pleistocene times on a SW-dipping subduction zone. As the subducting slab was also subject to roll back, the chain migrated progressively to the NE while incorporating new and new thrust sheets at its front. Simultaneously, the Tyrrhenian Sea basin was forming and progressively enlarging towards E and SE due to extensional tectonics, at the rear of the chain. The enlargement of the back-arc basin was accomplished by tectonically drowning new and new slices of the chain in the Tyrrhenian Sea. The last episode of this kind occurred in the Early Pleistocene. In the Campania Region two wide coastal grabens were created at that time: the one hosting the Naples Gulf and the Campania Plain and the one hosting the Salerno Gulf and the Sele River Plain (Fig. 34.1). The Lattari Mts. ridge is the horst separating those two grabens; a narrow strip of the Apennines that escaped the collapse and underwent additional uplift (200–350 m) during Lower and Middle Pleistocene (Caiazzo et al. 2006).

In terms of bedrock lithology, the ridge is made of shallow marine dolostones and limestones of Late Triassic to Late Cretaceous age (totalling a thickness of about 4500 m) followed by transgressive synorogenic sandstones and shales of Mid-Late Miocene age (preserved only on the Sorrento Peninsula and up to 500 m thick). Moreover, unconformably on the bedrock there are Pliocene and Quaternary formations (Fig. 34.1) most of which are continental and clastic (talus debris and alluvial fan deposits), but locally of littoral origin and their present elevations indicate the amount of uplift which occurred during the Early and Middle Pleistocene. Finally, there are the pyroclastic materials deriving from ancient explosive eruptions of Mt. Vesuvius and Campi Flegrei; they occur both as matrix of the Late Quaternary clastic formations and as purely volcanic cover on the hill slopes and terraces (ISPRA 2013).

34.3 Landforms and Landscapes

This section describes some representative landscapes and landforms of the area ordered as in an ideal 7-stops visit tour. It departs from Castellammare di Stabia, crosses counterclockwise the area and reaches finally Salerno.

34.3.1 The Sorrento Terrace

The northern coast of the Sorrento Peninsula—well observable from the Castellammare-Sorrento road—shows an alternation of rocky promontories and bays. This depends largely on the presence of NW trending faults creating an alternation of structural highs and lows (Fig. 34.1). On the landward side of the embayments Late Quaternary depositional terraces made of alluvial conglomerates and pyroclastic materials occur. On a couple of such terraces (80–100 m a.s.l.) rests—for example—the town of Vico Equense.

Further ahead, where the road turns around the Punta Scutolo promontory, one comes in sight of the much wider Sorrento terrace (Fig. 34.2). It consists of an even top surface, inclined to the NW by a few degrees, and a bounding sea cliff 40–55 m high. The latter exposes perfectly the deposit that created the former: a tens of metres thick bank of greyish welded tuff belonging to the formation named the Campanian Ignimbrite. Its emplacement occurred around 40,000 years ago upon huge fissural eruptions—emitting about 300 km^3 of materials—from various faults of the Campania Plain graben (Bellucci et al. 2006).

As to the origins of the cliff below the terrace, we have to consider that the Gulf of Naples suffered tens of metres of sudden subsidence soon after the eruption of the Campanian Ignimbrite, while the Sorrento Peninsula remained stable. Consequently, a NE trending fault scarp appeared about 1 km north of Sorrento (Cinque et al. 1997; Fig. 34.1). This straight tectonic scarp may be regarded as the ancestor of the present coastal cliff, whose curved plan shape and more retreated position are due to what happened during the Post-glacial sea-level rise (18,000–6000 years ago) and the following Holocene High Stand. In fact, the reaches where the fault scarp exposed the hard Cretaceous limestones (i.e. off Punta del Capo and Punta Scutolo capes) suffered little erosional retreat while being submerged. On the contrary, 1–1.5 km of retreat occurred in the reach between Sorrento and Meta, where the scarp was made of the ignimbritic tuff and also the underlying, loose continental sediments were easy to

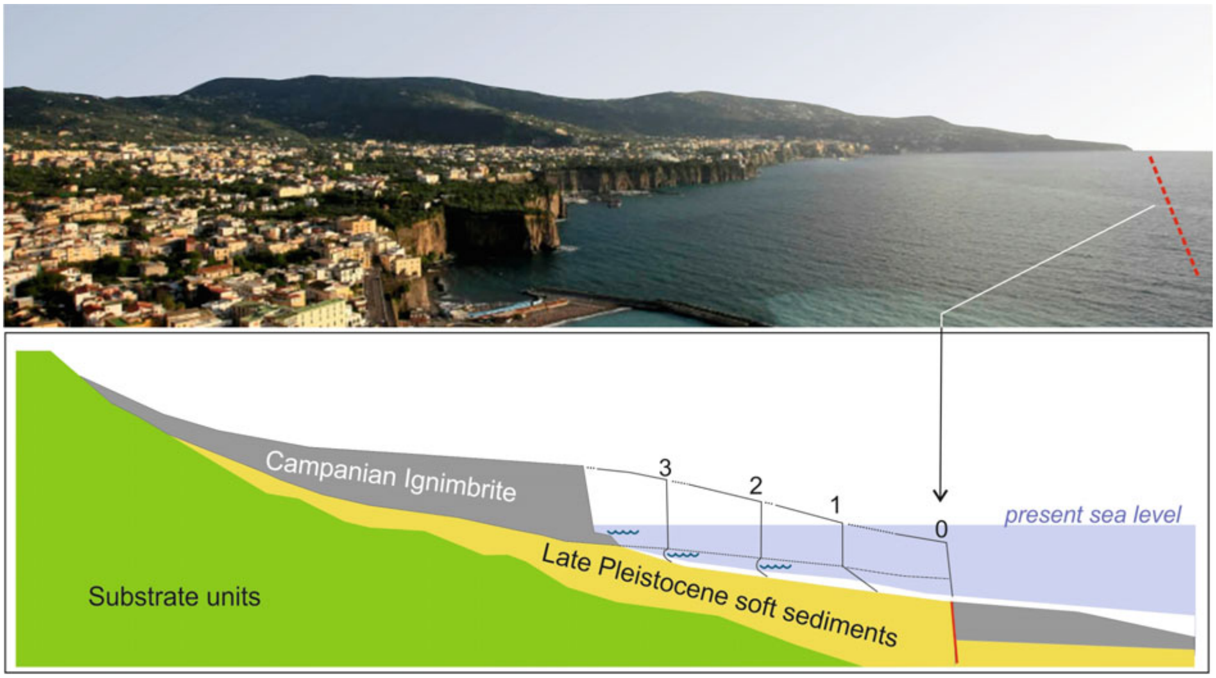

Fig. 34.2 The ignimbritic terrace of Sorrento. The photo is a view from Punta Scutolo (*red line* position of the fault reactivated after the eruption of the Campanian Ignimbrite). The drawing is a SW–NE geological section (not in scale) describing also the post-fault retreat (*0*, *1*, *2*, *3*) of the terrace margin

be eroded by sea waves. The rate of cliff retreat (initially close to 10 cm/year) decreased dramatically when the rising sea level came above the base of the ignimbritic plate (−5 to −20 m) with the consequence that waves started attacking directly the tuff—which is resistant enough—instead of dismantling it (as they were doing before) by removing the underlying soft sediments and provoking falls of tuff slabs.

While visiting the beautiful Sorrento and other towns resting on the same terrace, attention should be also devoted to the gorges that dissect the local tuff.

34.3.2 Views from Colli San Pietro Pass

The Meta-Positano road crosses the Sorrento Peninsula main divide at Colli San Pietro (317 m a.s.l.) and offers views revealing the strong asymmetry of the Peninsula itself, whose southern slope appears much steeper and shorter than the northern one. This is partly due to the NNW dip of the bedrock strata, but what matters even more is the difference in age of the two flanks. In fact, to the north there is a polycyclic morphology that started evolving in Pliocene times, when the area had not been yet reduced to a narrow peninsula; i.e. when the two grabens hosting the gulfs of Naples and Salerno did not exist yet. During the Pliocene the landscape was broken by NW trending faults (Fig. 34.1), but this was followed by a phase of erosion long enough to sensibly smooth the previous fault scarps. When a new tectonic phase reduced the area to a narrow and steep flanked peninsula (Early Pleistocene; Caiazzo et al. 2006), there was a renewal of both fluvial dissection and landslide activity. These erosion phenomena reduced the previous, mature landscape to some isolated remnants on the summits. In the meantime—at lower elevations—the NW trending faults opposing hard Cretaceous limestone to soft Miocene shale had parts of their planes exhumed by differential erosion, adding steep fault-line scarps to the landscape (e.g. the ones flanking the Meta-Sorrento depression).

More simple and short is the history of the southern slope of the Sorrento Peninsula, which is a fault scarp created anew during the Early Pleistocene. It belongs to the long and zigzagging fault-zone that borders the Salerno graben to the north (Fig. 34.1) and shapes the fundamental geometry of the spectacular Amalfi Coast.

Looking south from Colli San Pietro (or other places along the road to Positano) one can see a group of three small islands at about 4 km from the coast (Fig. 34.3). They are now known as Li Galli, while in Hellenistic and Roman times they were called *Seirenoussai* (meaning “Islands of the Mermaids”) because this was supposed to be the place where Odisseus met the mythical mermaids. Geologically speaking, Li Galli and other small islands further west are summits of a limestone block (originally standing hundreds of metres above the sea level) that subsided when the Salerno graben formed.

On the road to Positano one can also note how the coastal fault scarp (originally planar and sub-vertical) has been reshaped by both linear and areal processes of erosion. As normal on limestone hill slopes, the cutting of gullies and ravines was not only mechanical, but also chemical, creating diffuse karstic furrows, notches and other microforms. In the interfluvial sectors of the escarpment the typical cross profile includes (a) an active sea cliff at the base, followed upwards by (b) a segment about 35° inclined. Where the scarp is not higher than about 500 m, “b” reaches up to the top, while scarp sections exceeding that limit, disclose above “b” a third element, that is (c) a residual cliff (still to be consumed), sometimes made more complex (stepped) due to alternations of more and less resistant strata. The “b-c” couple is typical of scarps evolved by “slope replacement”. It implies that the initial cliff (the fault plane in our case) migrates gradually backwards and upslope due to repeated rock falls, leaving below it a gentler element (the “replacing slope”) having just the inclination required to permit the downwasting of the falling coarse debris. The above noted difference between lower and higher reaches of the escarpment at issue tells us that the time elapsed since faulting was insufficient for the complete slope replacement of cliffs higher than about 500 m.

Under the present mild climate, the cliffs produce very little debris and slow karstic degradation prevails on the whole slope. Instead, most of cliff recession occurred during the cold periods of Pleistocene when physical rock weathering was stronger. Consequently, thick screes of debris formed at the base of the scarp, but they are rarely visible today because they are submerged and eroded by the following sea-level rises (interglacial and post-glacial ones).

34.3.3 The Montepertuso Rock Arch and the Surrounding Landscape

As the Lattari Mts. ridge is made mostly of carbonate rocks, its landscape includes also karstic forms. In terms of epikarst, the most diffuse and pronounced forms are solution trenches, furrows and pits occurring where the rock has maintained for long a cover of pyroclastic material speeding up the dissolution process because of its acidic pH and its high water-retaining capacity. In terms of hypokarst, the tens of caverns and galleries so far discovered in the area (Del Vecchio and Fiore 2005) are relatively short, the longest one being the Cave of Scala, a gallery of 280 m. The existence of other hypogean cavities is locally revealed by large collapse dolines like the one hosting the Cemetery of Vico Equense and others nearby. Most of the explored caves were accessed through openings created by either Quaternary faults or canyons

Fig. 34.3 The steep Quaternary fault scarp forming the southern slope of the Sorrento Peninsula. A portion of the much gentler northern slope appears in the *right upper corner*. To the *extreme left* are the Li Galli islets

incised in response to the same Quaternary tectonics. This created also some rock arches, such as the one called *Finestra* (west periphery of Amalfi) and the one below Furore's cemetery, both of them visible from the Amalfi-Agerola road.

The most famous arch in the area (a real landmark) is the one called Montepertuso ("pierced mountain"), giving name also to the nearby hilly hamlet. It is visible from the road connecting Positano to Montepertuso (Fig. 34.4a) and from inside the hamlet. Visitors willing a closer glance may ascend through an ancient stairway of 450 steps (Via Campola) that ends up inside the arch (Fig. 34.4b).

The narrow and cliffed rocky spur that carries the Montepertuso arch belongs to the SW flank of Mt. S. Angelo a Tre Pizzi; a NW trending fault scarp that goes from Positano to Praiano and whose vertical throw (1.5 km) was generated half in the Middle-Late Pliocene and half during the Early Pleistocene (Amato and Robustelli 2002). The second movement, which belongs to the opening of the Salerno Gulf, by adding a very steep basal portion to the scarp, caused the beginning of a still ongoing phase of fluvial dissection of the scarp itself. Among the resulting incisions the longest and deepest one is the wonderful Vallone Porto, admirable from bridges along both the Positano-Praiano and the Montepertuso-Nocelle roads.

The shaping of the Montepertuso spur as a cliffed crest separating two adjacent valley heads can be related to the above mentioned phase of fluvial dissection and to combined processes of cliff retreat. During such events, an ancient karstic system (probably made of galleries and caverns) was unroofed and a small remnant of it became the present Montepertuso rock arch.

34.3.4 The Emerald Grotto

After phases of uplift in the Late Tertiary and in the Early and Middle Pleistocene, the Lattari Mts. attained a final stability. Consequently, relative sea-level change stopped being controlled mainly by movements of the landmass and started being determined only by eustasy (i.e. absolute and global changes of water level in the oceans due mostly to cyclic expansions and contractions of glaciers).

The local record of such Late Quaternary eustatic palaeo-sea levels spans from −120 to +8 m; respectively corresponding to the coolest moment of the Last Glacial (about 18,000 years ago) and to the warmest period of the Last Interglacial (about 130,000 years ago; Riccio et al. 2001).

Eustasy influenced also the evolution of some karstic caves, as it can be seen, for example, in the beautiful Emerald Grotto (Grotta dello Smeraldo) near Conca dei Marini (Fig. 34.5). One can access it either by the special lift located alongside the coastal road or by a boat service departing from the Amalfi port.

The Emerald Grotto is a cavern having a trilobite plan of about 35 by 35 m. Its vaulted roof reaches almost 20 m a.s.l., while its floor reaches 11 m below sea level. Four narrow galleries (two emerged and two submerged) open into the cavern from the mountain interior (NW). To the south, another gallery about ten metres long departs from the cavern and reaches into the plunging sea cliff outside. Its roof is at −7 m and its section (about 6 m wide and 4 m high) reveals signs of an enlargement due to ancient wave erosion. The sunlight penetrating through this submerged

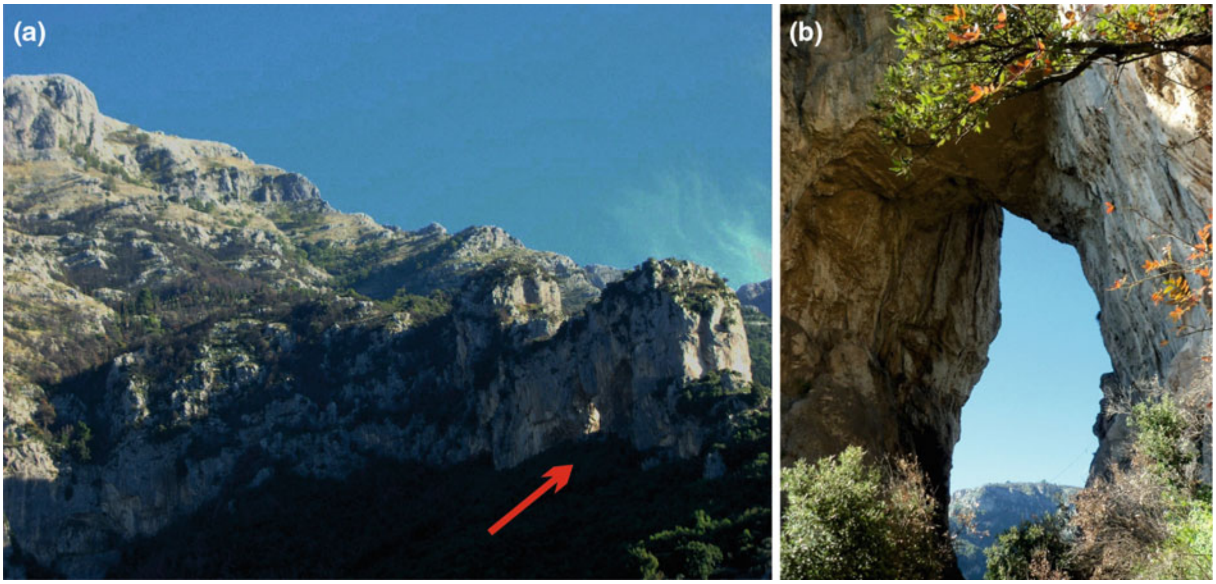

Fig. 34.4 The southwestern flank of Mt. S. Angelo a Tre Pizzi and the perforated rock spur of Montepertuso (*arrow* on photo **a**). Image **b** offers a close view of the arch from the SE

Fig. 34.5 The Emerald Grotto near Conca dei Marini. Note the half-submerged stalagmitic column to the *right* and the bluish light arriving through the submarine entrance tunnel

passage imparts a distinctive emerald colour to both the water and the cave walls.

The first speleogenetic stages of the Emerald Grotto are poorly known. Probably the cavern formed during the Middle Pleistocene upon the enlargement of originally pressurized karstic galleries. At the beginning of the Last Interglacial (about 130,000 years ago), when a strong global warming occurred, the sea level rose enough to reach the cavern and to flood it up to about 8 m above the present sea level. The most striking evidence of such marine transgression can be found on the cavern walls which appear perforated up to the height of 8 m by marine molluscs *Lithodomus lithofagus.* The holes are particularly evident in the western part of the cave, were they occur both on the substrate rock and on the calcite concretions that predate the marine transgression (Colantoni 1970).

Aside from minor sea level fluctuations that occurred during the Last Interglacial, the other major change that affected the cave is the long period of very low sea level characterizing the last glacial period (about 70–15 ka ago). All over that period the Emerald Grotto remained out of sea water and a second generation of calcite concretions formed on its roof, walls and pavement. On the cavern walls these younger calcitic formations can be distinguished from the older one because they show no *Lithodomus* perforations above the present sea level. Two solid and tall stalagmitic columns reaching well below the present sea level can be ascribed to the same younger generation of calcitic formations. As we all know, such columns grow upwards from the floor and cannot form inside a flooded cavern; their present condition shows the sea-level changes that affected the Emerald Grotto in the recent geological past. The cave was partially submerged after the end of the last glaciation and the onset of the current warm period (Post-glacial) due to a rise in sea level of about 120 m induced by melting of ice sheets. The last 10 m of sea-level change, which occurred in the past 7000 years, are well recorded in the Emerald Grotto.

34.3.5 The Suspended Agerola Basin

Overtaking the last curve of the road from Amalfi to Agerola is like making a jump in the geological past. In fact, at that point, one suddenly loses the sight of the steep coastal escarpment (shaped by Quaternary tectonics and erosion) and gains the view of the much gentler landscape characterizing the highest part of the Lattari Mts., which dates back to the Pliocene.

Agerola is composed of four villages resting on terraces between 600 and 675 m a.s.l. These terraces testify to a stage of landscape evolution when the Agerola basin had its floor flattened by alluvial fan deposits discharged by creeks dissecting the flanks (Pliocene fault scarps) of the surrounding mountains. These fault scarps differ from the younger ones of the coastal zone by having unbroken, slightly convex-concave cross-profiles that rarely exceed 30° of inclination; proving that there was enough time not only to complete slope replacement, but also to allow some slope decline after that.

As regards the long-term morphostructural evolution of the Agerola basin, good evidence is found in the area of *Grotta Biscotto* cave, which is along a mule-track called *Sentiero degli Dei* (i.e. Gods path). This pathway, renovated in part during recent times, was created in the early Middle Ages to connect Agerola with Montepertuso and Positano. Nowadays it is a great tourist attraction, as it cuts along the cliffs offering amazing views to the visitors.

The path departs from the main square of Bomerano (one of the villages forming Agerola), passes through a tributary incision of the Praia Valley and—after 600 m—reaches a cliffed rocky spur at the base of Mt. Tre Calli where the Grotta Biscotto cave is located. Here, over a substratum made of extremely fractured Mesozoic strata, there are thick continental conglomerates of the Mid-Late Pliocene. They include two different facies: (a) matrix rich detrital beds dipping 10–15° to NE and (b) beds of angular debris, generally matrix poor, dipping 30–35° to E. The latter represents the rock debris that slid and rolled down from Mt. Tre Calli block soon after its upfaulting with respect to Agerola's one. On the other hand, the sub-coeval facies "a" witnesses an ancient alluvial fan that was fed by a mountain catchment existing SW of the spot. But in that direction there is now a descending topography, not a rising one! (Fig. 34.6). This change of landscape is due to the Early Pleistocene phase of extensional tectonics, which created and progressively enlarged the Salerno Gulf graben by throwing down blocks of the previous relief (Caiazzo et al. 2006).

Of course, the newborn Early Pleistocene fault scarp soon started being dissected by running water and two of the resulting ravines (developing on more fractured rocks) retreated enough to capture the Agerola basin: the Praia and the Penise valleys (Fig. 34.6).

Grotta Biscotto area offers also a good example of rock dwelling (houses built in small caves centuries ago) around which are ancient stairs of artificial terraces that permitted agriculture on slopes as steep as 100%. In many cases, the ground contained in the terraces (weathered pyroclastic material) was not found on the spot, but it had to be collected around and patiently carried there ladle by ladle. The retaining walls (locally called *macerine*) are made of limestone slabs without mortar, so as to ensure a good internal drainage and minimize the soil pressure against the wall itself. Of course, because of the lack of mortar, great attention was paid to proper fitting of the stones and to the maintenance of the walls.

34.3.6 The Canneto River Canyon (Valle delle Ferriere)

Being formed of pervious carbonate rocks, the Lattari Mts. have few perennial streams. One of them is the Canneto River, which debouches on the Amalfi beach (Fig. 34.7). Its valley is named Valle delle Ferriere after the iron mills that have been operating there between the fourteenth and the eighteenth century. However, since the early Middle Ages the same water course has been used to power also grain mills, paper mills and factories of other kinds. The ruins of such early industrial buildings are well worth visiting, also

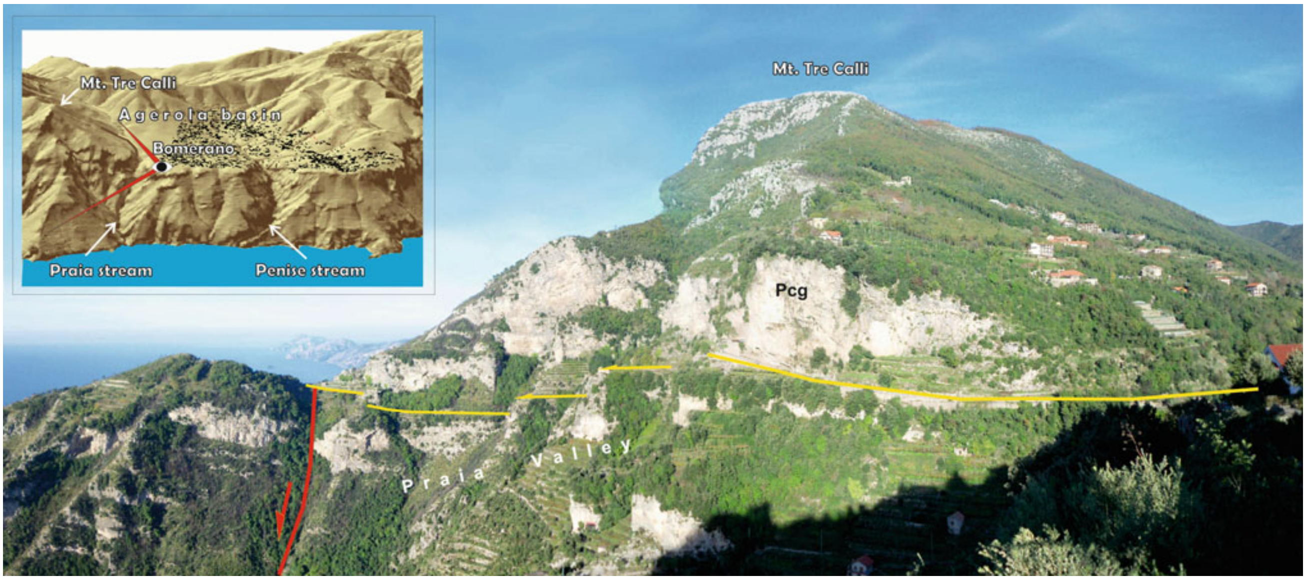

Fig. 34.6 View of Mt. Tre Calli from the southern edge of Bomerano terrace. *Pcg* outcrop of Pliocene conglomerates near Grotta Biscotto; *Yellow line* Sentiero degli Dei pathway; *red line with arrow* one of the faults that truncate the Pliocene landscape. *On the left*, a DEM-derived perspective from the south showing the whole Agerola basin and the coastal fault scarp below it (*eye with rays* location of the photographic shot)

Fig. 34.7 View of the Canneto River canyon from Amalfi

because they are immersed in a landscape of remarkable beauty and great biodiversity. This is especially true for the upper part of the basin, where a governmental protected area was created in 1972.

The Canneto canyon is approximately 5.5 km long, 1–1.5 km wide and up to 800 m deep. It is the greatest fluvial dissection of the whole Amalfi Coast, being surpassed only by some basins originating from tectonic depressions (e.g. Agerola basin). The mentioned primacy depends largely on the fact that here fluvial dissection started both earlier and from higher elevation than elsewhere in the Lattari Mts.

In fact, the mountains through which the Ferriere canyon is cut carries remnants of an Early Pliocene erosional landscape (Caiazzo et al. 2000) in the summit position (1000–

1200 m a.s.l.). This area started being dissected by an ancestor of the Canneto River in Mid-Pliocene times, when the area turned into an uplifted block with respect to the surroundings (e.g. Agerola basin and Scala-Ravello area). Then—in the Early Pleistocene—the formation of the Salerno Gulf graben caused a dramatic truncation of the palaeo-Canneto valley. With this event, the valley portion that remained suspended above the newborn coastal escarpment—suffering also additional uplift—entered the still ongoing period of regressive erosion that has turned it in a deep canyon.

The easiest way to visit the canyon is to follow the path in the valley floor that departs from inside Amalfi. However, for a better view we recommend descending into the canyon from Scala (about 400 m a.s.l.) and then walking along the valley floor path to reach Amalfi. In any case, a place to not miss is Acqualta, a section of the valley floor with beautiful waterfalls, some of which generated by karstic springs in the cliffed sides of the canyon. This place is located at 320 m a.s.l. beyond the gate leading to the protected area. Here the spray released by the falling water creates a condition of abundant and constant moisture that allows the presence of a luxuriant vegetation, including rare plants such as the giant subtropical fern *Woodwardia radicans,* two species of *Pteris* and several others.

Downslope of some springs, the wet slope is densely vegetated by moss and herbs. As they subtract CO_2 to the spring water passing on them, the dissolved calcium bicarbonate precipitates as calcite, so encrusting the vegetation carpet and forming lobes of calcareous tufa.

Where lying on steep slopes—or against cliffs—those lobes disclose an internal structure that includes curtain-like and stalactite-like pendants of encrusted vegetation.

Fluvial deposits are rare in the upper-middle reach of the valley, consisting of few patches of gravels accumulated upstream of obstacles given by blocky rock fall deposits. On the contrary, valley floor aggradation is widespread in the lowermost reach of the canyon, and a recent drilling near the river mouth has proved that bedrock rests at least 40 m below the present sea level. This datum combines well with the submerged mouths of the Praia and Penise valleys, narrating the downcutting occurred upon the marine regression of the last glacial periods of the Pleistocene.

34.3.7 The Capo d'Orso Promontory

The portion of Lattari Mts. located east of Maiori exposes the lower part of the Mesozoic sequence (Triassic strata). During diagenesis, this part had the calcium ions partly replaced by magnesium, so that dolomite ($CaMgCO_3$) instead of the original calcite ($CaCO_3$) became the dominant mineral and—therefore—the rock type changed from limestone to dolostone.

In general, dolostones are a little less pervious, less soluble and more erodible than limestones, and confirmation of this can be found by comparing landforms of the mountains east of Maiori with the ones observable on the limestones dominating the area around Positano and Agerola.

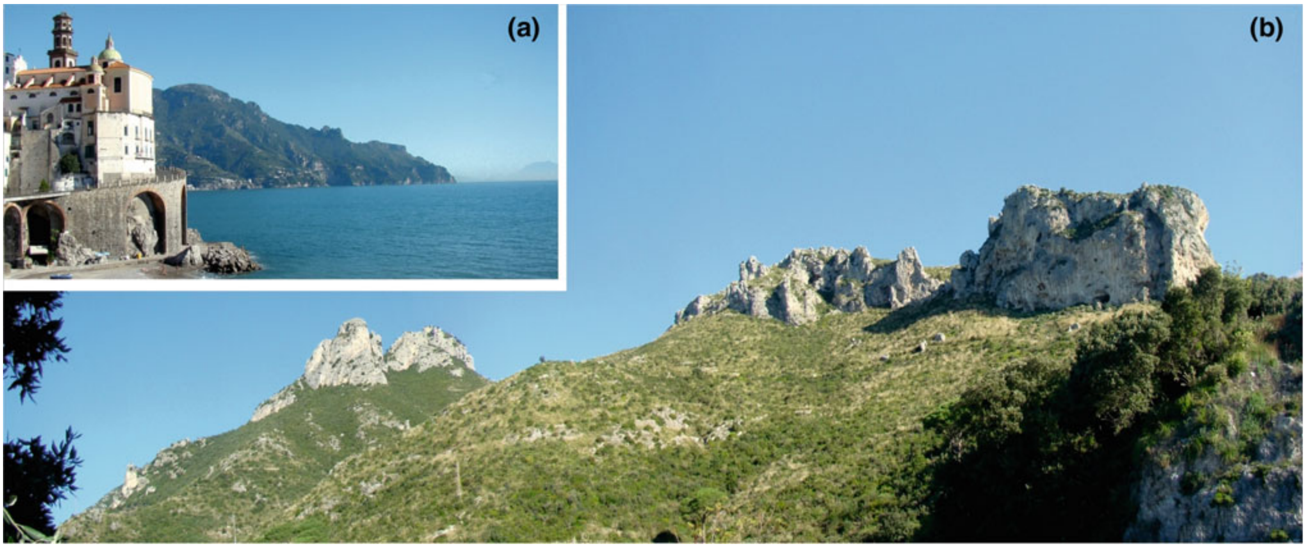

Fig. 34.8 Capo d'Orso promontory. General view from Amalfi (**a**) and the group of pinnacles visible from the coastal road while turning around the promontory end (**b**)

Following the road going from Maiori to Salerno, we go across the dolomitic Capo d'Orso promontory (Fig. 34.8) and observe that here the frequency of erosional valleys and ravines is clearly higher than in the western part of the Lattari Mts., because runoff is higher on dolostones and because this rock type—when exposed to weathering—disintegrates in fine particles easier to be washed away.

Other points of difference are that here—on the dolomitic part of the ridge—karstic landforms are more rare, sea cliffs are less precipitous and, finally, fault scarps—being more dissected by streams—have their original planarity less preserved than fault scarps in the calcareous part of the ridge.

Peculiar of Capo d'Orso are also landforms due to "selective erosion". They are due to the circumstance that the degree of dolomitization varies from place to place within the rock mass, so as to make variable the rock resistance to erosion. Consequently, processes such as backwearing of slopes and downwearing of crests did not proceed uniformly, resulting in the formation of spurs alternating with hollows, or pinnacles and towers alternating with saddles, where fully and poorly dolomitized rocks occur side by side.

Some of these features can be seen even from a distance in the outline of Capo d'Orso (Fig. 34.8), while a closer look at an interesting group of pinnacles of different shape and degree of evolution is possible from the point where the coastal road turns around the cape (Fig. 34.8).

Another recommended stop along the coastal road (km 39) is the small monastery of Santa Maria de Olearia, built in a cavern and displaying interesting features of Byzantine architecture along with frescos dating to the tenth century. The cavern opens in a coarse-grained conglomerate belonging to an uplifted and much dissected alluvial fan of Middle Pleistocene age.

34.4 Conclusion

The suggested visit tour across the Sorrento Peninsula and the Amalfi Coast permits to appreciate how much the present landscape of Southern Apennines is influenced—especially to the SW—by events of extensional block faulting occurred in Quaternary times, when the Tyrrhenian Sea basin had its last pulse of enlargment.

By creating high fault scarps, truncating pre-existing mature landforms and also triggering deep fluvial dissection, said tectonic events laid the foundations of the great physical beauty of the area.

Especially along the Amalfi Coast, this beauty couples with terrain roughness so often to determine remarkable settlement limitations. But the latter were brilliantly surmounted during Early Middle Ages, as the occurrence of widespread terracing works, ruins of factories and sparse towns rich of monuments demonstrate.

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35

The Coastal Landscape of Cilento (Southern Italy): A Challenge for Protection and Tourism Valorisation

Alessio Valente, Paolo Magliulo, and Filippo Russo

Abstract

A striking coastline, about 100 km long, characterizes the southernmost part of the Campania region. It is comprised within one of the largest National Parks of Italy, named "Cilento, Vallo di Diano and Alburni Park". The coast preserves a great number of geological and geomorphological features, frequently well integrated with anthropic structures, which makes it a unique landscape. The morphology of the coastal area of the Park is characterized by hills sloping down to the sea, where alternate bays with small beaches and rocky headlands, hosting a large number of Norman-Aragonese watchtowers. Limestone cliffs display impressive karst landforms, such as caves, which have undoubtedly favoured human presence since the Middle Paleolithic. In this suggestive landscape several landforms and deposits permit to reconstruct the Quaternary-aged sea-level changes.

Keywords

Coastal processes • Geomorphosites • Prehistoric traces • European Geopark Network • Cilento

35.1 Introduction

Beyond the sandy beaches of the Sele River Plain, with the background of the ancient temples of the Greek village of Poseidonia, currently known as Paestum, a large rocky promontory called Cilento juts out into the sea. In its coastal portion, it is characterized by the presence of steep cliffs, reshaped mainly by waves. These cliffs are mostly interrupted, in their spatial continuity, by steep and narrow valleys, in which short and ephemeral streams flow. At the mouths of these streams, small-sized pebbly beaches are present. The sculpting of the cliffs is faster where soft and mechanically weak Tertiary-aged flysch deposits outcrop, while it is slower where the bedrock consists of Mesozoic limestones, markedly more resistant to erosion.

The coastal landscape is here fairly diverse, as the morphogenetic processes, mainly related to the wave action, are currently different from the past (Baggioni 1975). The evidence of past marine processes are the numerous and sometimes suggestive landforms that are preserved along the cliffs. The setting of these landforms also emphasizes the tectonic movements that disjointed the Cilento area, making the orographic setting of these places unique and spectacular. However, to reduce the growing threat from mass tourism and connected economic land speculation, protection and enhancement strategies are needed.

The establishment in 1995 of the National Park of Cilento, Vallo di Diano and Alburni was aimed to reach these objectives. The Park includes almost the entire portion of the Cilento coast including the marine protected areas of Licosa—Santa Maria di Castellabate to the north, and Porto Infreschi to the south. Furthermore, the recent inclusion of the Park as part of the European and Global Network of Geoparks is a major achievement (Aloia et al. 2012). This inclusion emphasizes not only the desire to enhance the

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geological heritage, but also to develop initiatives aimed at sustainable development of this area.

35.2 Geographical and Geological Setting

The Cilento coastland, about 100 km long, is located in southwest sector of the Italian peninsula (Fig. 35.1), between the Salerno and Policastro gulfs, at the eastern margin of the Tyrrhenian Sea. The coast is always accessible by roads and footpaths, except for the southernmost stretches, where no roads and no buildings were built up.

The climate is temperate, with mean annual temperatures of about 17 °C (12.6–20.8 °C) and mean annual rainfall ranging from 730 mm in the northern sector to 790 mm in the southern one. The precipitations are concentrated in spring and late autumn, while long dry periods occur during summer.

The most important geomorphological controls are the geological setting, the rather homogenous marine energy and the precipitation regime, and, in particular, the frequent exceptionally intense rainfall events after prolonged periods of drought. The action of humans, both along the coast and in the hinterland, may also cause significant changes in the dynamics of marine and subaerial processes. These define the rates of erosion, sediment transfer and beach accumulation.

The Cilento area falls within the Southern Apennines fold-and-thrust belt, which developed between the Late Cretaceous and the Pleistocene, as a consequence of the interaction between the European and the African plates as well as of the spreading of the Tyrrhenian oceanic basin, located immediately to west (Patacca and Scandone 2007). The geological setting (Fig. 35.1) was determined by several tectonic phases, in which the sedimentary units, deposited since the Triassic, were progressively involved from west to east. The westernmost sedimentary unit, as well as the evidence of the Middle Miocene overthrusting of the latter on the nearest eastern unit, is exposed only in Cilento. A Neogene synorogenic unit was deposited in a basin, which was formed on the previously deformed units. Nowadays, this synorogenic unit is the most widespread in Cilento. At last,

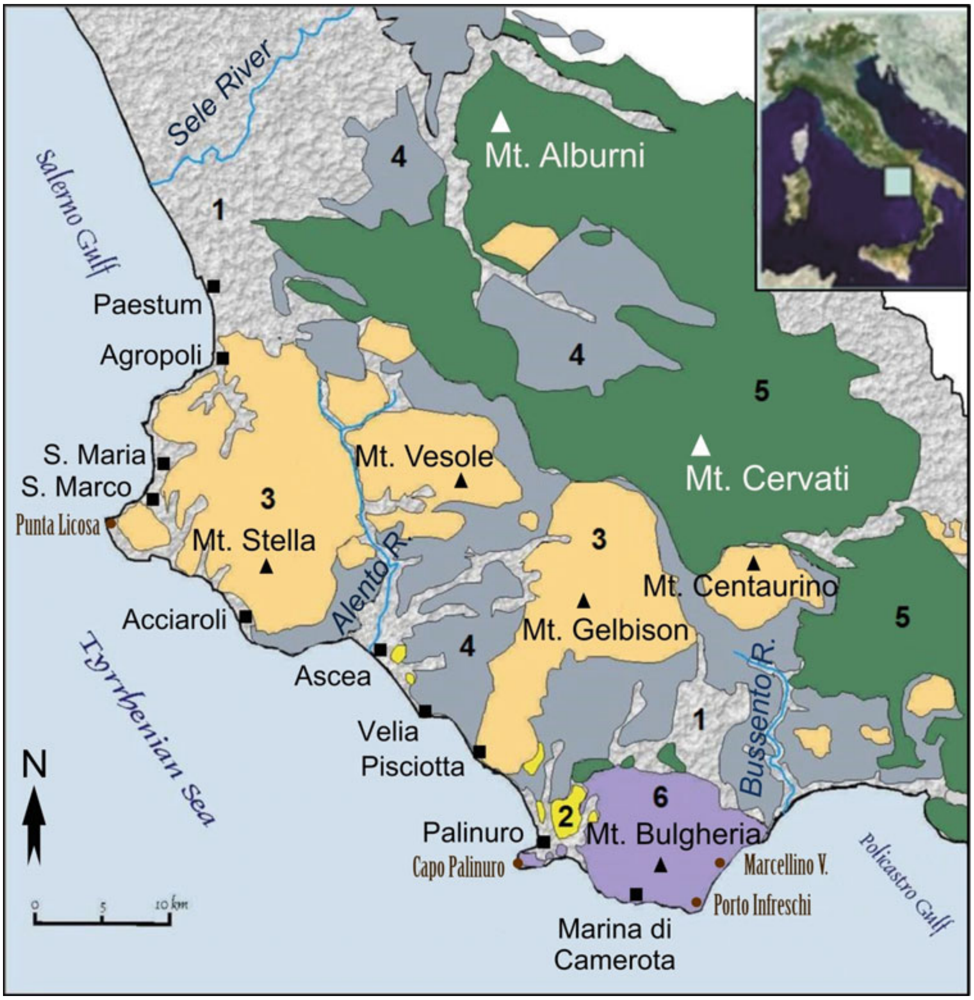

Fig. 35.1 Schematic geological map of Cilento. *Legend* (*1*) recent Quaternary deposits; (*2*) ancient Quaternary deposits; (*3*) Neogene synorogenic units; (*4*) North-Calabrian Unit (Lower Miocene–Late Cretaceous); (*5*–*6*) Bulgheria and Alburno-Cervati Units (Lower-Middle Miocene–Late Triassic) (see the text for details)

the Quaternary post-orogenic deposits accumulated mainly during the cold climatic stages, during which the slopes, scarcely protected by vegetation against erosion and subject to intense physical degradation phenomena, supplied huge amounts of detritus that infilled the morphological depressions located below.

More precisely, the westernmost sedimentary successions, named North-Calabrian Unit (Patacca and Scandone 2007; Vitale et al. 2010) (Fig. 35.1, Unit 4), include marly calcarenites, calcilutites, clays, often siliceous, with sandstones and rare conglomerates, which were deposited in a pelagic basin between the Late Cretaceous and the Lower Miocene. The main outcrops of these successions, strongly deformed and slightly metamorphosed, are located in the hilly coastal area and on the face of the most of sea cliffs (Fig. 35.2a).

The North-Calabrian unit overthrusts both the Bulgheria Unit and the Alburno-Cervati Unit (Patacca and Scandone 2007) (Fig. 35.1, Units 5–6). The latter are made up of carbonate sediments from Late Triassic to Lower-Middle Miocene in age, related to sedimentary environments ranging from shallow water, mainly in a back-reef area of a carbonatic platform, to relatively deep water of a sedimentary basin, whose depth increased with time before it was tectonically deformed. This deepening affected first the Bulgheria Unit, currently outcropping in the southern coastal area of Cilento (Mt. Bulgheria, 1225 m a.s.l.) (Fig. 35.2b), and then the Alburno-Cervati Unit, which is much more widespread in the southern Apennines and well exposed along the highest tracts of terrain in the internal areas of Cilento (e.g., Mt. Cervati, 1898 m; Mt. Alburni, 1742 m).

In the Neogene synorogenic units, several formations of Middle to Late Miocene age are grouped (Patacca and Scandone 2007) (Fig. 35.1, Unit 3). They consist of clays, sandstones and conglomerates, locally with significant marly interbeddings. They were mainly arranged in turbiditic deposits, generally lying unconformably on the previously mentioned units. These turbidites occurred within a deep sea fan developed at the base of a submarine slope. The Cilento Group (Cavuoto et al. 2004) crops out mainly in correspondence of the Stella, Gelbison and Centaurino coastal reliefs, as well as along the northern cliffs of Cilento (Fig. 35.2c).

At last, in the Quaternary post-orogenic units, all the continental and marine sediments deposited after the final emersion of the area (Late Pliocene—Early Pleistocene) are comprised (Fig. 35.1, Units 1–2). As regards the coastal outcrops, these groups are chiefly represented by conglomerates, roughly stratified, outcropping along the western portion of Mt. Bulgheria (Ascione and Romano 1999), fluvial sediments, both ancient and recent, distributed along the valleys of the main rivers (i.e. Alento and Bussento), and ancient aeolian sands and marine deposits (Early to upper Pleistocene in age), related to different sea levels, widespread along the coast of Cilento (Antonioli et al. 1994; Cinque et al. 1994).

35.3 Coastal Landforms

The coastal landscape of the Cilento is characterized by a succession of promontories and inlets, the latter generally small-sized, except at the mouth of the Alento River. Within the inlets, the deposition of sandy and/or gravelly sediments frequently occurs, and therefore beaches can form, albeit restricted and often bounded by steep slopes (Baggioni 1975) (Fig. 35.3). On promontories and on the mountain slopes reaching the sea, the wave energy increases, and so these sections of the coastline are generally affected by erosion (Baggioni 1975). The consequent coastal retreat is controlled by the interactions between several factors, such as the outcropping lithology, the morphological profile and the wave regime. The cliffs, especially when they are more than 100 m high, become particularly scenic, as is in the southernmost stretch of the Cilento, to the south of Capo Palinuro.

The Mesozoic carbonate rocks that are well exposed along these cliffs offer considerable resistance to erosion induced by waves. However, the presence of discontinuities on the wall (e.g. fractures, bedding surfaces, karst cavities) can accelerate the retreat and facilitate the formation of minor coastal landforms on the cliff or at the adjacent sea bottom. Among minor landforms, particularly characteristic are marine abrasion platforms at the foot of the cliffs and sea-notches incised at the level of the sea, and even below. These landforms, which are often associated with the deposition of sediments, are well preserved along the southern coast of Capo Palinuro, also at heights different from those at which they currently form. Therefore, their analysis represents a powerful tool to understand the Quaternary-aged sea-level changes.

Many landforms in the Cilento geomorphological landscape can be considered as geomorphosites according to Panizza (2001). In fact, several landforms, being representative of a process or event, “have acquired a scientific, cultural/historical, aesthetic and/or social/economic value”. The integration of each landform with the biological, historical, social and cultural values increases its importance and makes the Cilento coastland unique (Aloia et al. 2012).

Some of these landforms are also useful to reconstruct and understand the uplift history, and then the displacements that affected this stretch of coastline over time. For this reason, the coastal slopes appear typically segmented from the highest terrace positioned at 400 m a.s.l. (Borrelli et al. 1988), presumably formed in the Early Pleistocene, to the successively lower positions at 170/180, 130/140, 100/110,

Fig. 35.2 Examples of coastal cliffs. **a** Punta del Telegrafo, in front of Velia: outcrop of folded calcilutites and shales (Lower Miocene—Oligocene); *on the top* a tower of the coastal defence system of sixteenth century; **b** Cala di Monte della Luna, near Marina di Camerota: outcrop of *light grey and black* dolomite (upper Triassic); **c** cliff supported by flysch deposits (Middle-Upper Miocene) in the northern Cilento, near Punta Licosa

65/75 m and finally 50 m (Ascione and Romano 1999) (Fig. 35.4a). The difficulty to correctly date these terraces is mainly due to the lack of deposits. Downslope to the cliffs, other landforms shaped more recently by marine erosion (e.g. platforms and sea-notches), with associated marine and continental deposits, are present. In particular, at Lido

Fig. 35.3 Coastal stretch to the south of Marina di Camerota

Ficocelle, to the northwest of Palinuro village, a complete sedimentary sequence of Upper Pleistocene (Tyrrhenian) is well exposed along a cliff located upslope to a terraced surface at 2 m a.s.l. The sequence consists of coastal sands arranged in sets of layers with horizontal and oblique sedimentary structures, typical of a submerged and emerged beaches, covered by sand dunes (Antonioli et al. 1994) (Fig. 35.4b).

Locally, the retreat of the cliffs also left remnants on the adjacent seabed, so the latter looks articulated, with small terraces, arches and rocks emerging from sea. Among these, the natural arch of Palinuro is particularly important. It displays maximum height of 12 m and its width ranges between 15 and 10 m (Fig. 35.5). It formed during the last interglacial (about 100 ka BP), due to fracturing and the following collapse of the Jurassic limestone strata. At that time, the sea level was about 6–8 m higher than today. Subsequently, the re-emergence of the arch due to the sea-level lowering intensified wave action that nowadays continues to erode it. To prevent or delay the complete destruction of this spectacular landform, a submerged barrier was built and an artificial nourishment of the contiguous beach was carried out.

Another typical characteristic of these coasts is the great abundance of caves, whose entrances are located just above the sea level, or entirely below. The genesis of these caves is related mainly to karst phenomena that affect the limestone and dolomite in which the caves are shaped. In this chemical action, the role of the waves cannot be overlooked, as they enlarge each small cavity. Hence, a myriad of caves of various dimensions appear along this stretch of the Cilento coast, such as the Blue Caves near Capo Palinuro, or the caves of Noglio and Santa Maria, near Marina di Camerota, just to mention the most beautiful ones (Fig. 35.6). Inside them, we can admire stalactites, stalagmites and columns, but we can also observe, below the sea level, a large variety of plant and animal species growing in a particular environment referred to as “semi-dark caves”. These caves were inhabited by man since the Paleolithic period, as evidenced by the artefacts found within them (Benini et al. 1997).

On the high and rocky coasts shaped in the successions of the Tertiary-aged flysch, which can be observed in the remaining sections of the Cilento, the erosive action is more effective than that described above. The rates of retreat are significantly higher due to the lower mechanical resistance. Erosional processes are not limited to marine ones, but also include subaerial processes, acting on the emerged portion of the coast. The latter, generally less steep and lower than the carbonate cliffs, is usually covered by debris on which typical Mediterranean vegetation grows.

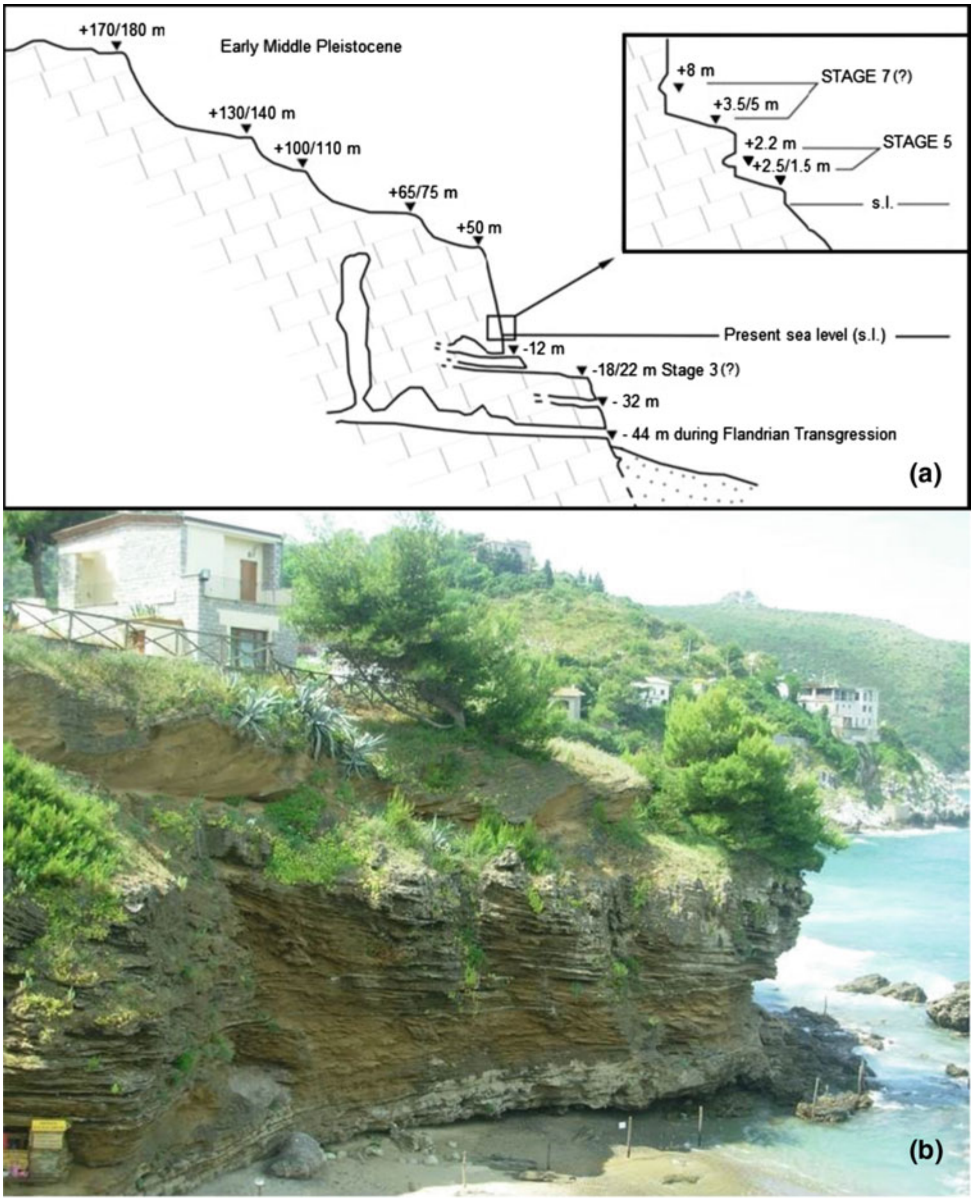

Fig. 35.4 Landforms associated to paleo-sea levels. **a** Sketch of terraced surfaces along the southern calcareous slope of Mt. Bulgheria; the highest terrace, at 400 m a.s.l., is not present in this cross-section (modified after Antonioli et al. 1994); **b** detail of the Tyrrhenian-aged (Marine Isotopic Stage 5) coastal sands outcrop at Palinuro village (Lido Ficocelle)

Landslides, sometimes of considerable size, occur due to different conditions of permeability between the cover and the bedrock, in response to significant changes in the amount of rain during the year, and to the constant action of waves at the base of the slopes. Among them, rotational slide of the coast of Pisciotta covers a large area and threatens important roads and railway infrastructures. The spread of these phenomena makes difficult to preserve coastal landforms on the cliffs shaped on flysch deposits. However, it is possible to observe, for example, a hanging marine abrasion platform dated back to the Middle Pleistocene (Marine Isotopic Stage 7: between 245 and 190 ka), clearly distinguishable at a height of about 20–25 m a.s.l. in the coastal profile of Licosa (Cinque et al. 1994) (Fig. 35.7). In the same profile, it is possible to recognize other, less-evident terraced land surfaces, which are younger and less elevated than the previously described one, due to rising sea levels reached during the late Pleistocene (Marine Isotopic Stage 5: 125 ka and 75 ka BP; Cinque et al. 1994; Ferranti et al. 2006). This is confirmed by the analysis performed on the major sedimentary successions of dune and marine environment that are associated with these abrasion landforms. The latter assume high geomorphological significance, as they can be followed with reasonable continuity for the entire coast of Cilento, unlike other coastal stretches of the Tyrrhenian coast.

As already mentioned, in the inlets of the Cilento coast, several beaches, mainly made up of sands, are currently developing. The most important ones are located between Santa Maria di Castellabate and San Marco di Castellabate,

Fig. 35.5 Natural arch shaped in Jurassic limestone, to the west of Capo Palinuro; in the *background* is the Cefalo beach, more than 3 km long

to the north of Punta Licosa and, finally, the largest one occurs at the Alento River mouth. This latter beach is about 8 km wide, is located at the end of a small coastal plain and can be divided into two sections. In the northernmost one, several man-made structures have been erected on the back-dune ridges, while in the southernmost one, the dune ridges are currently almost in their natural state (Cinque et al. 1995). Along the first section, as well as in other beaches mentioned above, where erosion has become significant, some defence structures, such as breakwaters and walls, were made.

At the southern end of the Cilento coastline, rocky cliffs protect small bays, not accessible by car, such as Cala Bianca and Porto Infreschi (Fig. 35.8a), or restricted coves, such as the Marcellino Valley (Fig. 35.8b). Inside them, strips of pebble beach were formed. According to the recent Italian inventory, Cala Bianca, near Porto Infreschi, is considered one of the most beautiful beaches of Italy, with its shining sediments and transparent shallow seabed. Porto Infreschi includes a rich geological heritage constituted by a number of indicators related to ancient sea levels (sea-notches, marine terraces and fossil deposits). Among these, the ones formed in the early Late Pleistocene (before 111 ka BP; Esposito et al. 2003) are evident (Fig. 35.8a). However, in the Marcellino Valley, a coastal gorge more than 350 m deep, landforms generated in a morphoclimatic scenario different from the present one are well preserved (Baggioni 1975; Borrelli et al. 1988) (Fig. 35.8b).

Fig. 35.6 Noglio Cave, to the west of Marina di Camerota; the entrance is at 5 m a.s.l.

Fig. 35.7 Aerial view of the Licosa promontory with the homonymous island. Note the well-preserved Tyrrhenian marine terrace from the foot of slope to the sea at 8–10 m a.s.l. (courtesy of National Park of Cilento, Vallo di Diano and Alburni)

35.4 The Imprint of Man

The coastal landscape of Cilento, despite the fact that, in several sections, it remained intact from a naturalistic point of view, retains traces of the action of man since ancient times. Earlier, this action was integrated with the territory, but recently it has brought substantial changes to the landscape, sometimes without any integration with the natural components and processes. Some of these interventions (coastal defence works, tourist resorts) have already been mentioned while describing the coastal landforms, while others, especially those integrated into the landscape, will be analysed briefly here, because they are not always recognizable by an observer.

The continental sediments that overlie marine deposits, or are interbedded with them, contain very significant traces of ancient human activities. These traces consist of tools for hunters and remains of settlements or temporary camps (hearths, pottery, etc.). The oldest formations date back to the Lower Paleolithic and were found in some locations around Marina di Camerota. They contain tools related to lithic industry known as Acheulean, dated back approximately to 500 ka BP. The middle Paleolithic artefacts were found more extensively in the surroundings of Capo Palinuro and Marina di Camerota. They contain advanced tools of the Mousterian, a technique that was developed prior to 35 ka BP. In this latter case, the Neanderthal hunters took shelter from the conditions of the cold climate of the last glaciation, especially in coastal caves.

One of these caves, named “Grotta della Cala”, located to the east of the village of Marina di Camerota, close to the beach, is almost entirely filled with continental sediments (talus breccias, aeolian and colluvial sands and silts), speleothems, stalagmites and brown soils, that are associated with a rich and almost continuous archaeological sequence from the middle Palaeolithic to the Bronze Age (Benini et al. 1997).

Remains of Greek and Roman settlements are mainly located in low-lying areas along the coast. The site of Velia (Fig. 35.9), in the coastal plain of the Alento River, is considered the most important one, being included in the UNESCO World Heritage List. The ruins are located on the

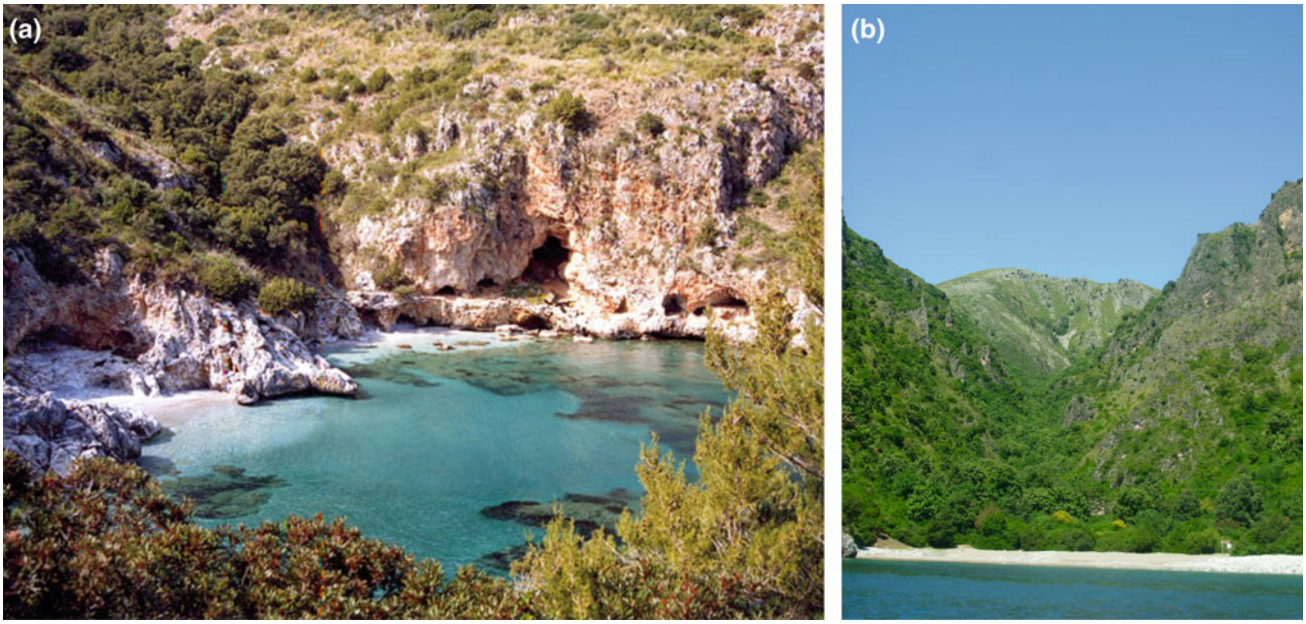

Fig. 35.8 Coastal landforms in Cilento: **a** Porto Infreschi, where the sea cliff displays various erosional indicators of ancient sea levels (wave-cut terrace at 4.5 m and sea-notches at 8.0 m and 3.5 m a.s.l.); inside the caves, a Mousterian lithic industry was found. **b** The beach at the mouth of Marcellino coastal gorge

Fig. 35.9 Velia: in the *foreground*, the ruins of the archaeological area (southern quarter); in the *background*, the structure of a medieval castle, the so-called "Angioina Tower" and several other remains are present

hillside that faces the sea, and include structures among which the oldest are dated back to the fifth century BC. These are the theatre, thermal installation, the sanctuary, the acropolis and the so-called "Porta Rosa" (fourth century BC), a beautiful stone-vaulted structure. The inhabitants of Velia were of Phocians origin, i.e. they came from the present western Turkey. Their economy was almost entirely based on fishing and maritime trade. These activities were carried out by using a port which nowadays is completely filled by the alluvial sediments of the Alento River. These sediments, emplaced during huge flood episodes, together with other ones referred to marine inundations induced by significant storm surges, were the results of several environmental crises (Ortolani et al. 1991). These crises, which also occurred at the site of Paestum, not far from Velia, led to the abandonment of the area due to the unhealthy conditions that had developed. Today, both archaeological sites, with their wonderful temples, are among the major tourist and cultural attractions of the Cilento coast. In addition, Velia, also known with the Greek name of Elea, was the seat of the pre-Socratic philosophical school founded by Parmenides and Zeno.

Finally, on these headlands one can see the ancient watchtowers, typically made with a square base. They were built in the sixteenth century as a system of defence from the raids of the Saracens, like that of San Marco of Castellabate, of Caleo at Acciaroli, or near the Punta Telegrafo, close to Ascea (Fig. 35.2a).

35.5 Protection and Valorization

The coastal landscape of Cilento has already shown a priceless heritage derived from the harmonic integration between natural environment and man-made settlements. In order to protect, in particular, the shores of Cilento, as well as the beautiful inland areas, the National Park of Cilento, Vallo di Diano and Alburni was established in 1995. It is unquestionably one of the most important biogeographic areas in southern Italy. It is also the first national park in the Mediterranean that has been included in the list of UNESCO World Heritage in the category of “cultural landscapes” as one of global significance. It was later included in the network of Biosphere Reserves of UNESCO program “Man and Biosphere”, whose objective is to maintain a long-lasting balance between man and his environment through conservation of biological diversity, promotion of economic development and preservation of cultural values. In 2010, it finally became part of the European and Global Network of Geoparks, being able “to tell”, in a comprehensive manner, the geological evolution of an area through its significant heritage, well integrated with the historical sites and cultural traditions.

The aim of safeguarding the territory does not end with the establishment of the National Park. In fact, two new marine protected areas have been set up recently: Licosa—Santa Maria di Castellabate in the north, and Porto Infreschi Coast to the south. Despite being different in the type of coast emerged, they both offer an underwater environment that host a wide variety of organisms.

Along the coast, there are also museums dedicated to the sea and its attractions (e.g. Acciaroli, Marina di Camerota). They represent centres of environmental education on marine and coastal ecosystems, but also indicate the attention of the resident population to conservation, protection and enhancement of the most vulnerable natural environments.

These particular actions, aimed at the protection of the landscape, are threatened by massive tourist exploitation of the coast, especially during summer. For this reason, several objectives must be pursued with the contribution of the park management, the municipality administration and the visitors of the Cilento coastland. In particular, everyone should raise the awareness of environmental conservation. To this aim, making the landscape easily “readable” in terms of landforms and processes, also by means of innovative media, could greatly help. In this framework, also the scientific community has an important role to communicate the knowledge about the coast, its landforms, processes and hazards.

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The Salento Peninsula (Apulia, Southern Italy): A Water-Shaped Landscape Without Rivers

36

Giuseppe Mastronuzzi and Paolo Sansò

Abstract

The Salento peninsula is the ‘heel of the boot’ drawn by the perimeter of the Italian coastline. It is placed to the south of the alignment Brindisi-Taranto cities, between the Ionian and the Adriatic seas. Its geological structure is made of a thick Mesozoic carbonate sequence covered by Tertiary and Quaternary deposits. Landscape evolution is the result of the interaction between tectonics, karst and marine processes controlled by climate and sea-level changes. The landscape of Salento peninsula is mainly composed of landforms shaped by the action of waters, both continental and marine ones, notwithstanding it is known to be currently a region without extended surficial drainage catchments.

Keywords

Coastal landforms • Karst landforms • Sapping valleys • Salento • Apulia

36.1 Introduction

The Salento Peninsula (southeastern Apulia) (Fig. 36.1) shows a rather flat landscape marked by low-elevated Mesozoic carbonatic ridges separated by grabens filled with Cenozoic sediments. A staircase of marine terraces can be recognized at different locations along the coastal area, whereas deep canyons engrave the entire stratigraphic sequence.

The Salento peninsula landscape hosts a number of pre-Quaternary subaerial landforms formed during a long period lasting from the end of Mesozoic to the Oligocene. A tropical karst landscape developed, mostly represented by wide and flat-floored dolines, along with an extensive bauxitic cover. A shorter karst morphogenetic phase occurred at the end of the Lower Pleistocene. Since then, landscape evolution was driven by the superimposition of regional tectonic uplift, started in the Middle Pleistocene, on the eustatic sea-level change.

For its long geomorphological history, Salento’s landscape is only apparently even. In fact, notwithstanding the high permeability of rocks that prevented the development of a well-organized hydrographic network, the action of water in the subsoil promoted the genesis of deep canyons and numerous caves, some of them exploited by humans from the Upper Paleolithic to the Neolithic.

36.2 Geographical Setting

The Salento peninsula is the southernmost part of the Apulia region; it stretches for about 120 km in NW–SE direction between the Ionian and the Adriatic Sea (Fig. 36.1). Historically, the Salento peninsula is the region placed to the south of *Soglia Messapica*, i.e. the line joining Taranto, on the Ionian coast, to Brindisi, on the Adriatic one. This area was first populated by Messapians, an ancient people who lived there since the eighth century BC; they were conquered by Romans in the second century BC. The Salento peninsula was under the Byzantine Empire until the arrival of Normans

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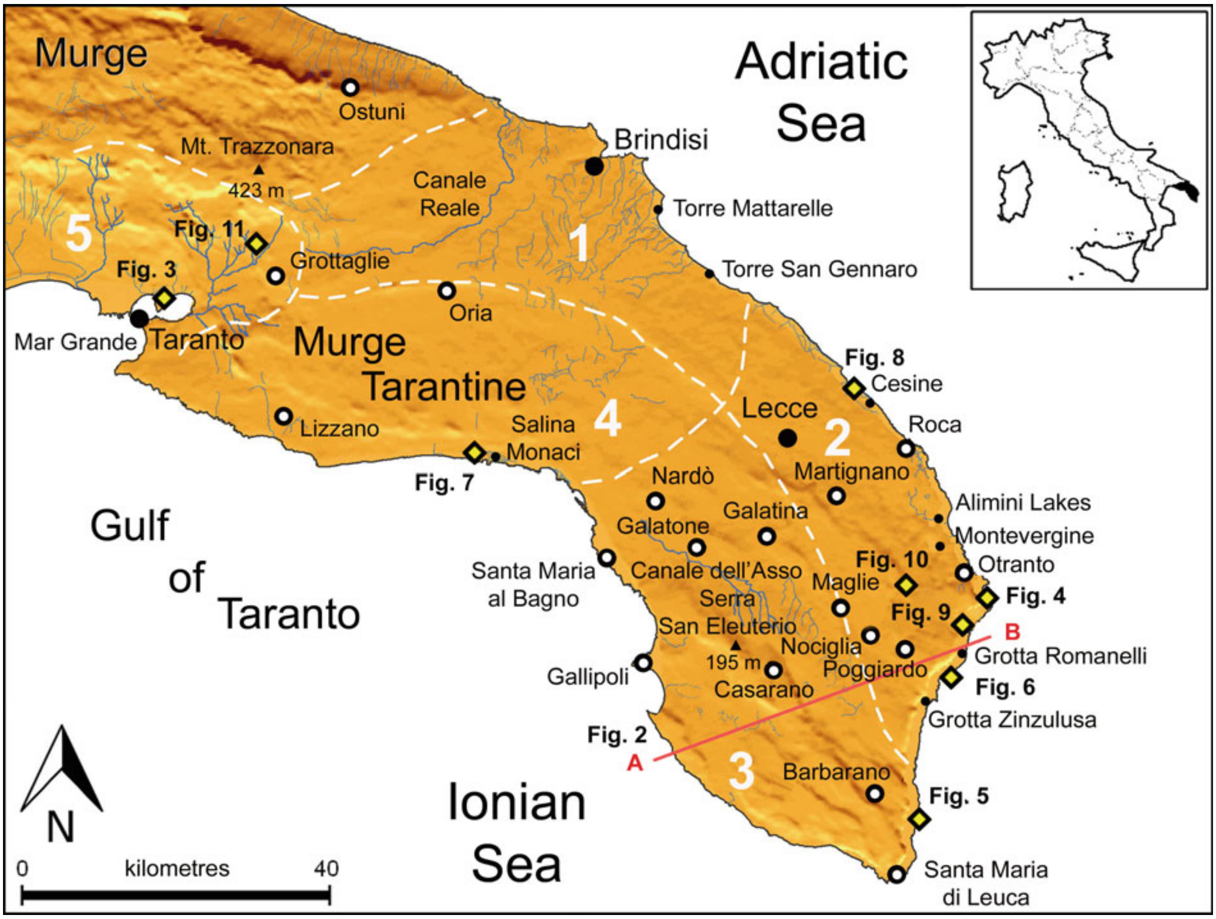

Fig. 36.1 Geographical setting of Salento peninsula. *Dashed white lines* pointed out the five main morphological districts which compound the Salento peninsula landscape. *Large black dots* main cities; *black and white dots* secondary cities; *small black dots* localities cited in the text; *yellow and black diamonds* figures; *blacks triangles* main relief; *blue* hydrographic network

in the eleventh century. At present, the Salento peninsula comprises the administrations of three main cities, Taranto, Brindisi and Lecce, with the population of about 1,800,000 people.

It is a low elevated region attaining the maximum altitude of 195 m a.s.l. on the top of Serra di San Eleuterio morphostructural ridge. From the geological point of view, three areas can be identified: (1) the Taranto marine terraces staircase on the Ionian coast; (2) the Brindisi sedimentary plain along the Adriatic coast; (3) the southernmost area of Salento peninsula, marked by a number of morphostructural carbonatic ridges, locally named *Serre*, elongated in NNW–SSE direction (Fig. 36.2).

The Salento peninsula has a typical Mediterranean climate characterized by mild winters and dry warm summers. Mean annual values of rainfall range from about 700–900 mm along the southeastern coast to 400–500 mm in the Taranto area. Mean annual temperature values are comprised between 14 and 17 °C; the highest values are recorded in August (monthly average 25.5 °C) whereas the lowest ones typify January (monthly average 9 °C). The low elevated landscape does not allow any vertical zonation so that the Mediterranean scrub (*Macchia Mediterranea)* and *Garigue* associations are the most common features. However, trees of high *Macchia* with *Quercus ilex* and *Arbutus unedo*, still survive in small areas. Along the coastal areas, high *Macchia* comprises mainly *Juniperus oxycedrus* and *Juniperus phoenicea*, *Pistacia lentiscus*, *Myrtus communis* and *Phillyrea latifolia*. Low *Macchia* with halophic vegetation is marked mainly by *Calicotome infesta, Myrtus communis, Pistacia lentiscus, Asparagus acutifolius* and, in the southern part of the peninsula, *Euphorbia dendrodes*, *Olea europea* var. *sylvestris*, *Ceratonia siliqua*, *Myrtus communis* and *Pistacia lentiscus* also. An interesting assemblage of both associations marks the thalweg of canyons. Moreover, *Garigue* is made of several herbaceous species and small size arbustive plants such us *Cistus* sp., *Rosmarinus officinalis, Tymus capitatus and Erica arborea.*

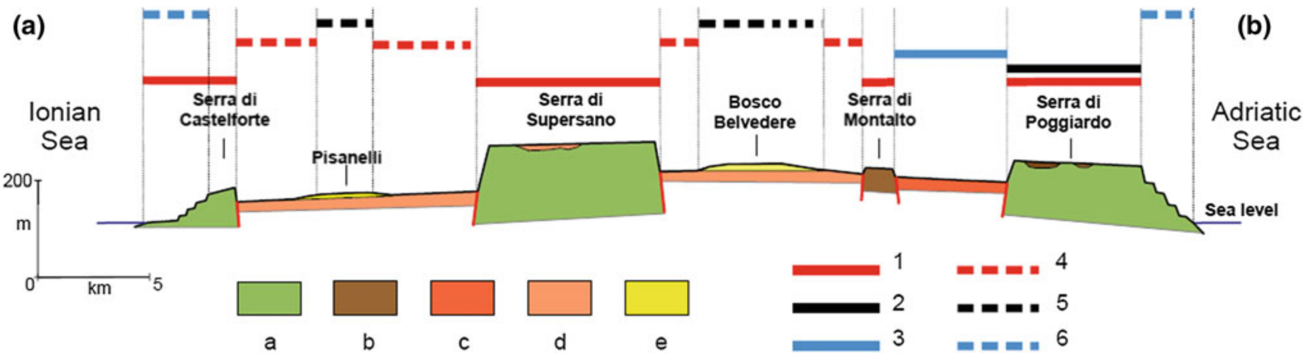

Fig. 36.2 Schematic geomorphological section of Salento peninsula from the western to the eastern coast. *Legend* (*a*) pre-Neogene units, (*b*) Miocene units, (*c*) Pliocene units, (*d*) Lower Pleistocene units, (*e*) Middle-Upper Pleistocene units, (*1*) morphostructural ridge, (*2*) Paleogene tropical karst surface, (*3*) denudation surface shaped on Pliocene units, (*4*) Lower Pleistocene karst surface, (*5*) Middle-Upper Pleistocene sedimentary plain, (*6*) Marine terraces (modified after Sansò et al. 2015)

36.3 Geological Setting

The Salento peninsula is the southernmost emerged part of Adria Plate, the foreland domain of both Apenninic and Dinaric orogens (Bosellini 2017). It comprises a Variscan basement covered by a 3–5 km thick Mesozoic carbonate sequence (the Calcari delle Murge unit), which in turn is overlain by thin deposits of Tertiary and Quaternary age (Sansò et al. 2015). The most ancient rocks of this cover were deposited as a result of transgressions after the final emersion of the Apulian carbonate platform occurred between the end of the Cretaceous and the beginning of the Paleogene. In some locations, bauxitic deposits can be found between Mesozoic limestones and Paleogene units.

Four sedimentary cycles occurred in the Neogene and Early Pleistocene. The first cycle comprises the *Pietra leccese Formation* and the overlying *Calcarenite di Andrano Formation*. The Miocene sedimentary cycle was interrupted by emersion of Salento which prevented the deposition of evaporites. The total thickness of Miocene formations is more than 150 m on the eastern side of the peninsula. The second cycle is represented by breccias and conglomerates belonging to the *Leuca Formation* that was deposited during the Early Pliocene period, reaching maximum thickness of 30 m. The *Uggiano la Chiesa Formation* (Upper Pliocene) is the result of the third sedimentary cycle; it is made of well-stratified and fossiliferous biodetritical limestones and yellowish calcareous sands showing maximum thickness of about 80 m. The fourth sedimentary cycle was responsible for the deposition of the *Calcareniti del Salento Formation*, which is basically formed by very fossiliferous biodetritical carbonatic sediments with *Artica islandica* Linneo. The *Calcareniti del Salento Formation,* formed in the Lower Pleistocene, reached maximum thickness of about 60 m. A number of Middle Pleistocene marine deposits can be also found in the Salento peninsula. Since the end of Middle Pleistocene, the uplift of the region superimposed on glacio-eustatic sea-level change produced a sequence of marine terraces all around the Salento peninsula.

Main tectonic phases occurred during the Eocene-Oligocene, the Middle Pliocene and the Middle Pleistocene periods, producing a landscape characterized by horst and graben morphology. The final uplift of the Apulia foreland started during the Middle Pleistocene, after general subsidence that took place in the early Pleistocene period. On the Salento peninsula the uplift rate strongly decreased at Marine Isotope Substage (MIS) 9.3, about 330 ka BP; since then, the highest uplift rates have been recorded in the Taranto area (about 0.25 mm/year) (Ferranti et al. 2006), whereas they lower to zero in the southernmost part of the region. Finally, subsidence has affected the peninsula's coast during the last four millennia, most likely due to dome-like deformation of the region.

36.4 Geomorphological Setting

The Salento peninsula comprises five areas marked by a peculiar assemblage of landforms. The northeastern area, stretching between Brindisi and Lecce just to the south of the *Soglia Messapica*, is characterized by a low-elevated Middle Pleistocene sedimentary plain gently sloping from west to east. It is drained by a relict hydrographic network flowing toward the Adriatic coast (Fig. 36.1, sector 1).

The southeastern area, placed to the east of Lecce—Santa Maria di Leuca alignment (Fig. 36.1, sector 2), emerged most likely at the beginning of the Pleistocene period and is mostly shaped on pre-Quaternary carbonatic rocks. Peculiar landforms can be observed: the Paleogene tropical karst surface on the top of morphostructural ridges (Capo d'Otranto, Serra di Montevergine, Serra di Poggiardo and Serra di Martignano) and tectonic depressions stretching from Roca to south. The widest of these depressions host the Alimini Lakes. The mid-western area, roughly stretching to the west of Lecce—Santa Maria di Leuca alignment, (Fig. 36.1, sector 3) emerged definitively during the Middle Pleistocene. It is marked by wide sedimentary plains interposed among NW–SE trending morphostructural carbonatic ridges, the *Serre* (Fig. 36.2). The particular stratigraphic architecture allowed the development of a contact karst, where a hydrographic network brings surficial waters into a number of sinkholes.

The Murge Tarantine is a singular landscape marked by a low-elevated, W–E oriented morphostructural ridge (Fig. 36.1, sector 4). Its northern limit is constituted by a low scarp of regional importance that in the surroundings of Oria village is marked by a long, elevated relict dune belt. At its foot, the Taranto area (Fig. 36.1, sector 5) is marked by a well-known sequence of Middle-Upper Pleistocene sedimentary plains and marine terraces (Belluomini et al. 2002).

36.5 Coastal Landscape

All around the Salento peninsula, a low-elevated landscape made of a number of Pleistocene marine terraces bordered by differential erosion scarps and relict cliffs can be recognized. Its development has been strictly connected to repeated marine regression–transgression cycles produced by glacio-eustatic sea-level changes which have occurred since the Middle Pleistocene and were superimposed on the tectonic uplift of the region. Some of these terraces display a thin sedimentary cover composed of calcareous sandstones very rich in fossil remains (*panchina*), associated in some places with dune deposits, whereas others are only wave-cut platforms.

Particularly interesting is the sequence of marine terraces recognizable along the coast from Taranto to Gallipoli formed during the Middle-Upper Pleistocene (Fig. 36.3a) (Belluomini et al. 2002). In fact, the lowest marine terrace is marked by the occurrence of a rich Senegalensis fauna marked out by specimens of *Persististrombus latus* (Gmelin) (=*Strombus bubonius* Lamarck) (Fig. 36.3b), that locally was only deposited during the Oxygen Isotope Substage (OIS) 5e, corresponding to the Marine Isotope Stage (MIS) 5.5 and ranging from 132 to 116 ka ago (Amorosi et al. 2014). However, Senegalensis fauna deposits are lacking along the Salento eastern coast, probably due to cold marine current pattern in the eastern Mediterranean Sea, which prevented the spreading of this species in the Adriatic Sea.

The present-day coastal landscape shows very different features (Caldara et al. 1998). The limestone coast extended from Otranto (Fig. 36.4) to Santa Maria di Leuca and in the surrounding of Santa Maria al Bagno is characterized by polycyclic landforms. Its development is due to submergence of high calcareous coastal slopes that occurred several times during the last 330 ka (Fig. 36.5). These slopes are marked by typical forms produced by karst and gravity-driven processes (caves, slope scree etc.) modified by coastal karst processes (pools, spitzkarren, notches etc.) (Mastronuzzi et al. 2007b). Along these coastal tracts, karstic caves open above and below present sea level (Fig. 36.5); some of them are famous since they have been exploited by prehistoric communities. The most famous coastal caves are Grotta Romanelli and Grotta Zinzulusa. The first one is important for the findings of palaeontological remains and evidence of Pleistocene sea-level change; the latter has been partly flooded during the Holocene sea-level rise and is open to the public.

High cliffs occur where the coastal landscape is shaped in soft Pliocene or Pleistocene rocks. A narrow beach stretching between Torre Mattarelle and Torre San Gennaro, to the south of Brindisi, is bordered landward by a fast retreating cliff cut in Middle Pleistocene clayey sands. Cliffs, arches and stacks shaped in the Upper Pliocene calcarenites constitute the spectacular coastal landscape north of Otranto. Finally, at Porto Miggiano, cliffs are retreating by rock falls of jointed Lower Pleistocene calcarenites (Fig. 36.6).

The Holocene submergence of relict river valleys formed deep inlets as in the case of Brindisi, Otranto and Taranto. In this last locality, a circular bay (Mar Grande) developed due to erosion of diffracted waves (Mastronuzzi and Sansò 1998).

Wide platforms gently sloping seaward are widespread along the Ionian coast of peninsula (Fig. 36.7). In this area, the roof collapse of tabular caves shaped into the Pleistocene calcarenitic bedrock, due to mixing of fresh and salt waters, produced wide depressions, locally named *spunnulate*. Few beaches can be found on the eastern side of the Salento peninsula; the presence of dark heavy minerals of Monte Vulture volcano reveals that beaches are mainly nourished by Ofanto river solid load (Fig. 36.8). The volcano cone is, in fact, entirely within the limits of the drainage basin of this river which flows in W–E direction from the Southern Apennines to reach the Apulian Adriatic coastline about 200 km to the northeast of Salento. On the western side of the peninsula, bioclastic long beaches are fed by bioclasts deriving from the *Posidonia oceanica* biocoenosis. Three Holocene dune generations have been detected along the coast of Salento peninsula (Mastronuzzi and Sansò 2002a). The oldest one is cemented and has been referred to the Mid-Holocene; loose aeolian sands with numerous soil levels mark the second generation of dunes, dated back to 2500 years BP. The youngest dune belt borders main beaches landward, isolating wetlands with valuable phyto- and zoological associations. Finally, boulder accumulations produced by historical tsunamis can be recognized at different localities along the Salento rocky coast (Fig. 36.9) (Mastronuzzi et al. 2007a).

Fig. 36.3 In the Taranto area, the marine terrace formed during the last interglacial period (Marine Isotope Substage 5.5, about 125 ka BP) is marked by a rich Senegalensis fauna (**a**). Specimens of *P. latus* collected near Taranto (**b**). These gastropods colonized the Italian coast only during the Marine Isotope Substage 5.5 ranging from 132 to 116 ka

Fig. 36.4 The eastern coast of the Salento peninsula, between Otranto and Santa Maria di Leuca, formed by the submergence of a calcareous coastal slope, extended from about 100 m a.s.l. down to 50 m of depth. The Capo d'Otranto lighthouse is the easternmost point of Italy (longitude 18°31′ 13″, 7 East) and only 70 km far from Albanian coast

Fig. 36.5 The impressive coastal landscape of eastern Salento, between Otranto and Santa Maria di Leuca, is due to action of karst, slope and marine processes (*photo* M. Caldara)

Fig. 36.6 Retreating cliffs can be recognized along several tracts of the Salento peninsula's coast. At Porto Miggiano locality, cliffs are cut into Lower Pleistocene calcarenites

Fig. 36.7 Along the Ionian coast of the Salento peninsula the development of narrow bioclastic beaches produced wide marsh areas in landward direction. Most of them have been reclaimed during the past century. During medieval times, at Salina Monaci, monks used the coastal depression to produce marine salt (after Pennetta et al. 2011)

Fig. 36.8 The Holocene sea-level rise resulted in the flooding of dolines along the Adriatic coast of the Salento peninsula as for as in the Cesine locality (after Pennetta et al. 2011)

Fig. 36.9 Megaboulder deposits have been recognized along several tracts of the coast of Salento peninsula. They suggest the impact of tsunami that struck several times the coast during the last one thousand years. At Torre Sant'Emiliano, two megaboulder ridges formed because of the impact of a tsunami generated by the strong earthquake of 20 February, 1743

36.6 Karst Landscape

The complex geological evolution of Salento peninsula strongly influenced karst processes so that a very peculiar karst landscape has developed during three distinct morphogenetic phases.

Small relicts of an ancient karst landscape, mostly compound of wide dolines shaped on Mesozoic limestones, mark the top surfaces of the main morphostructural highs. This landscape developed during a long period of continental conditions that occurred between the end of Mesozoic and the Oligocene (65–25 million years). During this phase the bauxitic deposits cropping out at Otranto (*Le Orte* locality), at Poggiardo (*Li Reali* locality) and Montevergine, formed under humid tropical climatic conditions. Rejuvenation of this karst landscape due to Pleistocene denudation along with the particular geological structure of the area produced a very peculiar karst landform, the Masso della Vecchia, produced by soil surface lowering because of renewed sinkhole activity (Fig. 36.10).

A new karst landscape developed at the end of Lower Pleistocene. It shows a wide assemblage of epigenic and hypogenic landforms and was buried under Middle Pleistocene non-carbonatic marine sands.

The uplift of the Salento peninsula during the Middle Pleistocene was associated with intense denudation which resulted in the progradation of continental shelf for about 15 km. On the newly emerged surfaces an endorheic hydrographic network developed. It flows from SW to NE in response to the higher uplift of the southern part of Salento peninsula and eroded the Middle Pleistocene non-carbonatic cover in the mid-southern area of Salento, contributing to the re-activation of Lower Pleistocene karst landforms. This karst landscape is still buried under Middle-Upper Pleistocene marine covers at the northernmost part of Salento peninsula which has been affected by less intense uplift.

Fig. 36.10 The Masso della Vecchia is a very peculiar karst landform; its emergence is consequence of the re-activation of near sinkholes which produced the lowering of the soil surface

Exhumation of Lower Pleistocene karst landscape has been accomplished by its local re-activation. The hydrographic network developed on the non-carbonatic cover, in fact, brings allogenic waters to marginal depressions whose bottom is studded by a number of cave collapse sinkholes promoting karst processes (contact karst) (Selleri et al. 2002).

The widest endorheic drainage catchment is that of *Canale dell'Asso*, which brings surficial waters from the wide area between the Casarano-Galatone and Nociglia-Galatina morphostructural ridges towards a wide depression placed in the surroundings of Nardò. At present it is broken into smaller basins due to the development of numerous sinkholes along its talweg.

Collapse dolines are common features in the region. They have been produced by roof collapse of caves shaped in Pliocene and Pleistocene calcarenites. The deepest and most famous are the *Vore di Barbarano*, two collapse dolines in Lower Pleistocene calcarenites which show a diameter of about 20 and 15 m, and a depth of about 35 and 25 m, respectively.

36.7 Sapping Valleys

The northernmost area of the Salento penisula is marked by a network of canyons with peculiar features, locally called *gravin*e or *lame*. They are short, straight valleys, deeply entrenched in the Plio-Pleistocene calcareous sandstones and Mesozoic limestones. Different generations of valleys are recognizable, each one of them leading to the inner margin of a marine terrace which represents its base level.

Morphological features and local hydrogeological conditions suggest that sapping processes, i.e. intense chemical weathering due to groundwater and related mass movements, were responsible for the development of the southern Apulia valley network. Valleys show, in fact, constant width, steep heads and walls with occasional rock slides or slid blocks, aggraded and nearly flat floors, forming abrupt angles with adjacent slopes (Fig. 36.11).

Moreover, geomorphological analysis showed that: (1) valley growth is affected by joint pattern; (2) valleys do not have a surficial watershed; (3) surfaces of the marine terraces, into which the valleys are extended, show no evidence of surface run off (Mastronuzzi and Sansò 2002b).

Sapping valley development starts with the formation of a small embayment due to the outcrop of a main fracture zone or the occurrence of an erosional notch. This ground depression induces deformation of the shape of water table, with flow lines concentrating at the edge of the initial indentation promoting very effective sapping processes. Subsequently, the valley extends headwards, producing a progressive increase in flow convergence, in the intensity of sapping processes and in the related rate of headward erosion. Headward sapping proceeds faster than valley widening because the valley head is the site of the greatest groundwater flow convergence.

Sapping processes were enhanced during interglacial high sea-level stands since the local aquifer rests on sea water intruding from the nearby coastal area, so that each ancient coastline is marked by its own generation of valleys. However, the longest and deepest valleys formed on the Ionian side of the Salento peninsula during the Oxygen Isotope Stage 7, corresponding to about 240 ka. This is most likely due to fast sea-level rise accompanied by very humid climatic conditions that increased the hydraulic head at springs and the intensity of sapping processes.

Fig. 36.11 Gravina di Riggio and its human settlement (near Taranto); the peculiar hydrogeological features of the Salento peninsula enhanced the development of sapping valleys, locally named *gravine* or *lame*

36.8 Conclusions

The landscape of Salento peninsula retains landforms developed during the long geological evolution that has occurred during the past 65 millions of years. Water has always been the main actor: tropical surficial waters contributed to deep weathering of Mesozoic bedrock producing a bauxitic cover, surficial and underground waters enhanced the modelling of a complex karst landscape, groundwater promoted sapping processes during the Middle-Upper Pleistocene and the development of spectacular deep and narrow canyons. Moreover, during Middle-Upper Pleistocene, relative sea-level change and marine processes resulted in the development of marine terraces along several tracts of Salento peninsula coast. Holocene sea-level rise flooded relict river valleys and caves, whereas at present waves unrestly shape the Salento peninsula coast, cutting cliffs and building beaches. During historical times, huge tsunami waves left on the coast narrow ridges of megaboulders.

In summary, notwithstanding the present scarcity of running waters, the Salento peninsula can exibit a complex and spectacular water-shaped landscape developed during its long geological history. This valuable geological heritage has attracted numerous researchers during the last 150 years and has been the focus of field trips during scientific geological meetings and conferences over the last 30 years (Sansò et al. 2015). However, the geological heritage is still completely unexploited by the local tourism industry, despite the fact that it could significantly improve the tourist offer of Salento region through realization and promotion of a network of "geological paths" along the most scenic areas of the peninsula.

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The Landscape of the Aspromonte Massif: A Geomorphological Open-Air Laboratory

37

Gaetano Robustelli and Marino Sorriso-Valvo

Abstract

The Aspromonte Massif, literally “Wild Mountain”, shows a very rugged and uneven topography due to a dense alternation of V-shaped valleys and interfluves. Three broad sets of geomorphic processes are principally responsible for landscape modelling and for carving the wide variety of landforms occurring in Aspromonte: tectonic uplift, river dissection and slope processes. These geomorphic processes, combined with weathering processes and contrasting rock erodibility, make Aspromonte one of the most landslide-prone areas in the Mediterranean basin, and the local river network a large in-channel sediment storage to be conveyed to the sea.

Keywords

Fiumara • Landslide • Marine terrace • Aspromonte Massif • Calabria

37.1 Introduction

The Aspromonte Massif in southernmost Italy shows a very rugged landscape, characterised by a dense river valley network alternating with sharp or flat interfluves. Unlike other massifs of the Calabria Region, Aspromonte has not been sufficiently appreciated either by the scientific community or by the common people. The main reasons lie in the hard accessibility of the area from the main cities, the difficult conditions of mountain path networks, but also in the high impact of slope instability and flooding upon urban centres and communications.

Despite this, the Aspromonte Massif provides a wide range of landscapes and landforms that have long captivated some geoscientists. Here, we describe the widest range of geomorphological features of the Aspromonte massif, with the aim of fascinating all readers with this wild and appealing landscape.

37.2 Geographical Setting

The Aspromonte Massif is located in south Calabria, the tip of the Italian “boot”, with Sicily to the southeast (Fig. 37.1). The term Aspromonte can be literally translated as “Wild Mountain”, and provides an idea of the rugged landscape of the massif. It is believed that its name comes from the term *asper*, meaning rugged in Latin, or from the Greek *aspròs*, that is white, the colour of rocks constituting the core of the massif.

Aspromonte extends southwards from the Limina Pass (Limina SS 582, Fig. 37.1), and hosts the National Park of Aspromonte that covers some 650 km^2. It rises from sea level to an average elevation of approximately 1100 m a.s.l. at the highest plateau, with peaks higher than 1400 m. Montalto is the highest peak (1956 m) at a distance of only 20 km from the sea. Many of these places offer wonderful panorama of the coast of Sicily and Calabria.

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Fig. 37.1 Location of the Aspromonte Massif

Especially on the Ionian side, the massif is strongly dissected by a dense river network consisting of short, high-gradient streams, many of them known with the local name of "*fiumara*". The *fiumara* river valleys, along with landslide phenomena, provide its typical rugged landscape (Fig. 37.2).

Because of its geographic position and its mountainous nature, Aspromonte records a high climatic variability. The climate is Mediterranean with montane modifications (wetter summers and colder winters, with more than one month of snow cover). There is a strong precipitation gradient ranging from 300 to 1500 mm. However, based on the analysis of daily and monthly rainfall concentration (Coscarelli and Caloiero 2012), the eastern side presents a greater seasonality of rainfall distribution, with high-intensity, short-duration thunderstorms (maximum daily rain up to 125 mm) strongly affecting the total yearly rainfall volume.

Vegetation on Aspromonte is strongly vertically zoned in response to the precipitation and temperature gradients, but some plant species are also affected by rainfall distribution and morphology. Exclusively on the Ionian side the Citrus Bergamot is commercially grown, which is known for the essence extracted from its aromatic skin that is abundantly used in perfumery, as well as to flavour teas and confectionery.

37.3 Geological Control on Processes and Landforms

The landscape of the Aspromonte Massif is strongly controlled by lithology and structure, as well as by the intense uplift that occurred during the Quaternary. This headland lies in one of the most geodynamically active sectors in the central Mediterranean area, where complex crustal deformation is ongoing as a result of the Africa–Europe collision (Billi et al. 2007).

Fig. 37.2 View of the typical rugged landscape of Aspromonte in the upper reach of the Amendolea river valley. Large landslides (*arrows*) provide great amount of sediment to the valley floor

The core of the massif and much of the western part is composed of Palaeozoic metamorphics (slate, phyllite, schist and gneiss) intruded by granitoids. In Aspromonte three tectono-metamorphic units are usually recognised (Fig. 37.3), which are, from bottom to top and from north to south, the Lower Metapelite Group, the Aspromonte Unit and the Stilo Unit (Cirrincione et al. 2008). These terrains are strongly affected by slope instability because of high degree of jointing, weathering processes, rock mass strength and river dissection. The uppermost Stilo Unit is unconformably covered by limestone and dolostone of Jurassic-Cretaceous age, with disconformities marked by palaeo-karst surfaces.

The pre-Cenozoic basement is overlain by late Oligocene-Quaternary siliciclastic sediments (>2000 m thick) deposited in the Ionian forearc basin (Cavazza and Ingersoll 2005). The alternating weak and resistant lithologies underpin the structurally controlled landforms and provide a background to varying landslide scenarios, well noticeable along the Ionian side of Aspromonte. Worthy to note is the Stilo-Capo d'Orlando Formation (Chattian-Burdigalian) (Fig. 37.3), a 600-m thick unit that, where composed of coarse-grained terrigenous detritus, shows amazing weathering landforms. This formation passes upward to "Varicoloured clays", a clayey melange strongly affected by landsliding.

37.4 Weathering Landforms

Today, Calabria experiences a Mediterranean climate and, as a result of relief ranging from 0 to 2000 m, mean annual precipitation higher than 1000 mm and temperatures from 10 to 16 °C. Such climate conditions, together with one of the highest leaching factor in Europe (Le Pera and Sorriso-Valvo 2000), caused severe weathering processes. Deeply weathered rocks are widespread throughout the region. Weathering products indicate humid temperate to subtropical environment and a Late Cenozoic to Quaternary age for the deep weathering (Guzzetta 1974; Le Pera and Sorriso-Valvo 2000). Although not all the massifs have been treated in the same detail, the existence of deeply weathered rock in Aspromonte is well known (Calcaterra and Parise 2010).

The gentle topography of the summit plateaus is dominated by transport-limited erosion, with the development of great thickness of quartz-rich regoliths. Although very uncommon, boulders locally occur as a result of spheroidal weathering and subsequent removal of the sandy-textured regolith.

Moving away from the highlands, a sharp increase in slope gradients marks the transition to the weathering-limited slopes. Here, the rapid dismantling of highly erodible and/or more weathered material can also accentuate the topographic relief. As a consequence, the decrease of confining pressure produces large or small fractures and joints that run parallel to the surface, encouraging spalling of rock sheets from the main rock body to give exfoliation domes very apparent in some rocks of Aspromonte, such as granitoids (Fig. 37.4a) and conglomerates of the Stilo-Capo d'Orlando Formation (Fig. 37.4b–d). The Pietra Cappa Dome (Fig. 37.4c), 140 m high, is the most famous among exfoliation domes clearly evident in the *Valle delle Grandi Pietre* (literally *Big Stones Valley*), westward of San Luca. Locally the dip of the beds

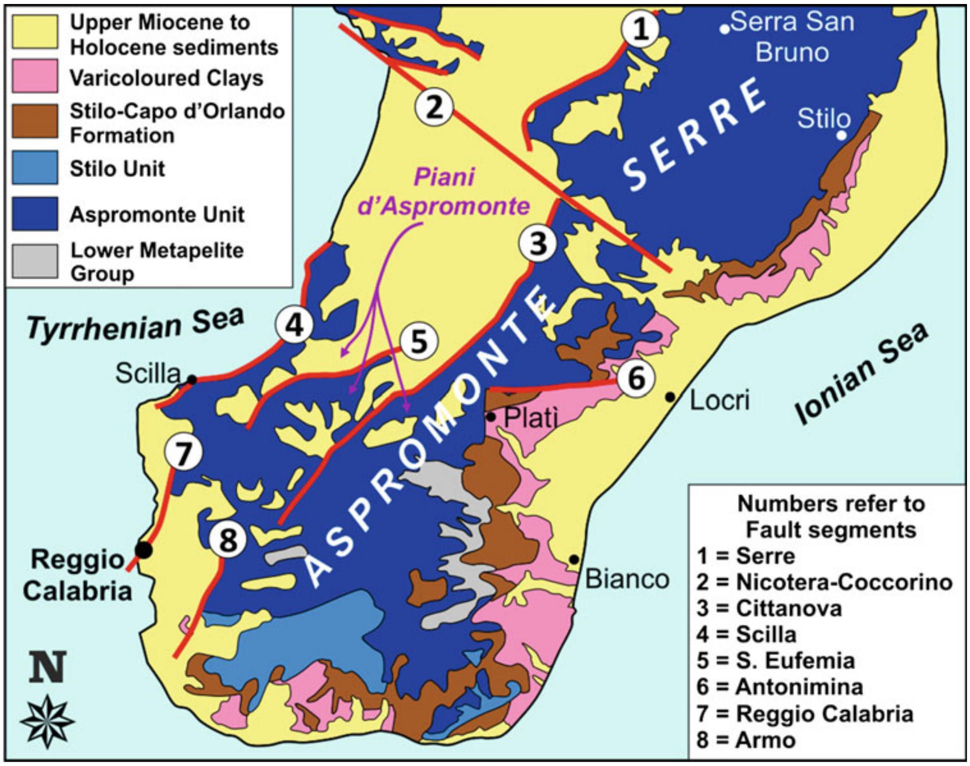

Fig. 37.3 Geological sketch map of Aspromonte Massif and location of the main fault segments of the Siculo–Calabrian rift zone (in *red*)

underpins the character of this landform, leading to the development of hogback.

Tafoni are also present and take the form of hollows or cavities, with overhanging margins like visors, in vertical or near-vertical faces especially of the Stilo-Capo d'Orlando Formation (Fig. 37.4c). Although the origin of tafoni is still debated, many of those found in Aspromonte may have developed from early hollows and/or coalescent hollows that result from falling of cobble to boulder clasts of sandy matrix-supported conglomerates. Similarly, the numerous small pits affecting conglomerates of the Stilo-Capo d'Orlando Formation closely resemble honeycomb weathering. At a small scale, undercutting and selective dismantling processes locally produce amazing mushroom/pedestal and bollard-shaped rocks (Fig. 37.4b, d).

37.5 Slope Processes and Landforms

Slope processes and landforms are widespread throughout the Aspromonte Massif.

Above 1200–1400 m, from the Aspromonte Plateaus to the top of Montalto, slope wash and rill/gully erosion affect the unconsolidated soil cover. Human activity (ploughing and occasional quarrying) interferes with superficial processes essentially through human-induced creeping. The overall effect is a smooth *inselberg*-and-piedmont low-relief system dissected by gullies arranged in a radial pattern. Moving away from plateaus, dominating slope processes are mass movement and related erosion.

Sharp increase in slope gradients marks the transition to the downstream area, where deeply incised valleys originate, the thickness of regolith strongly decreases and slope movement becomes the dominant process. Landslides are widespread and intense, and form all-size scars, scree slopes and landslide-related fans (Sorriso-Valvo 1988) on both side of Aspromonte. However, due to outcropping of more erodible rocks, the Ionian side is more deeply dissected and affected by deep-seated mass movement. This is also the area where erosion rate is the highest one, amounting to 0.8 mm/year in the past 1 million years (Ergenzinger 1988).

Greco et al. (2007) and Calcaterra and Parise (2010) highlighted that factors favouring such morphogenetic attitude to mass movement are the extremely pervasive and intense tectonic deformation of rocks, especially in gneiss and schist, as well as rock mass weathering (Fig. 37.5a).

On crystalline bedrock, the most frequent type of mass movement is complex rock slide evolving to rock avalanche and debris flow (Greco et al. 2007), resulting from the ultimate creep collapse concluding the long-term creep deformation of high, steep slopes. They may reach considerable dimensions (Fig. 37.4a), as the Costantino landslide of January 1973 (up to 700 m wide and 100 m thick, and over 21 × 10^6 m^3 in volume) or the Vallone Colella land-

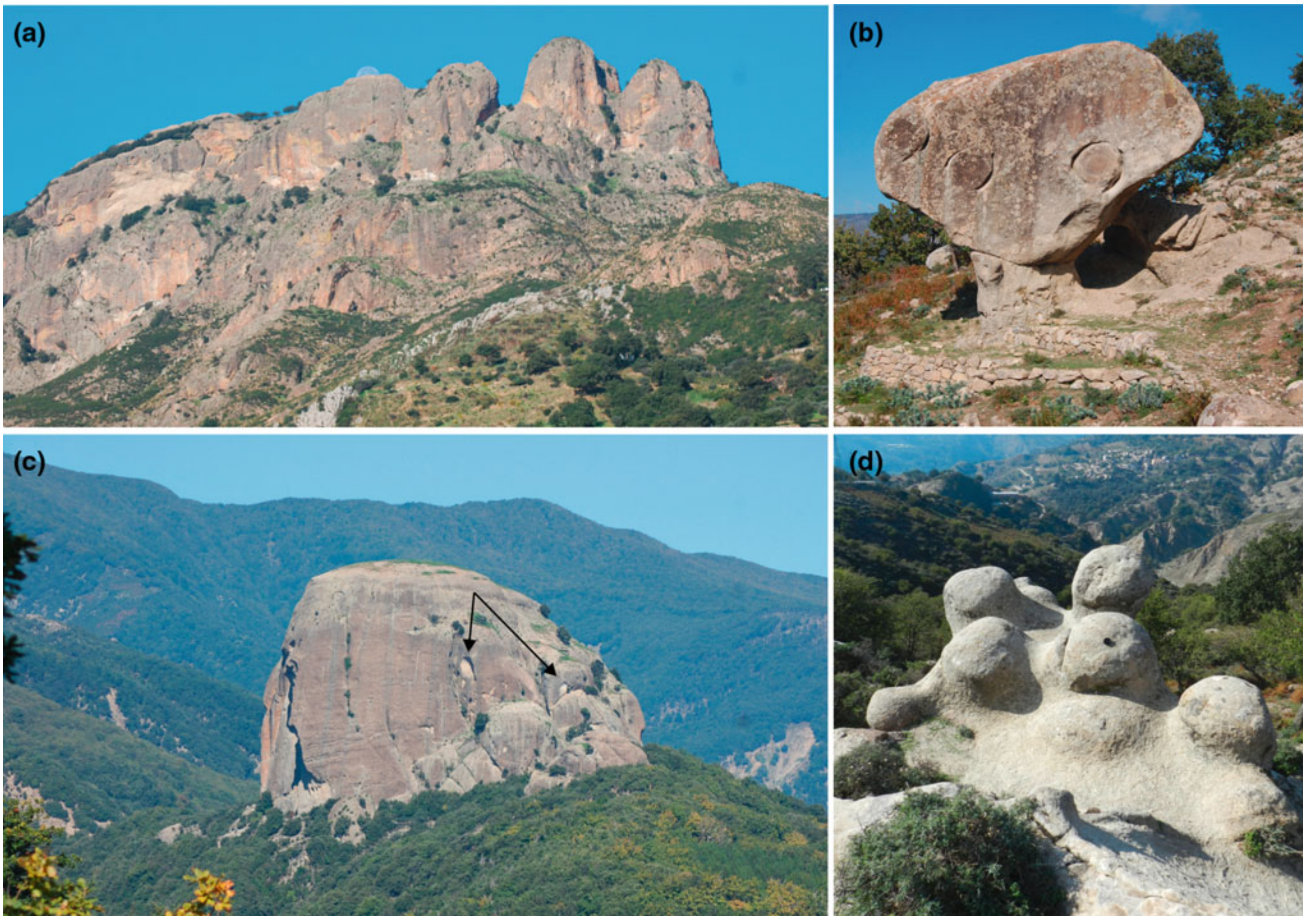

Fig. 37.4 Weathering landforms. **a** Mt. Tre Pizzi (literally "Three Peaks") shows exfoliation landforms in granite (Aspromonte upland near Antonimina fault). **b** The Roccia del Drago (literally "Rock of the Dragon") is a 6 m high, pedestal rock carved in conglomerates of the Stilo-Capo d'Orlando Formation. **c** The Pietra Cappa Dome is the highest exfoliation conglomerate dome of the Grandi Pietre valley, displaying some tafoni (*arrows*) in its vertical or near-vertical faces. **d** Bollard-shaped rocks near Roghudi (Caldaie del Latte, literally "Milk Boilers"). They develop through the deepening and widening of joints by weathering, rounding off the tops of the polygonal blocks to form karst-like landforms in conglomerates

slide of October 1951 (more than 1.5 km wide, with a maximum local relief exceeding 400 m).

On sedimentary rocks outcropping along the Ionian side of Aspromonte, landforms depend on the dominance of mass movement or running-water modelling processes. Where flysch and clayey melanges significantly crop out, a wide range of landslides occurs among which earth slides and flows are the predominant phenomena, and they may reach very large dimensions. Occasionally, landsliding may cover more than 90% of slopes carved in the clayey melange. Alternating weak and resistant lithologies also provide fascinating landslide scenarios (Fig. 37.5b).

On silty marls close to the coast, and onto old landslide bodies, badlands widely develop, against which the effectiveness of planned mitigation strategies (reforestation, land use change, minimising rainfall erosivity, etc.) is limited in time to 7–10 years. On the Tyrrhenian side, slope processes are less intense so that structural landforms are better preserved. Between Villa San Giovanni and Palmi, the Aspromonte extends down to the sea coast with high cliffs where landslides (rock fall, rock slide, debris slide and debris flow) are also evident. At the base of such cliffs, where deep gorges reach the sea, pocket beaches and discontinuous, narrow coastal plains develop on which some villages are hosted such as Bagnara Calabra and Scilla.

37.6 Fluvial Processes and Landforms

Fluvial processes and landforms reflect the morphology of highlands, major slopes and piedmont zones. Relatively calm streams gently dissect the Aspromonte highland, apparently at very low erosion rates that, however, rapidly increase while approaching the abrupt break in slope that marks the highland edge. Here, streams change dramatically becoming roaring torrents excavating deep gorges and

Fig. 37.5 Landsliding is one of geomorphic processes mostly responsible for landscape modelling in Aspromonte. **a** The Costantino landslide occurred after a 24 h precipitation of about 390 mm in January 1973. The landslide affected highly weathered gneisses, and dammed the Fiumara Buonamico, forming a wide lake that lasted only a few hours before breaching occurred. **b** Slope movements at Bova consist of lateral spreading in welded sandstones accompanied by toppling, falling or sliding

canyons, with riverbeds excavated in bare rock or lined with very coarse-grained lag deposits, often moved downstream by mass transport phenomena.

Fiumara is the typical local name given to river valleys of Aspromonte, and indicates streams typically of high gradient and short length, characterised by an ephemeral and torrential regime. International scientific community acknowledges this term, which thus can be used in geomorphological literature. The corresponding catchment areas develop almost entirely in high relief mountain areas. A braided pattern and gravel-bed load characterise their middle and lower courses (Fig. 37.6a, b). Sorriso-Valvo and Terranova (2006) provide a thorough review of the characteristics of *fiumara* streams.

In plan view, the related valleys have a very apparent meander-like trend (Fig. 37.6a), which is believed to result from the role of some key factors (structural controls, rock mass weathering grades, lateral stream erosion induced by landslide and vice versa, etc.), all acting to form meandering valleys. Based on geological and stratigraphical setting, other hypotheses such as antecedence, superimposition and stream persistence may be also considered. Within bedrock of elevated resistance to erosion, thresholds and narrow gorges form, upstream of which river aggradation occurs (Fig. 37.6b). This is also observed upstream of huge landslides or tributary alluvial fans.

Fiumara floodplains are not stabilised by dense vegetation (Fig. 37.6a, b), hence sediment yields are relatively high. The presence of armour and abundant sediment supply does not allow even small to moderate flow events to scour the bed and alter channel morphology. However, when large

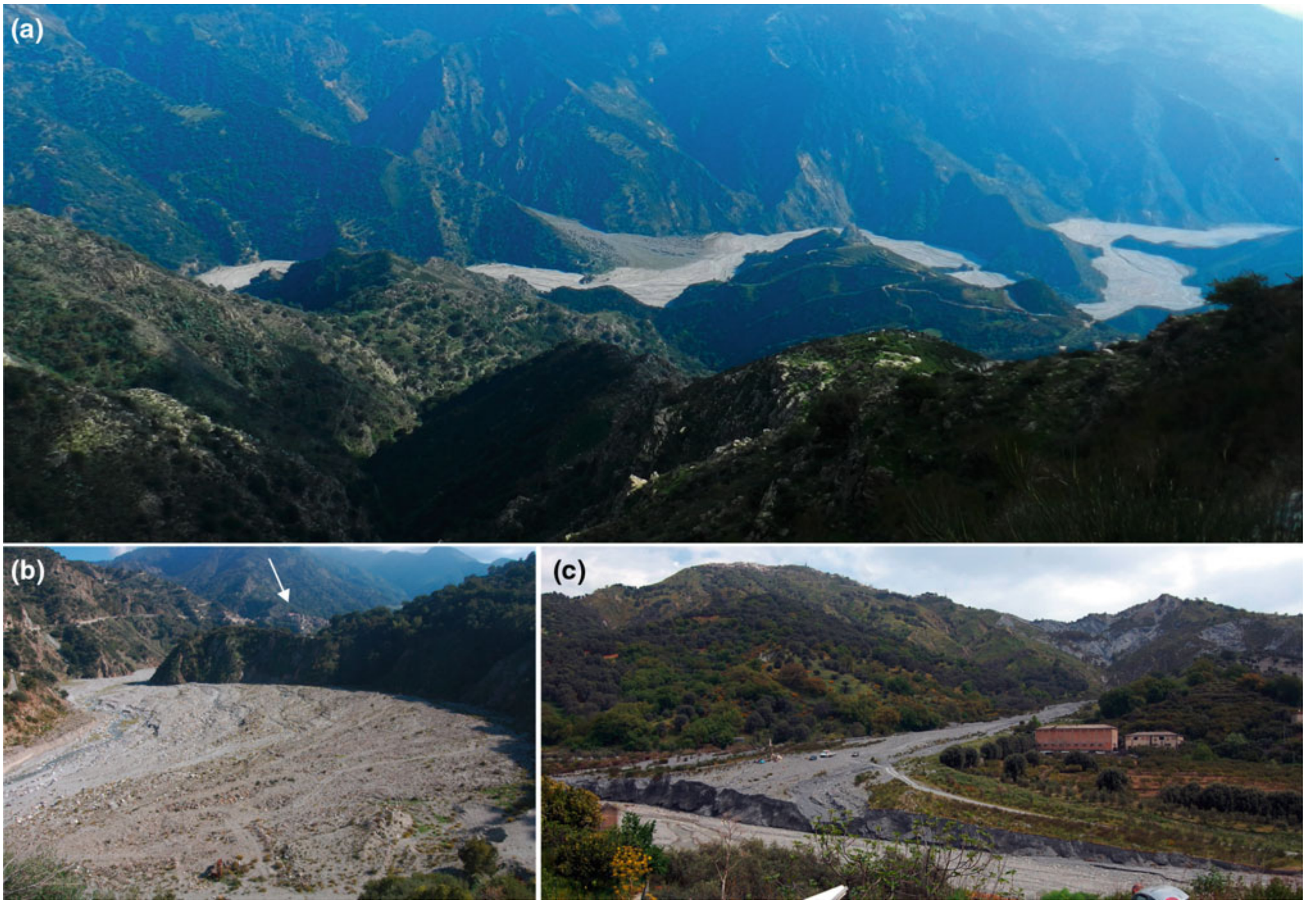

Fig. 37.6 Fluvial landforms. **a** Overview of the middle reach of Amendolea, the most famous *fiumara* of Aspromonte. Note the sinuous trend of river valley, characterised by braided pattern and gravel-bed load, and the active alluvial fan developed from a left tributary. **b** Close-up view of the upper reach of the Fiumara Amendolea which is up to 300 m wide. The village of Roghudi (*arrow*) was relocated after two large floods occurred in December 1972 and January 1973. **c** The active alluvial fan developed from left tributary of the Fiumara di Melito, associated with active landslides (in the *background*). The fan toe is affected by severe retreat due to trimming by the main river

rainstorms occur, the resulting sediment yield can be magnitudes higher than one recorded in perennial streams.

The banks of the main channels show coarse alluvial sandy-gravelly sediments alternating with sand and silt layers. Channel beds consist of coarse gravel, cobbles and boulders. The state of aggradation/degradation of alluvial beds depends on the balance between debris input from the slopes and transport capacity of streams. Recurrent heavy rainstorms increase landsliding that results in sudden aggradation of streambeds. Later, as sediment supply reduces, erosion promotes low-rate streambed degradation. However, these alternating phases, whose duration is a few decades, do not modify the general, over-filled aspect of *fiumara* riverbeds in the long term. The river beds are essentially in a cyclical, but stationary state since at least 3 ka BP, based on dating of vegetation remnants (Sorriso-Valvo and Terranova 2006).

Occasionally, if a very large landslide occurs, an aggradation cycle may last longer and aggradation may be more relevant than usual. For instance, the huge Vallone Colella landslide triggered by October 1951 thunderstorms is responsible for the severe aggradation of the Fiumara Amendolea riverbed (Fig. 37.6a), which attained about 10 m in the upper reach, and more than 2 m close to coastline.

Intramontane-valley fans are also widespread throughout Aspromonte (Fig. 37.6a, c), and many of them show evidence of current activity, being usually associated with active landslides (Fig. 37.6c). These confined fans are not able to prograde over a low-angle surface, particularly due to trimming by erosion of the main rivers (Fig. 37.6c). In the past decades, they have experienced several changes in fan and feeder channel dynamics between phases of aggradation/progradation and dissection. This is likely to result from continuous sediment inputs that were progressively stored in the feeder channels until their slopes reach a threshold value due both to aggradation and fan toe retreat.

37.7 Stepped Landscapes

Since the Pliocene, contractional structures have been superimposed by extensional faults which have fragmented the Calabria region into structural highs and subsiding basins, such that today an array of active normal faults runs southwards from Calabria to the Ionian coast of Sicily (Tortorici et al. 1995; Catalano et al. 2008).

Since the Early–Middle Pleistocene, Calabria was affected by strong uplift, largely coeval with motion on these extensional faults. It is worthy to emphasise that above the fault escarpments produced by the active fault belt crossing the Calabria, the landscape is dominated by hanging remnants of gentle land surfaces, known as Piani d'Aspromonte (Aspromonte Plateaus), which form a staircase between 500 and 1350 m, considered to be four stepped marine terrace of Early Pleistocene age (Miyauchi et al. 1994). More likely, these land surfaces can be related to the oldest stages of landscape evolution, which occurred during Late Pliocene–Early Pleistocene through relief smoothing processes.

Anyway, the long-term uplift that affected the region is spectacularly documented by flights of marine terraces, resulting from the interaction between tectonics and eustatic sea-level changes and well developed along the coasts (Fig. 37.7). Notably, the high relief rocky coasts of the Tyrrhenian sector better preserve sequences of stair-like terraces. This zone is famed because of its beauty, and is known as the Violet Coast by the nuances of the sea.

Along the 60 km of coastline from Scilla to Mèlito di Porto Salvo, fourteen marine terraces form a staircase between the present sea level and 520 m a.s.l. (Dumas et al. 2000). Five of them (10, 170, 290, 400 and 510 m) are correlated with interglacial stages (MIS) 1, 5.5, 7.5, 9 and 11 respectively, corresponding to peaks of warmer climate on isotopic curves. The longer term uplift established using these Middle Pleistocene markers is 1.24 mm/year, but uplifted Holocene tidal notches and marine deposits indicate a recent increase of uplift rates up to 2.1 mm/year (Antonioli et al. 2006).

37.8 Tectonic and Structural Landforms

The imprint of tectonics on geomorphology of the Aspromonte Massif is evident not only in the size, extent, and location of landforms, but also in the steepness of river profiles, the features of mountain slopes, and in the pattern of river network.

Tectonics influences geomorphological processes and landforms of Aspromonte through the direct action of faulting and the indirect influence of spatial variability in rock erodibility and the effects of geological structure. Notably, the present landscape of the Tyrrhenian side is strongly related to tectonic activity, whereas structurally controlled erosional features dominate on the Ionian side. In addition, the different landscapes are due to the contrasting influence of bedrock on both sides of Aspromonte.

The most impressive tectonic feature of the region is represented by the Siculo–Calabrian rift zone (Tortorici et al. 1995), which forms a N-striking normal fault belt about 370 km long that runs more or less continuously along the inner side of the Calabrian arc, extending through the Strait of Messina along the Ionian coast of Sicily. Some segments of the fault systems are still active (Galli and Bosi 2002; Catalano et al. 2008; Ferranti et al. 2008), making the area a key point for characterising the seismic hazard of southern Calabria.

The fault belt is made up of five major segments showing an overall *en-echelon* arrangement and formed by west-facing normal fault segments that strongly articulate the Aspromonte Massif (Catalano et al. 2008). From the north to the south it includes the Cittanova, S. Eufemia, Scilla, Reggio Calabria and Armo faults, which are morphologically well detectable thanks to very evident, steep and straight fault scarps (Fig. 37.8a). These fault segments exhibit very sharp rectilinear escarpments, showing well developed triangular facets separated by wineglass canyons. They are tens to hundreds of metres high and noticeable from the A3 Highway, state roads and many panoramic viewpoints (Fig. 37.8a).

Fig. 37.7 Looking from a distance, the landscape of Aspromonte resembles a flight of steps facing the sea. Overview of the sequence of stair-like marine terraces from the south of the Villa San Giovanni

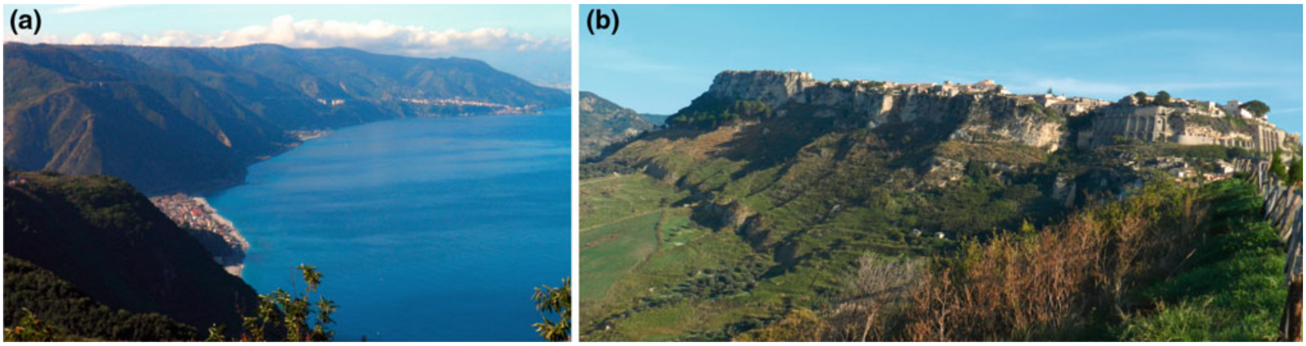

Fig. 37.8 Tectonic landforms **a** overview from the north of the Scilla fault scarp; the village of Scilla, in the *background*, is located on the MIS 5.5 marine terrace. **b** Close-up view of the isolated cuesta landform of Gerace. Cliffs are dissected by widened vertical joints, which form open clefts resulting from lateral spreading phenomena

According to Tortorici et al. (1995) and Galli and Bosi (2002), the 1783 and the 1894 seismic events are related to the west-dipping Cittanova, Scilla and S. Eufemia faults, whereas the offshore branch of the Reggio Calabria fault is considered to be the seismogenic source of the intense 1908 Messina earthquake (M 7.1).

On the Ionian side, several pieces of evidence highlight the key role of lithological controls, through which geological structure receives its topographic expression. Conversely, it is hard to discern a clear topographic signature of tectonic landforms because of high rates of erosional processes. Nevertheless, through the indirect influences of spatial variability in erodibility generated by faulting and juxtaposition of rocks with variable erosion resistance, the influence of faults on landscape is easy to detect (fault line scarps).

Because of lithological heterogeneity, a diverse gallery of homoclinal structures eroded in the late Oligocene-Quaternary siliciclastic sediments is evident. Notably, the sedimentary succession forms an overall E-dipping monocline, with tectonic growth structures increasing upward. The ensuing progressive unconformity is morphologically well apparent between Bianco and Roccella Jonica, through the topographic expression resulting from differential erosion of strata with variable erosion resistance. Due to river erosion, landscape is, therefore, characterised by undulating, along-strike ridges resulting from changes in dip angle and strata unit thickness that make the upper surfaces of these landform very sinuous. At small scale, various structural landforms (hogbacks, homoclinal ridges and cuestas) develop according to the dip of the beds (Fig. 37.8b).

37.9 Human Settling and Cultural Heritage

In such a difficult land, human settlement has constantly been a difficult task. New cities and villages since ever have been settled on the coastal plains by Greek colonies, or on top of piedmont hills after the fall of Roman Empire. On the difficult slopes of Aspromonte, Orthodox Catholic monasteries, or just dormitories, were built in tenth–eleventh centuries, whereas small settlements were built in fifteenth century by new Greek migrants escaping from Turkish invaders. Greek colonies are spread in the south part of Aspromonte (Bova, Condofuri, Gallicianò, Africo, Pentedattilo and so forth), but any witness of Greek origin has nearly completely disappeared, even though at present an attempt is being made of rescuing ancient traditions. The most relevant, still active legacy of Greek tradition is the popular dance music, the *tarantella*, that is still danced in occasion of special recurrences, and in the pilgrimage tradition to the Virgin of Polsi Sanctuary, down in the Fiumara Buonamico canyon, where the ancient Greek tradition of *ecatombe* (100 sacrificial victims, goats and lambs) is yearly renewed with a feast that reminds Dionysiac rituals.

After the tremendous storms of 1053, 1953 and 1973, some of the most uncomfortable villages have been moved to more comfortable, but seldom safer, places. As a consequence, people used to timber logging and goat pasture as a source of their living, had to transform themselves, without any technical or economic assistance, into fishermen or else. The result has been an increment of illegal activity. After a while, most of these villages have been reclaimed, but in a quasi-illegal way, so that they are now inhabited (such as Pentedattilo) but cannot get regular services by the Municipalities.

Besides rainstorms, earthquakes have also caused villages abandonment. Earthquakes, in addition to being the destructive side of tectonics that also should be accounted for the natural beauty of Aspromonte, are the reason why very little of the valuable architecture patrimony is still preserved. In Greek and Roman times (between sixth century BC and sixth century AD), and then the Norman and Svevian times (between tenth and thirteenth centuries AD) this territory was one of the most beautiful, peaceful and rich lands of Europe. However, after the eras of French and Spanish ruling, nothing of that has been left.

37.10 Geomorphological Hazards and Their Mitigation

In such a rugged area with such an aggressive climate, geomorphological hazards are the major concern for land managers. Landsliding of every type, flash floods and intense erosion are so frequent and widespread that the economic and social development of this area is hampered. The rugged morphology makes the building of lifelines and roads very difficult and expensive. Geomorphic phenomena are occasionally so violent that infrastructures and settlements may be threatened. The situation can be worse in the lowlands, where there are more infrastructure and persons exposed to the danger of geomorphological disasters than in the high mountain zone. The 1951, 1953 and 1973 storms caused more than 100 victims and the abandonment of several mountain villages. However, the situation is much better in the highlands, where morphology is gentle.

Protecting the territory is quite difficult and expensive and its maintenance very expensive in respect to construction costs. Traditional protective measures such as reforestation is of little use against landslides because of rocky, steep slopes involved. Erosion by surface water is also difficult to combat because the high gradient of slopes eases runoff rate and velocity, so that badland-like landforms develop also on weathered, crystalline rocks.

In this situation, corrective measures are undertaken only where extremely necessary. On the other hand, the large rate of debris budget that reaches the coast, allows for a relatively steady condition of shorelines, while the effects of a diffused building and of corrective measures on drainage basins during the 1950s and 1960s included worrying and diffused beach erosion that has damaged several marine villages and lifelines. On the Tyrrhenian side, the narrow coastal plain is densely inhabited and crossed by the most important railway and main roads, rather frequently affected by landslide phenomena, sometimes causing casualties. Here corrective measures, though expensive, seldom inefficient and of limited duration, are a must and go further than strictly necessary. Sometimes it would be better to let some areas to evolve wild, limiting intervention where absolutely necessary.

37.11 Conclusions

The Aspromonte Massif provides a wide range of landscapes that result from the interaction of tectonic uplift, river dissection, and slope processes, giving Aspromonte its rugged and uneven topography. At times, landscapes are arranged in such a beautiful, ever-changing scenario that some landscapes may be considered unique and incomparable geomorphological examples, making Aspromonte potentially one of the most significant earth science sites in South Italy. Many of the best examples lie within the national park of Aspromonte, which provides visitor centres and accompanying explanations of the natural environment.

Notwithstanding its relative access difficulty, it would be desirable that the geomorphological significance of Aspromonte improves in the future by attracting more and more scientists and people, which may enhance its importance as a training ground for research programmes and recreation activities in a wonderful scenery overhanging the sea.

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38

Volcanic Landforms and Landscapes of the Aeolian Islands (Southern Tyrrhenian Sea, Sicily): Implications for Hazard Evaluation

Federico Lucchi, Claudia Romagnoli, and Claudio Antonio Tranne

Abstract

The Aeolian Islands are a Quaternary active volcanic structure in Southern Italy. These volcanic islands are characterized by an outstanding display of volcanic landforms (stratocones, lava flows, domes, fissures, dykes, calderas, lateral collapses) derived from repeated episodes of volcanic activity and volcano-tectonic collapse under the control of regional tectonic trends. Stromboli and Vulcano are particularly characterized by ongoing eruptive and gravity-driven instability processes. Geomorphic evolution there plays a fundamental role on the localization of eruptive vents and conduits and the distribution of volcanogenic flows, with important insights on volcanic hazard and risk assessment.

Keywords

Volcanic landforms • Caldera • Lateral collapse • Volcanic hazard • Aeolian Islands

38.1 Introduction

The Aeolian Islands are the most active volcanic structure in the Mediterranean area, including presently active (Stromboli and Vulcano), dormant (Panarea and Lipari) and extinct volcanoes (Salina, Filicudi, Alicudi). Well known since prehistoric times, the Aeolian volcanoes have attracted the interest of many naturalists, historians, travellers, artists and scientists, being rightfully assumed as the cradle of the modern scientific discipline of Volcanology from the study and description of the world-famous eruption localities of Stromboli and Vulcano. There is a large variety of volcanic landforms and spectacular landscapes which enabled the Aeolian Islands to become one of the UNESCO World Heritage sites. In this highly dynamic and active environment, landform investigation provides a fundamental contribution to geological mapping and stratigraphic analysis, and to risk assessment and hazard zonation (Lucchi 2013).

38.2 Geographical and Geological Setting

The Aeolian Islands are the emergent portions of large volcanic edifices rising *ca.* 2000–3000 m above the seafloor. Together with the surrounding seamounts, they are arranged in an articulated, arc-shaped structure around the Marsili basin (Fig. 38.1), in a complex subduction-related geodynamic setting (De Astis et al. 2003). The morphostructural context and geological evolution of the Aeolian Islands are directly conditioned by regional fault systems. In particular, the active or dormant volcanoes are located in the central (Vulcano and Lipari) and eastern (Stromboli and Panarea) sectors, to the northeast of the Tindari-Letojanni lithospheric fault system, developing in an extensional stress regime related to active subduction. The extinct volcanoes (Alicudi, Filicudi and Salina) are instead sited in the western (and central) sector, now dominated by a compressional tectonic regime.

The Aeolian volcanism has developed entirely during the Quaternary, starting from *ca.* 1.3 Ma in the submarine areas (Beccaluva et al. 1985) and *ca.* 270–250 ka in the emergent portions (Fig. 38.2; Lucchi et al. 2013a). The oldest calc-alkaline mafic products were emplaced on Lipari, Salina and Filicudi before the marine oxygen isotope stage (MIS)

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Fig. 38.1 Sketch bathymetry of the southern Tyrrhenian Sea and the Aeolian Islands. The main Tindari–Letojanni (TL) fault system is shown. *Depth contour lines* in metres below sea level

7.3 (*ca.* 220 ka). Between 220 and 124 ka, volcanism occurred on Lipari, Salina, Filicudi and Panarea producing mafic to intermediate rocks. Lipari, Panarea, Vulcano and Alicudi were active during MIS 5 (124–81 ka), mostly erupting high-potassium intermediate rocks. More evolved silicic rocks appeared since *ca.* 75–70 ka on Lipari, Salina, Vulcano, Filicudi and Panarea, also producing a series of major subplinian eruptions. Shoshonite and leucite-bearing lavas were emitted during the younger stages of Vulcano. Stromboli was entirely constructed by calc-alkaline to shoshonite rocks during the past 85 ka up to the present, and is characterized by ongoing strombolian activity. Historical eruptions are recorded on Lipari (AD 776–1230) and Vulcano (AD 1888–90), whereas intense hydrothermal activity is presently documented on Vulcano (La Fossa cone) and Panarea (submarine areas).

38.3 Landforms and Landscapes

The Aeolian Islands are characterized by a large variety of volcanic landforms, both in the emerged and submerged portions of the volcanic edifices (cf. Lucchi et al. 2013b). Differently from any other geological setting, the landforms in volcanic areas may result from a combination of constructive and destructive processes acting simultaneously or strictly connected (Thouret 1999). The volcanic edifices generally have a relatively short-lived existence due to the effects of slope instability and high-energy erosion and denudation processes, which are particularly intense and rapid due to high topographic relief, steep-sided slopes and unstable nature of volcanic products. This is the direct consequence of the episodic nature of volcanism, which usually results in a rapid supply of volcanic products during

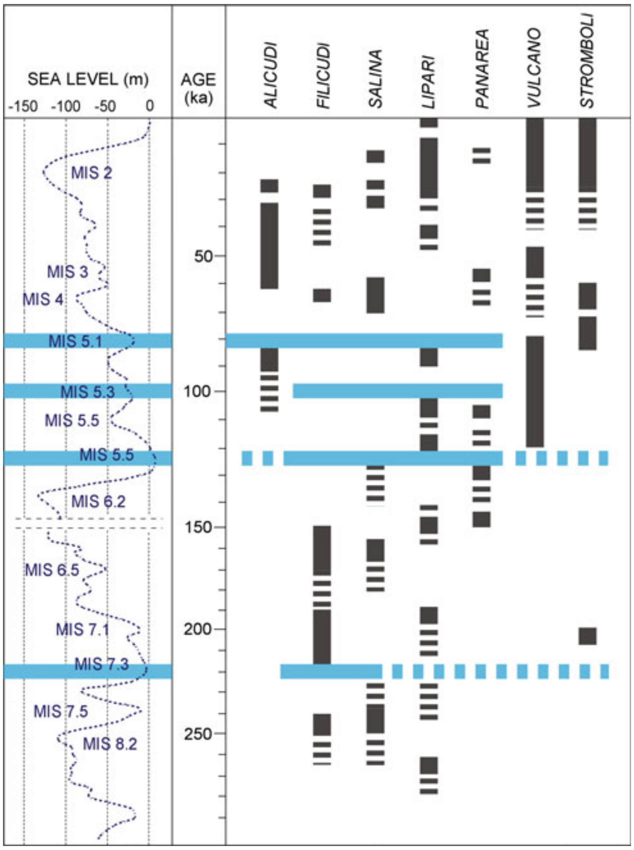

Fig. 38.2 Schematic diagram showing the chronology of eruptive activity in the Aeolian volcanic islands, as emerges from the available radiometric ages of volcanic products (*vertical bars*) and tephrostratigraphy (see Lucchi et al. 2013a, for complete age references). The age of marine terraces (*light blue horizontal bars*) is displayed by comparison with specific peaks of the Late Quaternary sea-level curve of Waelbroeck et al. (2002)

relatively short-lived constructional stages, separated by longer periods of quiescence between the eruptions. The higher degradation rates generally follow closely the eruptions and may be frequently accompanied by catastrophic landsliding and lateral collapse of the flanks (and summit) of the edifices. The various volcanic landforms derived from primary eruptive processes thus can be largely modified and altered by volcano-tectonic collapses and structural features, and erosional processes in subaerial and marine environments.

38.3.1 Volcanic Landforms

Several volcanic landforms are observed in the Aeolian Islands, reflecting the diversity of eruption types, composition of magmas and erupted products, monogenic or polygenic evolution, influence of regional tectonic trends and the role played by volcano-tectonic activity and erosional processes. Selected volcanic landforms are listed in Table 38.1.

All the Aeolian Islands are polygenic composite volcanic edifices resulting from the interplay of successive eruptive sequences and volcano-tectonic collapses through time (Fig. 38.3). Alicudi and Stromboli are truncated cone-shaped stratocones with a central conduit and summit craters producing radially distributed lavas and pyroclastic products. Their craters are generally located within a summit caldera or near the headwall of lateral collapses that interrupted the polygenic growth of the stratocones (see Sect. 38.3.2). Filicudi, Salina, Lipari and Vulcano are instead compound or multiple volcanic edifices composed of several eruptive centres of variable size (superposed in space and time) interplaying with successive calderas and lateral collapses.

The main landforms are a number of polygenic stratocones or composite volcanoes, reaching heights of 600–900 m (Table 38.1). The best-preserved stratocones are Monte dei Porri and Monte Fossa delle Felci on Salina (Fig. 38.4a), Monte S. Angelo and Monte Chirica on Lipari, Fossa Felci and Casa Ficarisi on Filicudi (Fig. 38.4b) and La Fossa cone on Vulcano (Fig. 38.5a). The stratocones generally have a simple summit crater, although some of them are characterized by different compound crater rims and/or eccentric eruptive fissures departing along the main tectonic trends. Most of these stratocones have a steady-state geometry with a concave-upward profile, with radial erosional gullies along the flanks relative to the progressive degradation of the edifices (Fig. 38.4a). These are generally connected with voluminous detritic deposits at the foot of the slopes (Fig. 38.4b). Marine terraces and submarine shelves cut the slopes of the older stratocones (Figs. 38.3 and 38.4b) as the result of the interaction between Late Quaternary sea-level fluctuations and crustal vertical movements (Lucchi 2009; Romagnoli et al. 2013).

The stratocones are generally juxtaposed to several monogenic (to polygenic) volcanic landforms represented by tuff ring/tuff cones, scoria (spatter) and pumice cones or lava domes (Fig. 38.3; Table 38.1). Selected examples are the Monte Pilato pumice cone in NE Lipari erupted in the early Middle Ages (Fig. 38.4c) and the Pollara asymmetric tuff ring in NW Salina, whereas isolated scoria cones are Monte Guardia on Filicudi and San Vincenzo on Stromboli. Most of them are largely dissected by subsequent erosion and excavation of the unconsolidated pumice or scoria deposits. A N–S alignment of scoria cones associated to lava flows is instead recognized along the W coast of Lipari (Timponi cones) reflecting the control of main regional tectonic trends. The lava domes have variable dimensions and shape, from small adventive and plug domes to large endogenous domes with well-developed flow foliation and rampart structures. They may be isolated (Monte Montagnola on Filicudi; Basiluzzo at Panarea; Fig. 38.4d) or grouped together in clusters or alignments of coeval domes along faults (Monte

Table 38.1 Morphological and volcanological features of selected volcanic landforms in the Aeolian Islands

Name	Island	Morphology					Age (ka)	Type of activity	
		Height (m)	Thickness (m)	Length (m)	Width (m)	Crater type (diameter in m)		Eruption style	Feature
Lava flows and domes (at increasing viscosity)									
San Bartolo	Stromboli		∼20	1500	Up to 1200	NE–SW fissure	∼2	Effusive	Lava flow field
Vulcanello	Vulcano		∼30	∼500 (subcircular)		Vulcanello scoria cone	∼2	Effusive	Lava flow field
Pietre Cotte	Vulcano		∼20	∼380	∼180	La Fossa crater	*AD 1739*	Effusive	Coulee
Rocche Rosse	Lipari		∼60	∼4000 (plus submarine)	∼1000	M. Pilato crater	*AD 1230*	Effusive	Coulee
Monte Montagnola	Filicudi		∼120–150	∼1000 (subcircular)			∼64	Effusive	Endogenous dome (lobate)
Basiluzzo	Panarea		∼165	830 × 400 (elliptical)			∼54	Effusive	Endogenous dome
Monte Lentia	Vulcano		∼190	Up to 550 × 500 (subcircular)			27–8	Effusive	Alignment of domes along caldera rim
M. Guardia–M. Giardina	Lipari		∼100–170	Up to 1200 × 1000 (subcircular)			27–24	Effusive	Alignment of domes along a fissure
Pyroclastic cones (and fissures)									
Monte Guardia	Filicudi	∼140		300–400 (subcircular)		Simple crater	∼190	Explosive	Scoria cone (with lava flows)
San Vincenzo	Stromboli	70–80	(∼15)	∼450 (subcircular)		Simple crater	∼12.5	Explosive	Scoria cone (with lava flows)
Nel Cannestrà	Stromboli		(∼10)	∼500 (elongated)		NE–SW fissure	∼8	Explosive/effusive	Scoria agglomerate (with lava flows)
Timponi	Lipari	Up to 350		∼500–600 (subcircular)		N–S fissure	∼267	Explosive	Alignment of scoria cones (with lava flows)
Pollara	Salina	Up to ∼200		∼600 (crater-subcircular)		Simple crater	27.5–15.6	Explosive	Tuff ring (asymmetric)
Monte Pilato	Lipari	∼350	(∼150)	∼2000 (subcircular)		Composite crater (∼1000)	*AD 776*	Explosive	Pumice cone
Stratocones and composite volcanoes									
Fossa Felci	Filicudi	774		∼2200 (subcircular)		Simple crater (+fissures)	∼246–195	Mixed	Stratocone
Monte Fossa delle Felci	Salina	960		∼3200 (subcircular)		Simple crater (580)	∼160–121	Mixed	Stratocone
Monte dei Porri	Salina	859		∼2900 (subcircular)		Simple crater (260)	∼70–57	Mixed	Stratocone (collapsed)
Monte Chirica	Lipari	∼602		∼1300 (half-diameter)		Simple crater (370)	∼256–81	Mixed	Stratocone (collapsed)
Monte S. Angelo	Lipari	593		∼3800 (subcircular)		Simple crater (∼500)	∼114–81	Mixed	Composite volcano (collapsed)
La Fossa	Vulcano	∼602		∼2000 (subcircular)		Composite crater (∼500)	<5.5	Mixed	Stratocone
Eroded landforms									
Canna	Filicudi	71			∼50		∼29	Effusive	Lava neck (submerged edifice)
Strombolicchio	Stromboli	49			∼140		∼204	Effusive	Lava neck (submerged edifice)

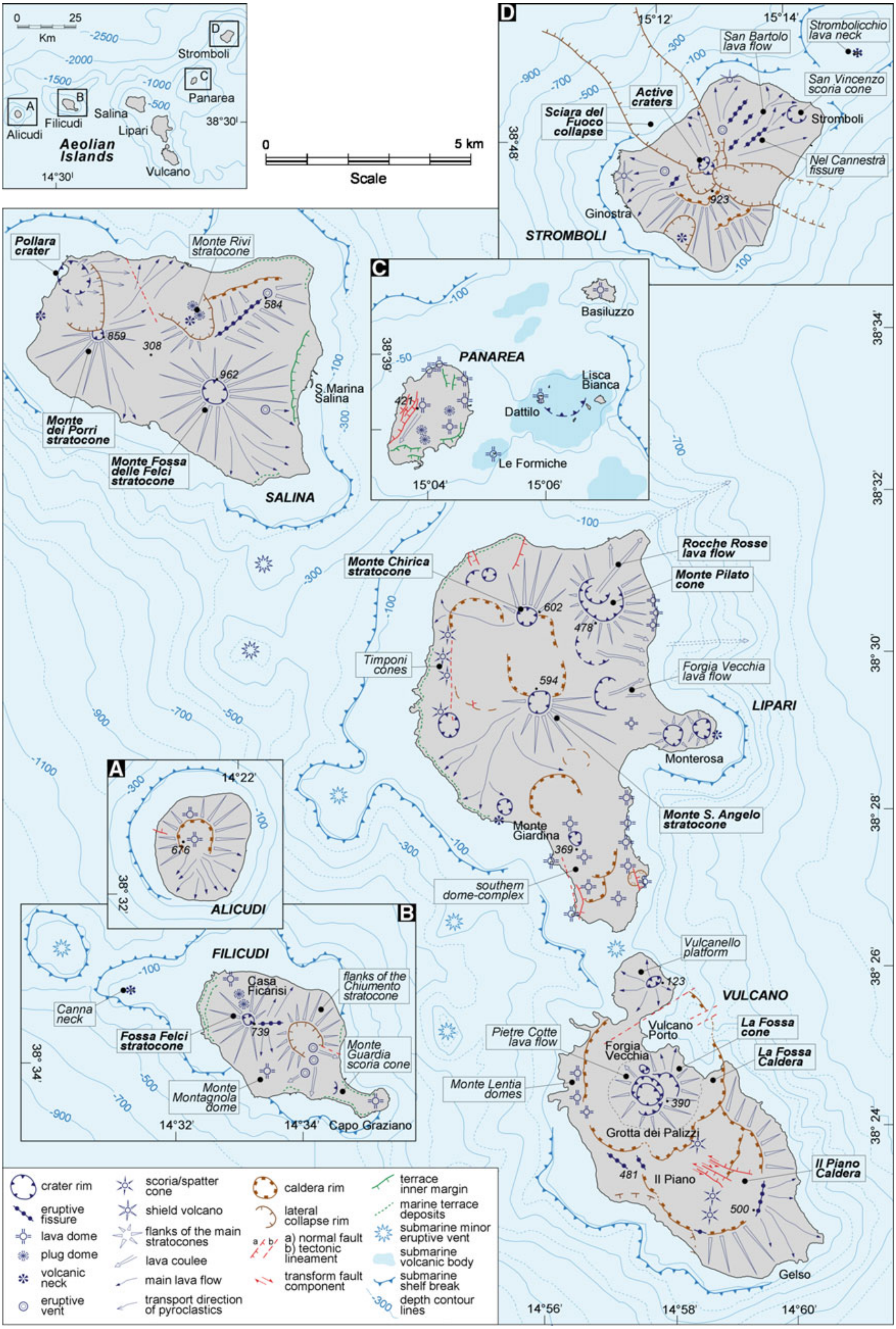

Fig. 38.3 Morphostructural sketch maps of the Aeolian Islands with the main volcanic and volcano-tectonic landforms and structural features. Dykes are not displayed because they are out of scale. Late Quaternary marine terraces and submarine erosive shelf breaks are also shown. *Numbers on the islands* indicate metres above sea level. *Depth contour lines* are in metres below sea level

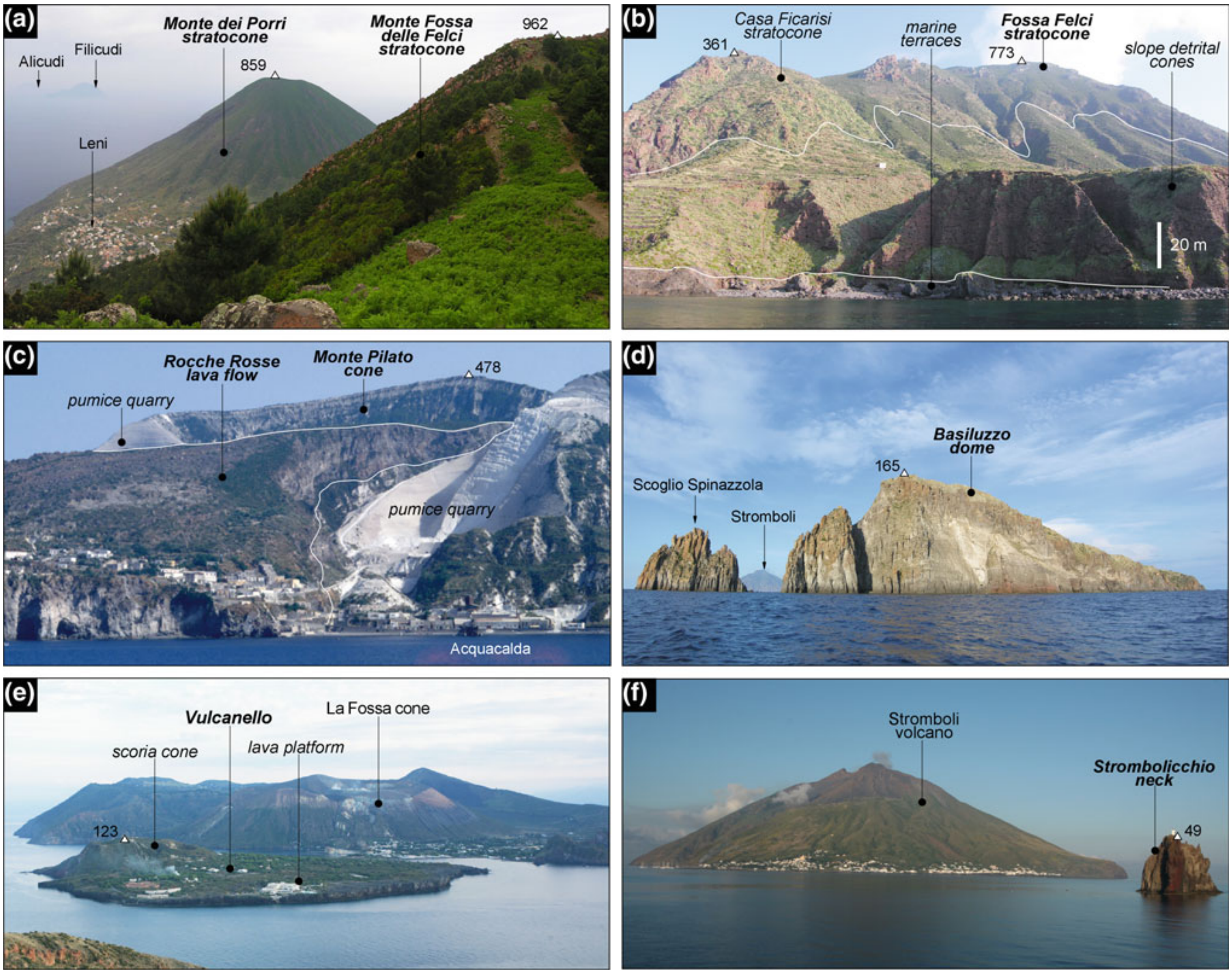

Fig. 38.4 Selected volcanic landforms in the Aeolian Islands. *Numbered points* in the figures indicate metres a.s.l. **a** Monte dei Porri and Monte Fossa delle Felci stratocones on Salina. **b** Northern side of the Fossa Felci and Casa Ficarisi stratocones on Filicudi, with thick detrital slope cones resulting from epivolcanic processes. **c** Northern view of the Rocche Rosse obsidian coulee originated from the rim of the Monte Pilato pumice cone (Lipari), the flanks of which are deeply cut by pumice quarries. **d** Basiluzzo endogenous dome, NE of Panarea. **e** Vulcanello lava platform and composite scoria cone in the northern sector of Vulcano. **f** Strombolicchio lava neck, NE of Stromboli (Stromboli in the *background*)

Giardina—Monte Guardia—San Lazzaro domes on Lipari) or caldera rims (Monte Lentia domes on Vulcano; Fig. 38.5a). Panarea and the surrounding islets are particularly assumed as a polygenic, multivent cluster of endogenous and plug domes (partly eroded and destroyed) lacking of a central vent.

There are some lava flows, both silicic and mafic, that constitute independent distinctive landforms. The Rocche Rosse obsidian-rich rhyolite coulee originated from the Monte Pilato cone in the High Middle Ages is known worldwide (Fig. 38.4c), whereas other examples of silicic coulees are well preserved on Lipari (Forgia Vecchia) and Vulcano (Pietre Cotte; Fig. 38.3). Mafic lava flow fields are instead recognized on Stromboli (San Bartolo) and Vulcano (Vulcanello; Fig. 38.4e). Moreover, peculiar features are represented by welded scoriaceous agglomerates related to fountain-fed explosive phases of independent fissures developed along regional tectonic trends on the northeastern flank of Stromboli (e.g. Nel Cannestrà fissure) or different caldera rims along the western coast of Vulcano (Fig. 38.3).

Eroded volcanic landforms are the result of erosion and denudation of the volcanic edifices leading to substantial inversion of topographic relief (Thouret 1999). They are mostly represented by volcanic necks and dykes. The Canna and Strombolicchio necks (Fig. 38.4f), located offshore the coasts of Filicudi and Stromboli (Fig. 38.3), are the solidified conduits of almost entirely dismantled (and submerged) stratocones, the original geometry of which is made evident by sub-rounded, flattish submarine shelves. Dykes are numerous in the Aeolian archipelago, mostly with a

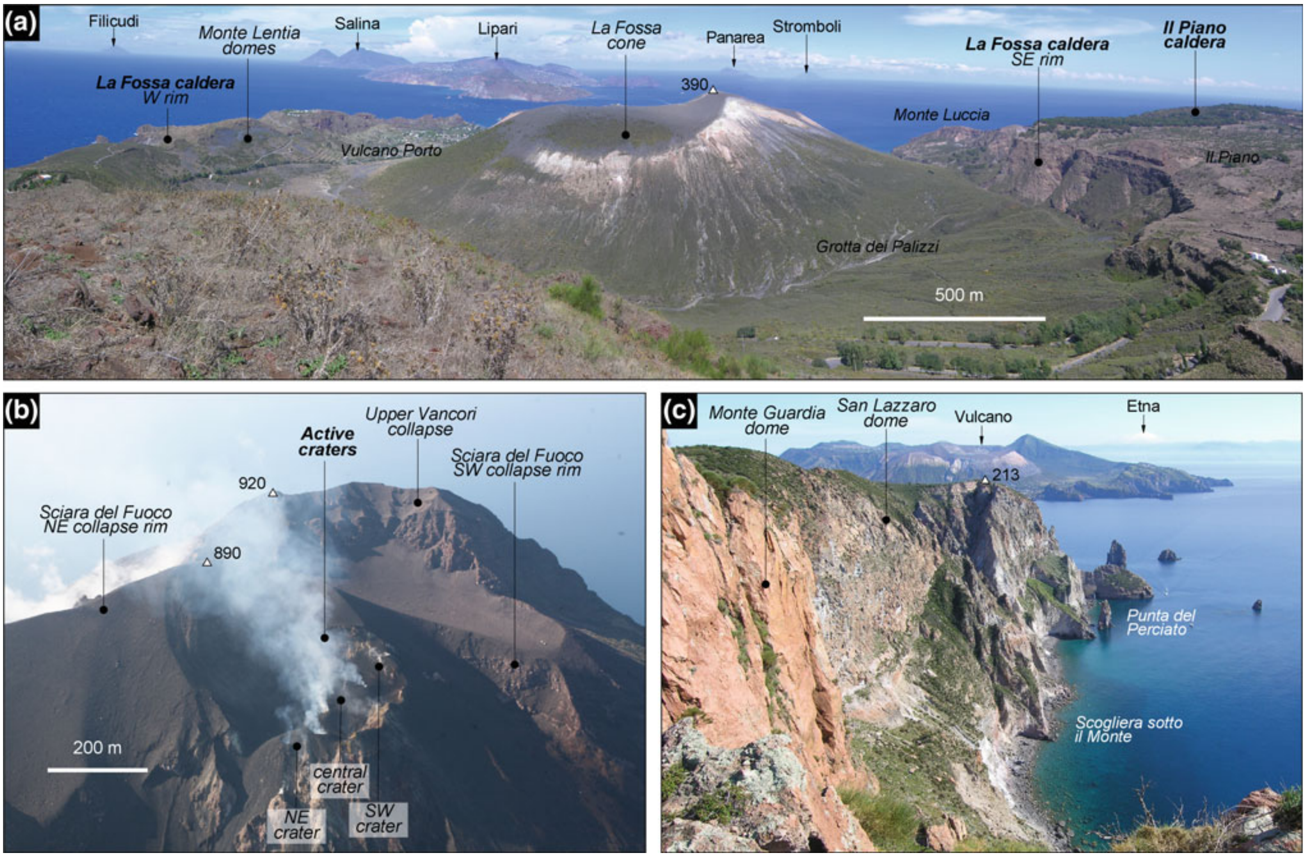

Fig. 38.5 Volcano-tectonic collapses and structural features in the Aeolian Islands. *Numbered points* in the figures indicate metres a.s.l. **a** La Fossa caldera rims on Vulcano, surrounding La Fossa cone. The rim of the older Il Piano caldera is visible on the right side. **b** Aerial view of the summit area of Stromboli with the active craters (NE, central and SW) aligned in NE–SW direction near the headwall of Sciara del Fuoco collapse. **c** NNW–SSE normal faults along the Tindari-Letojanni structural trend truncate the southern dome-complex of Lipari producing a steep coastal cliff. The southern part of the Monte Giardina-Monte Guardia-San Lazzaro dome-alignment is also exposed

subvertical and radial arrangement around the main stratocones, and represent the feeders of the successive eruptive sequences. Parts of the dykes are aligned along specific directions reflecting the influence of the main tectonic trends, whereas several dykes are recognized on Stromboli along the walls of the Sciara del Fuoco collapse (Tibaldi 2001).

38.3.2 Volcano-Tectonic Collapses

A substantial part of the morphogenetic activity in volcanic areas is related to events of catastrophic volcano-tectonic failure of volcanic edifices, which are represented by calderas or lateral collapses. These collapses produce impressive landforms, and also exert direct control on the localization of the subsequent eruptive vents, which are generally sited along the rims or in the centre of the collapse depressions.

Calderas are subcircular to elliptical (km large) depressions formed by the vertical collapse of the roof of shallow magma reservoirs. They are recognized in most of the Aeolian Islands (Fig. 38.3), interrupting the construction of the Alicudi and Stromboli composite volcanoes or truncating some of the major stratocones on Salina, Lipari and Vulcano. The best examples are the piecemeal La Fossa and Il Piano calderas on Vulcano (De Astis et al. 2013), formed between ~100 and ~13 ka and partly filled by the subsequent eruptive sequences of La Fossa cone (Fig. 38.5a; see Sect. 38.4.1). Most calderas in the Aeolians (e.g. on Alicudi and Stromboli) are almost completely filled by more recent volcanic successions, and are generally made visible by structural discordances along the flanks of the cones.

Lateral collapses (sector or flank collapses) affect the summit and flanks of the main stratocones (Monte dei Porri and Monte Rivi on Salina, Chiumento on Filicudi), as recorded in steep-sided (exceeding 30°), amphi-theatre-shaped scars delimited by subvertical rims and with volumes of 0.5–2 km^3. These collapses are mostly induced by high topographic relief and steep dipping slopes of the stratocones, combined with high eruption rates and repeated intrusion of dykes. Recurrent lateral failures during the Holocene (Tibaldi 2001; Francalanci et al. 2013) are recorded in the multi-stage Sciara del Fuoco collapse structure on the summit and NW flank of Stromboli (Fig. 38.5b; Sect. 38.4.2). As typical in volcanic islands, the lateral collapses of Stromboli are associated with voluminous debris avalanche deposits with megablocks, documented at the foot of the submarine volcano slopes (Bosman et al. 2009).

38.3.3 Structural Features

The structural trends acting in the Aeolian Islands are directly outlined by normal and strike-slip faults (Fig. 38.3), although they generally have a low degree of preservation due to subsequent erosion and covering. Impressive strike-slip to normal faults with *ca.* 100 m high subvertical fault scarps truncate the silicic dome-complex in the southern sector of Lipari (Fig. 38.5c). They are NNW–SSE-aligned along the Tindari–Letojanni fault system that dominates the structural setting of the central Aeolian sector. A series of high-angle normal faults with tens-of-metres vertical dip slips cut the western side of Panarea along the NE–SW direction of the main structural trend acting in the eastern Aeolian sector (Fig. 38.3).

Other structure-related features characteristic of volcanic areas are the alignments of coeval domes (Fig. 38.5c) or cones, aligned crater rims or vents (e.g. the active craters of Stromboli; Fig. 38.5b) or elongated eruptive fissures and dykes that provide information on the tectonic trends acting on magma ascent through the crust up to surface.

38.4 Contemporary Activity

Stromboli and Vulcano are characterized by active volcanic and volcano-tectonic landforms, and recent to ongoing manifestations of eruptive and hydrothermal activity. There, volcanic geomorphology can provide a fundamental contribution to risk assessment through (1) geomorphic hazard zonation, (2) recognition of the more probable areas of future opening of eruptive vents and fissures and (3) evaluation of the influence of landforms on the transport and deposition of the erupted products and volcanogenic flows.

38.4.1 La Fossa Cone and Caldera (Vulcano)

The Holocene history of Vulcano has been mostly characterized by the construction of La Fossa cone (De Astis et al. 2013), standing out in the centre of La Fossa caldera in the northern sector of the island (Fig. 38.5a). Recurrent eruptive phases have occurred there during the past two millennia (alternating with Vulcanello) up to the well-known AD 1888–1890 eruption that gave the name to the “vulcanian” eruption style. This cone is presently characterized by an active hydrothermal system with several high-temperature fumaroles around the summit crater. Different hazard scenarios are related either to the active geomorphic evolution of the cone or the short-term renewal of eruptive activity. Volcanic risk is high here because La Fossa cone is located near to the main inhabited area of Vulcano Porto, which is crowded by thousands of tourists during the summer.

La Fossa cone is 391 m high and steep-sided (average slope angles of 30°), and is constructed by stratified, coherent to incoherent pyroclastic successions and a few viscous lava flows. Large portions of the cone are inherently unstable due to oversteepened slopes and the stratified internal structure of the cone, with unconsolidated layers acting as potential sliding planes. The conditions of gravity-driven instability may be enhanced by shallow seismicity and ground deformation associated with movements of magma. In 1988 a landslide of *ca.* 200,000 m^3 occurred along the NE flank of La Fossa cone during a period of volcanic quiescence (Fig. 38.6), sliding into the sea and producing a small tsunami (Romagnoli et al. 2012). The entire NE flank of the edifice is in fact in conditions of poor stability due to ongoing sea-wave undercutting and cliff-retreat and to active submarine erosion (Fig. 38.6), which particularly threaten the coastal settlement of Vulcano Porto (Romagnoli et al. 2012). Other areas of slope instability are sited along the N (Forgia Vecchia) and SE flanks of the cone (Grotta dei Palizzi; Figs. 38.5a and 38.6) due to weakening of hydrothermally altered rocks.

A different hazard scenario involves the short-term (tens to hundreds of years) eruptive reactivation of La Fossa cone (Dellino et al. 2011). This is expected to occur as a vulcanian eruption giving rise to pyroclastic density currents accompanied by fallout of ballistic blocks and bread-crust bombs. Over most of La Fossa history ($\sim$5 ka), the currents laterally spreading from the summit crater have been confined by the steep and subvertical walls of the La Fossa caldera surrounding the cone (Figs. 38.5a and 38.6). Only a few currents during the Grotta dei Palizzi activity ($\sim$1.6 ka) were able to pass over the topographic barrier of the caldera walls and reached the inhabited area of Il Piano in central Vulcano (Fig. 38.3), thus being considered the most hazardous eruptive event on the short-term.

38.4.2 Active Craters of Stromboli and Sciara del Fuoco Collapse

The active craters of Stromboli are located near the headwall of the Sciara del Fuoco collapse (Figs. 38.5b and 38.7), and

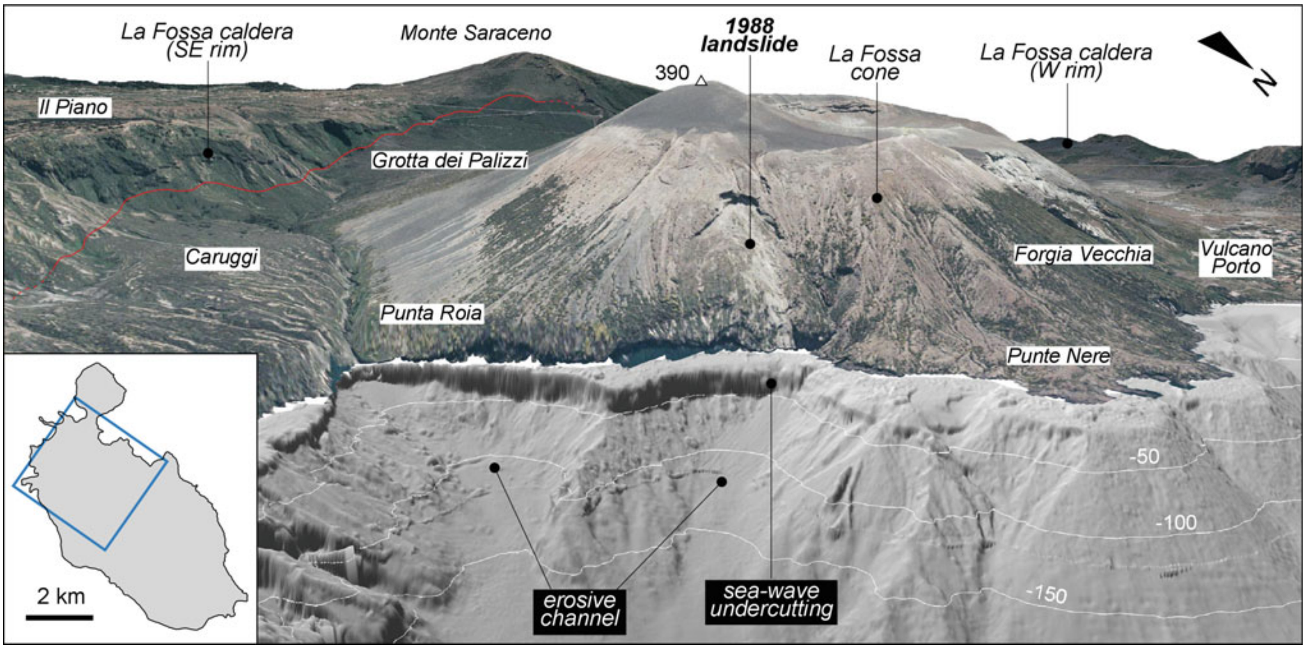

Fig. 38.6 3D image of the NE flank and submarine slopes of La Fossa cone, with the 1988 landslide scar and evidence for sea-level undercutting and submarine erosive channels (modified after Romagnoli et al. 2012). It is shown that the distribution of La Fossa cone pyroclastic deposits (*outer border in red*) is conditioned by the La Fossa caldera rims. *Depth contour lines* and *quoted points* are in metres b.s.l. and a.s.l

are characterized by persistent and mildly explosive activity typical of the “strombolian” eruption style. This activity has been continuous starting from the eighth century (Francalanci et al. 2013). The relevant scoriaceous products are mostly confined within the borders of Sciara del Fuoco and accumulate in the area around the craters and along the collapse slope (Fig. 38.7a). Spatter and lithic fragments related to intermittent, more energetic explosions (paroxysms) can overcome the collapse walls and are deposited along the flanks of the cone, occasionally reaching the inhabited areas of Stromboli and Ginostra (Fig. 38.3). The collapse particularly acts as a topographic trap for episodic lava flows originated from the summit craters and vents/fissures opened inside the collapse depression (Fig. 38.7a). These lava flows go through the steep collapse scar and frequently reach the sea forming lava deltas that are rapidly dismantled by marine erosion (Fig. 38.7a; Calvari et al. 2010). Through the Holocene, the Sciara del Fuoco collapse area has been episodically filled up to the rim by lava flows that surmounted its lateral rims and laterally expanded along the flanks of the cone. The latest lava overflow of the collapse rims was recorded in the High Middle Ages (Francalanci et al. 2013).

The progressive rapid accumulation of volcanic products along the steep and unstable slopes of Sciara del Fuoco (average slope angles of 35–38°) may easily induce events of lateral failure by overloading and oversteepening effects, enhanced by the recurrent intrusion of NE-trending dykes. Five major NW-dipping collapses are recorded during the Holocene, with the latest one occurred in the Late Middle Ages (Francalanci et al. 2013). These large-scale sector collapses are catastrophic events that mobilize up to few km^3 of material, but the related hazard is not very high as these events show recurrence periods of some (or more) thousand years. Conversely, medium-scale landslides (volumes up to some millions of m^3) affecting the Sciara del Fuoco slope are more hazardous as they occur with higher frequency, i.e. from some hundreds up to a few tens of years (Casalbore et al. 2011). These events are able to generate local but severe tsunamis when occurring in shallow-water, as demonstrated by the recent 2002 tsunamigenic landslide of $\sim 25 \times 10^6$ m^3 that affected the subaerial and submerged slopes of Sciara del Fuoco (Fig. 38.7b; Baldi et al. 2008). This landslide resulted in a small tsunami with waves up to 10 m high that struck the Stromboli coasts and the surrounding areas. Previous small tsunamis were reported in 1879, 1916, 1919, 1930, 1944 and 1954, mostly associated with hot avalanches or pyroclastic flows entering the sea during paroxysms (Barberi et al. 1993).

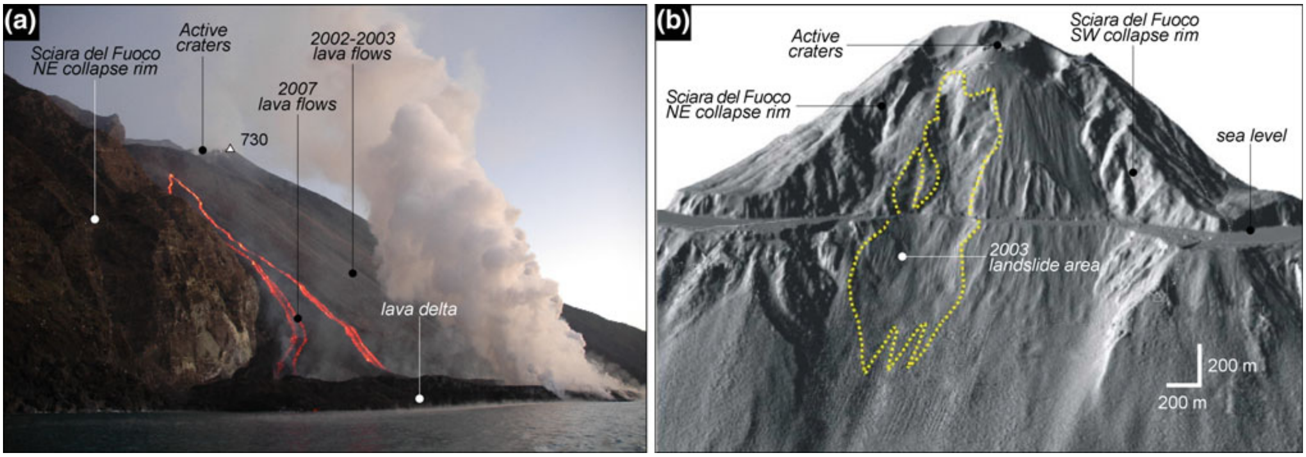

Fig. 38.7 **a** View of the Sciara del Fuoco collapse showing the lavas erupted in 2007 flowing down the steep slopes delimited by the NE collapse rim and forming a lava delta. The 2002–2003 lava flows and other products of the recent activity of Stromboli also fill the collapse. **b** 3D frontal view of Sciara del Fuoco showing the 2002 landslide area along the emerged and submerged slopes (modified after Baldi et al. 2008)

38.5 Conclusions

Landform analysis of the Aeolian Islands volcanoes allows for the recognition of the main volcanic landforms (stratocones, domes, lava flows, fissures), and their subsequent modification by erosion processes and volcano-tectonic collapses (caldera, lateral collapses). Moreover, volcanic geomorphology can give information on the localization through time of active eruptive vents, calderas, and lateral collapses under control of the regional tectonic trends acting in the different sectors of the archipelago. This provides important information for geological mapping and reconstruction of the main steps of island-building and destruction through the interaction between volcanism, volcano-tectonic events, tectonic activity, and sea-level fluctuations. Implications for volcanic hazard and risk assessment are primarily related to the currently active volcanoes of Stromboli and Vulcano, where the volcanic landforms and collapses play a fundamental role in controlling the localization of active vents and conduits and the distribution of volcanogenic flows, and in promoting flank instability.

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39

Geomorphology of the Capo San Vito Peninsula (NW Sicily): An Example of Tectonically and Climatically Controlled Landscape

Valerio Agnesi, Christian Conoscenti, Cipriano Di Maggio, and Edoardo Rotigliano

Abstract

The Capo San Vito peninsula is located along the north-westernmost sector of the Sicilian coastline. It is characterized by a complex geomorphological setting, where a large variety of coastal, gravity-induced and karst landforms allow the visitor to easily detect the interactions between Quaternary tectonics and climate changes as well as morphodynamic processes responsible for shaping the landscape. Thanks to natural reserves, the peninsula preserves a typical Mediterranean natural environment, marked by spectacular and suggestive landforms.

Keywords

Marine terraces • Landslides • Karst landforms • Sicily

39.1 Introduction

The Capo San Vito peninsula stretches northward for near 18 km into the Tyrrhenian Sea from the north-westernmost Sicilian coastline, with a width narrowing from 20 to 5 km (Fig. 39.1). Two main carbonatic ridges limit its landscape from the south and east, leaving space, in the central-western and northernmost sectors, for nearly level areas. The peninsula is characterized by a complex geomorphological setting and shows spectacular coastal, gravity-induced and karst landforms, such as marine terraces limited by high cliffs, large rafted rock blocks sunk into a clayey substratum, large polje and dolines. In spite of low density of population, human activity has locally had a great impact on the landscape due to intense quarrying. At the same time, the peninsula hosts some of the most important natural reserves of Sicily.

The great scenic value of the landscape of the Capo San Vito peninsula is directly linked to the same reasons that determine its high scientific interest. In fact, relict well-preserved and active spectacular landforms are the result of the controlling role that tectonic and climate exerted on the main morphodynamic processes shaping the peninsula during the Quaternary. Visitors are thus allowed to easily read such interactions in the field, through a large set of landforms and in the framework of a suggestive and evocative Mediterranean scenario.

39.2 Geographical and Geological Setting

The Capo San Vito peninsula is marked by a S–N oriented ridge declining from Mt. Sparagio (1110 m a.s.l.) to Mt. Monaco (532 m). The ridge, which is limited in the south by the E–W oriented structure of Mt. Sparagio, runs along the eastern side of the peninsula, whereas coastal plains of Castelluzzo and San Vito lo Capo occur in the western and northernmost sectors.

From a geological point of view, the peninsula is part of the Sicilian fold and thrust belt, structured along the Africa–Europe plate boundary in the Central Mediterranean, made of several imbricate units, essentially emplaced during the Miocene. In the study area, two main tectonic units have been recognized (Catalano et al. 2011): (1) an imbricate fan composed of Mesozoic-Paleogene platform carbonates (*Panormide units*) overlain by Miocene pelagic deposits; (2) Upper Triassic to Liassic shelf and Jurassic to Paleogene deep-water carbonate rocks (*Trapanese units*), overlain by Miocene pelagic clays and marls. The Panormide units overthrust the Trapanese units.

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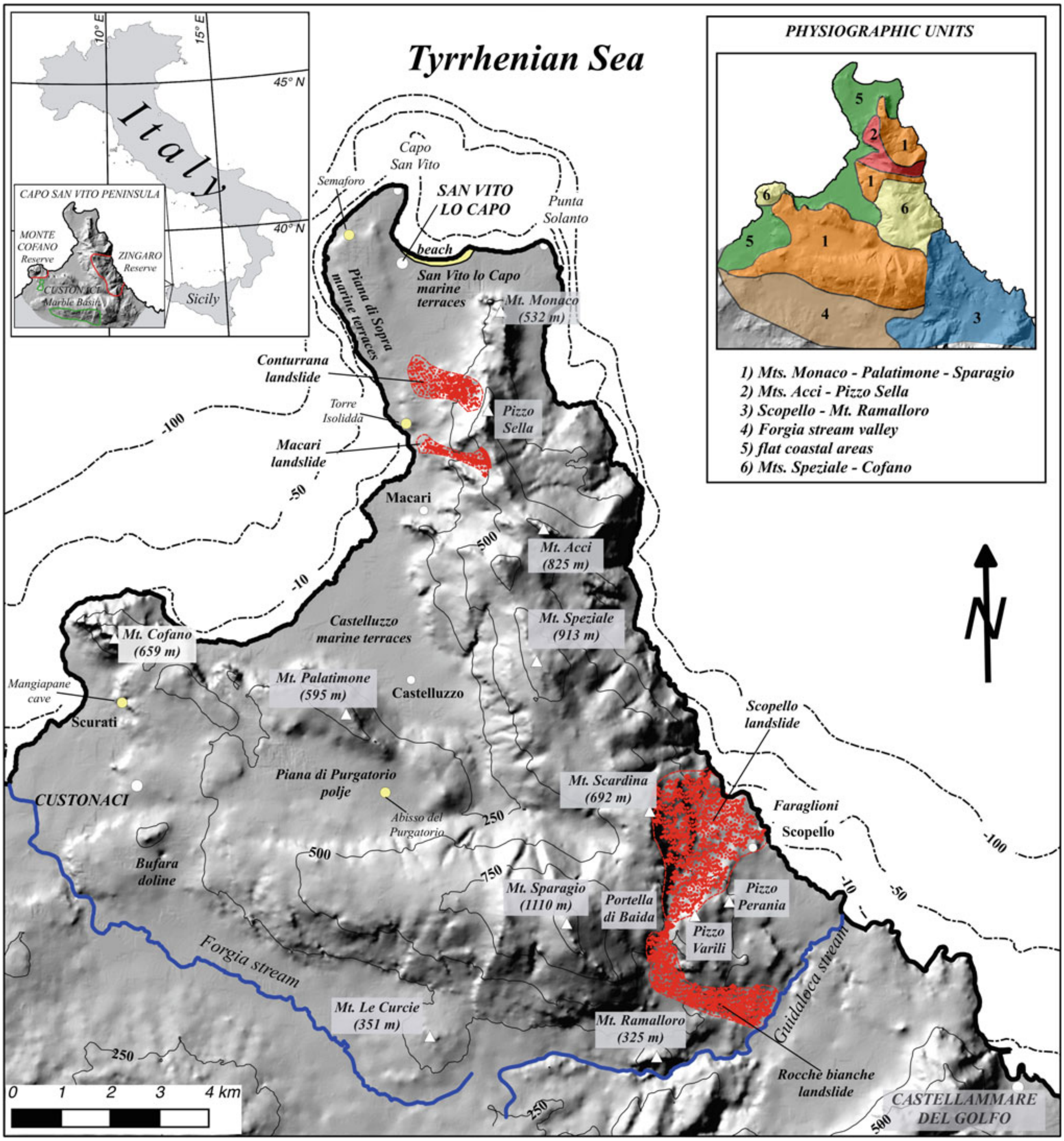

Fig. 39.1 Geographical setting of the Capo San Vito peninsula, main geomorphological features and physiographic units

Finally, Lower Pleistocene neritic bioclastic calcarenites (*Marsala synthem*) crop out in the Castelluzzo area.

According to the Köppen classification, the climate is typical Mediterranean (Csa) with mean annual rainfall of about 475 mm, concentrated between September and March–April. The monthly temperature (19 °C on average) ranges between 12 °C in January and 28 °C in August.

The whole territory of the Capo San Vito peninsula is part of the Trapani province, and its main municipalities are Custonaci (5441 inhabitants, 186 m a.s.l.), San Vito lo Capo (4577 inhabitants, 5 m)—including the hamlets of Castelluzzo and Macari—and Castellammare del Golfo (15,116 inhabitants, 24 m), including the village of Scopello.

39.3 Geomorphological Features

On a large scale, the geomorphological setting of the study area is marked by large tectonic structures/forms, such as horsts and half-grabens, bounded by fault scarps hundreds of metres high (Di Maggio et al. 2017). On a smaller scale, landforms connected to (a) "lateral bevelling" (planation surfaces and wave-cut platforms), (b) deepening processes (fluvio-karst canyons, V-shaped valleys and hanging and isolated abandoned valleys) and (c) enhancement of relief energy (landforms due to differential erosion or deep-seated/shallow mass movements) are observed.

Considering geological structure and the consequent geomorphic landscape, Capo San Vito peninsula can be partitioned into six physiographic units (Fig. 39.1):

1. Mt. Monaco, Mt. Palatimone and Mt. Sparagio areas, where karstified planation surfaces at different heights, karst depressions, abandoned valleys, fluvio-karst canyons, cliffs and structurally controlled slopes are responsible for a mountainous landscape bordered by large scarps and frequently hosting small to widespread flat areas at the summits;
2. Mt. Acci–Pizzo Sella area, whose uneven landscape, made of non-uniform slopes, is the result of the alternation of gentle denudation slopes and abrupt scarps due to selective erosion;
3. Scopello–Mt. Ramalloro area, in the south-westernmost edge of the peninsula, which shows a very rough landscape, mainly shaped by surficial to deep-seated landslides, water erosion processes and selective denudation;
4. Forgia stream valley, which limits the peninsula in the south, with a hilly landscape developed on marly-clayey rocks;
5. Flat coastal areas, where successions of marine terraces produce a homogeneous landscape interrupted by scarp systems corresponding to abandoned sea cliffs;
6. Mt. Speziale and Mt. Cofano areas, with large summit planation surfaces, bordered by wide and weathered structurally controlled scarps and internally cut by tectonic-karst depressions.

On the whole, the landscape of the Capo San Vito peninsula merges low (marine terraces) and high (karstified planation surfaces) flat areas, presently located at different heights as a result of tectonic and climate changes. The flat areas are laterally bordered by low to high slopes (abandoned sea cliffs and structurally controlled slopes), while in the inner zone karst, fluvio-karst or tectonic depressions as well as landslides and landforms due to selective erosion interrupt their continuity. Anthropogenic processes are responsible for very recent and, in some areas, profound landscape changes, which affected both the coastal (tourism activities) and the inner sectors (quarries). At the same time, the peninsula hosts two of the most important protected areas of Sicily (the "Zingaro" and the "Monte Cofano" natural reserves).

39.4 Coastal Landforms

39.4.1 Marine Terraces

Marine terraces are located in the northern and western areas of the Capo San Vito peninsula. They are the result of wave erosion, responsible for long-lasting parallel retreat of the cliffs and the genesis of platforms at their foot, during the phases of marine highstand connected to several warm climate phases, in the Middle and Late Pleistocene. Their emergence above the present sea level is mainly due to the Quaternary tectonic uplift (Di Maggio et al. 1999; Antonioli et al. 2002; Bonfiglio et al. 2004). The phases of marine highstand are indicated by bands of lithodome holes, wave-cut notches and sea caves partially filled by marine/continental fossiliferous deposits (Di Maggio et al. 1999). Due to their genesis, this set of well-preserved coastal features plays a crucial role in the understanding of the relationships between tectonics, climate changes, and eustatic fluctuations of Sicily during the Quaternary.

The successions of marine terraces occur in different settings, depending on the tectonic features of the areas in which the terraces lie. Where the uplift rate was low, the successions consist of few large polycyclic wave-cut platforms; where the uplift rate was high, the successions are characterized by more frequent but smaller platforms (Di Maggio et al. 1999; Antonioli et al. 2002).

The existence of these well-preserved relict landforms is linked to the presence of resistant carbonate rocks. In the plain where the San Vito lo Capo village is located and in the Piana di Sopra area, the marine terraces are cut in Mesozoic marine carbonate rocks (Panormide Units), while in the plain of Castelluzzo they are carved in Lower Pleistocene marine calcarenite rocks.

The Piana di Sopra area is a tableland delimited by scarps tens of metres high, located in the northwestern area of the peninsula (Fig. 39.2). This landscape is the result of marine erosion, which, controlled by eustatic fluctuations and Quaternary tectonic uplift, carved several sub-planar surfaces producing seven different levels of marine terraces. The top flat surface, extended for near 4 km^2, is deformed by a NNE–SSW fault showing a left-lateral displacement. The phase of marine highstand, which produced this terrace, is recorded by inactive wave-cut notches and sea caves cut in the high abandoned cliffs (e.g. Torre Isolidda site). The inner surfaces of these caves show bands of lithodome holes and locally are partially filled by deposits bearing marine

Fig. 39.2 Piana di Sopra area. The uppermost abrasion platform crossed by a fault scarp and bordered by structurally controlled sea cliffs tens of metres high

invertebrates and occasionally mammals and pulmonate mollusc remains. The vertebrate fossils can be attributed to the *Elephas falconeri* Sicilian Faunal Complex, dated to the Lower-Middle Pleistocene. Locally, the lower more recent marine platforms are covered by coastal conglomerates and calcarenites with a rich warm-temperate fauna, including *Strombus bubonius*, or by continental deposits with mammal assemblages attributed to the *Elephas mnaidriensis* Sicilian Faunal Complex, dated to the Upper Pleistocene (Bonfiglio et al. 2004).

The areas of the San Vito lo Capo and the Castelluzzo villages (Fig. 39.3) consist of coastal plains bounded by inland scarps hundreds of metres high. The coastal plains are old wave-cut platforms; the high scarps are abandoned sea cliffs, whose development has been mainly controlled by N–S, NNW–SSE and E–W fault systems (Catalano et al. 2011). About 0.5 km wide abrasion surfaces follow the present-day coastline, forming a lateral continuous strip located at altitudes between 0 and 18 m. Rare patches of coastal/marine deposits with *Strombus bubonius* or continental breccias with *Elephas mnaidriensis* locally overlie the abrasion surfaces (Cottignoli et al. 2002).

The succession of emerged marine terraces from 0 to about 100 m indicates an uplifted area and the correlation with coastal and mammal deposits at Piana di Sopra allowed us to define a morphoevolutive model of the marine terraces system, starting from the first emersion of the area (Fig. 39.4). The older terrace orders (I order), cut into Lower Pleistocene rocks, permit to date the beginning of the terrace succession to the interglacial phases of the post-Lower Pleistocene, whilst the younger (VII order) can be correlated with more recent marine highstands (100–90 ka ago).

The Capo San Vito peninsula, where successions of marine terraces are very clearly exposed, constitutes a highly didactic area for the understanding of the control on marine processes exerted by Quaternary climatic changes and neo-tectonic uplift. The presence of fault scarps and displaced wave-cut platforms or terrace deposits, in fact, points to the occurrence of tectonic events. In particular, the faults that produce fault scarps within the I order, uppermost terrace surface and that displace the II order terrace and its deposits at Semaforo site, responsible for the difference in altitude within its sea caves and inner edge at Piana di Sopra area, are linked to one or several tectonic events younger than genesis of the I and II order terraces and older than genesis of the III order terrace. The difference in altitude within the inner edges of the marine terraces as far as the VI order indicates tectonic events up to Eutyrrhenian age (125,000 years BP) and beyond.

39.4.2 Beaches

The San Vito beach is the only beach along the peninsula and is located in its northernmost edge. It extends for more than 2 km and is made of bioclastic sand, mainly composed

Fig. 39.3 Marine terraces in the Castelluzzo area

by shell fragments (Fig. 39.5). The submerged zone is covered by a well-developed Posidonia prairie. The San Vito Cape protects the strand from the prevailing northwestern (*Maestrale*) winds, so that the beach drift is E-W oriented, being controlled by eastern winds (*Grecale*).

Starting from the 1960s, the morphology of the beach has been strongly affected by construction of the little harbour of San Vito lo Capo, whose docks have modified the littoral drift, and by the huge expansion of the town, which largely occupied the backshore. Moreover, trawling and summer touristic sailing are responsible for the partial erosion of the Posidonia prairie.

Notwithstanding the recent modifications of the natural landscape, the San Vito beach still preserves its scenic quality and touristic value, being included among the most beautiful beaches of Italy.

39.5 Landslides

Landslide types and dimensions at the Capo San Vito peninsula are strictly related to its geological setting, whilst Quaternary climate changes and tectonics have controlled their activity and evolution. In light of the widespread outcropping of brittle rocks, landslides took place in areas where these rocks contain mechanical discontinuities (e.g. lithologic variation, tectonic surfaces and bedding planes) or where erosion processes have exhumed the underlying ductile substratum. In particular, spectacular fast shallow (Macari–Conturrana area) and slow deep-seated (Scopello and Rocche Bianche area) landslide phenomena affect the northwestern and the southeastern sectors of the peninsula, respectively (Fig. 39.1).

39.5.1 The Macari–Conturrana Area

The Pizzo Sella area, due to the presence of high structural scarps made of carbonate rocks, is characterized by high rock fall hazard. The last relevant event occurred on 28 February 2001, when a rock fall hit the Macari village, detaching large blocks, which accumulated in a 470 m long and 90 m wide area. The detached blocks totally destroyed seven houses and heavily damaged twenty more. As a consequence of the rock fall, the civil protection authority ordered the evacuation of more than 200 people from the small village.

In the north-western sector of Pizzo Sella, the Conturrana landslide represents one of the largest gravity-induced phenomena of San Vito peninsula, involving an area of nearly 250,000 m^2. The landslide involved translational slide and rock avalanche, which affected a slope made of highly tectonized marls overlain by carbonatic rocks, locally forming a very narrow fold. The triggering mechanism is likely to be connected to a large earthquake that presumably occurred in the third or fourth century BC (Nicoletti and Parise 1996). The landslide body, which rests on the southern sector of the Piana di Sopra terrace, is 1.3 km long and 650 m wide.

A popular tradition of religious origin says that the landslide was the result of the wrath of God, who was

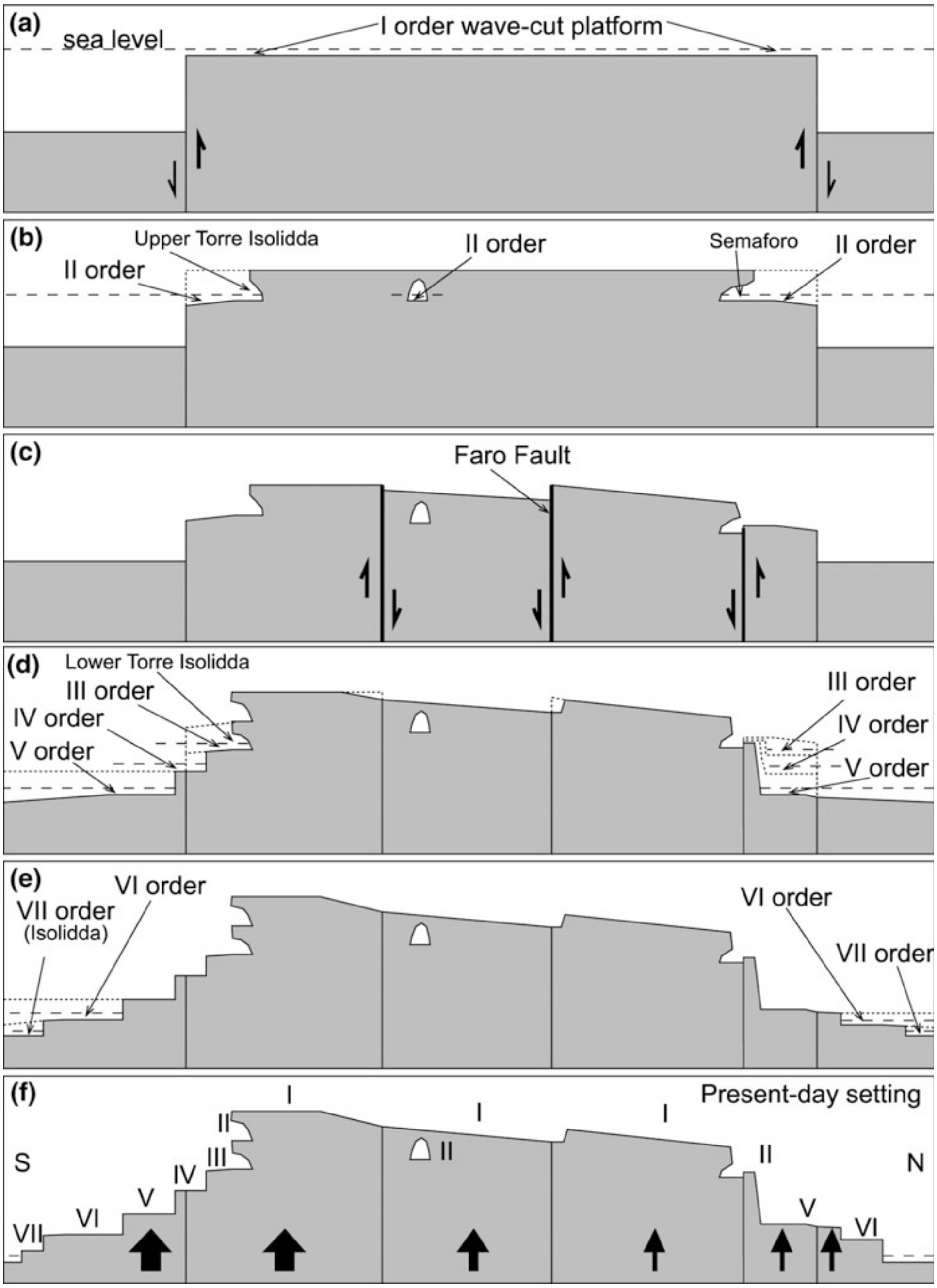

Fig. 39.4 Evolutionary model of the Piana di Sopra area. Note that the area is constantly being uplifted, except the relative subsidence and a local northward tilting due to the block-faulting movements (steps *a* and *c*). The current altitude of the inner edges of each order of marine terrace (step *f*) is growing from north to south, indicating overall uplift rates higher in the southern area (about 0.15 m/ka) and gradually lower in the northern area (about 0.1 m/ka). The *black arrows* in step *f* are proportional to rates of tectonic uplift: the larger the size, the higher is the uplift rate

offended by the blasphemous and licentious habits of the people living in the old Conturrana village, to the point of causing its total destruction and burial. The only survivors to the disaster were San Vito, a young mystic who was visiting preaching the village for, and his nurse Santa Crescenza. But during the escape, the nurse, transgressing God’s instruction, turned her view back to the village and, for this, was punished and suddenly petrified. In memory of this old legend, the San Vito lo Capo inhabitants erected a little votive chapel, dedicated to Santa Crescenza, located just on the tip of the landslide, where the devout followers use to leave a stone for any grace received.

39.5.2 The Scopello and Rocche Bianche Landslides

The Scopello and Rocche Bianche landslides (Agnesi et al. 2000, 2015; Di Maggio et al. 2014) are located in the southeastern edge of the Capo San Vito peninsula

Fig. 39.5 The San Vito lo Capo beach (Mt. Monaco and Pizzo Sella in the background from *left* to *right*)

(Fig. 39.1), where an overthrust plane outcrops, separating a rigid fractured slab made of Mesozoic carbonate rocks from the underlying ductile substratum, corresponding to Tertiary marly-clayey terrains.

During the Miocene-Pleistocene tectonic phases, the general uplift of the area and the related block-faulting phenomena determined fracturing of the carbonate slab, its emersion and activation of intense erosion processes. The following exhumation of the overthrust plane laterally unlocked the rigid carbonate slab so that deep deformation phenomena could have been activated (differential settling, back tilting, block sliding and lateral spreading), leading to the partitioning of the ancient rigid slab.

From the common crown area of the Portella di Baida saddle, two diverging "twin landslides" can be observed: the Scopello and the Rocche Bianche landslides, which stretch towards the sea coast (NNE) and the Guidaloca stream (S), respectively. The landslides involved complex movements, including deep to surficial deformation, affecting the rigid slab and the ductile substratum, respectively.

Starting from the same geomorphological setting, depending on the difference of the local erosion base level and the type of lateral eroding/unlocking process (coastal and stream erosion, respectively), the Scopello and the Rocche Bianche landslides show different evolution stages and dimensions, with the first being in a much more advanced stage and involving a much wider area. For this reason, since the late 1970s to which the first studies are dated, both scientific and geo-touristic interests almost exclusively focused on the Scopello landslide.

The activity of the Scopello landslides is presently due to both deep-seated deformations, still producing the detachment and seaward spreading/sliding of blocks from the carbonate slab scarps, and shallow to surficial phenomena involving either the thick debris cover or the exhumed ductile substratum. Furthermore, the long lasting deformation has displaced offshore a relevant part of the landslide body. The inner mountain edge of the carbonate slab is marked by a scarp, several tens of metres high, constituting the crown sector of the landslide. From the right and left flanks of scarp, several small to large blocks detached due to lateral spreading and block sliding movement, converging towards the central transportation zone. The blocks have rafted tens to hundreds of metres away from their detachment scarp, with their roots sunk in the underlain ductile substratum (Fig. 39.6).

In the southeastern side (Fig. 39.7), differential settling/back tilting and lateral spreading movements, having NNE direction, affect the carbonate slab, which in this sector is reduced to a narrow ridge (Pizzo Perania).

In the southern coastal sector of the landslide area, disarticulated rafting blocks are observed, reaching the coastline and producing the typical "Faraglioni" landscape (variously dimensioned sea stacks; Fig. 39.8). Oceanographic surveys by side-scan sonar and multi-beam soundings attest for an offshore prolongation of the landslide body up to about 2 km, with a general convex bathymetry and several isolated blocks variously displaced onto the landslide debris.

The Scopello landslide constitutes a unique and very spectacular landscape, where, thanks to the very advanced

Fig. 39.6 The inner mountain sector of the Scopello landslide: blocks of various dimensions are spreading/sliding toward the central sector of the landslide area

Fig. 39.7 The right southeastern sector of the Scopello landslide: the carbonate ridge is disarticulated into few large units by differential settling/back tilting and lateral spreading movements

stage of gravitational phenomena, it is possible to take a direct look on the Quaternary dismantling of an emerged Mesozoic carbonate platform. From the edge of the carbonate slab, it is possible for the viewer to get the whole scene of the phenomena acting on the highest sector of the area, clearly recognizing the “puzzle” of blocks and earth/debris flow bodies moving seaward. The small to large rafting blocks can be easily recognized as well as ideally connected upward to their detachment scarps, whose geometry almost perfectly fit the block shapes. Few kilometres downhill, the medieval Scopello small village itself is located on the top surface of a large disarticulated block. Downhill, where the blocks have reached the sea, spectacular stacks mark the coastal landscape of the “Faraglioni” area, which are at the same time one of the main touristic attraction, attracting a lot of people in summer, and a frequently exploited set for national and international film makers.

Fig. 39.8 The sea stacks in the coastal sector ("Faraglioni") are displaced carbonate blocks emerging from the sea

39.6 Karst Landforms

In a landscape which is largely made of carbonatic rocks, the large population of epigean (e.g. polje, dolines, canyons, karren field) or hypogean (caves)—and horizontally—(e.g. karst planation surfaces, passages) or vertically developed (e.g. canyons, shafts) karst landforms—allows to recognize the effects of the base erosion/karst level changes. In particular, a great number of epigean and hypogean karst landforms can be observed, whose largest example is represented by the Piana di Purgatorio polje, a 2 × 4 km sub-elliptical depression. Its origin was also controlled by tectonics and selective erosion. To the southwest, near Custonaci, the great (200 × 300 m) collapse doline of Contrada Bufara (Fig. 39.9) has long been erroneously considered by the local people as a meteoritic impact crater. Among the epigean landforms, fluvio-karst canyons and karren fields are present along tectonic alignments and over the summit sub-flat areas, respectively.

Dissolution processes are also responsible for the development of a diffused and structured hypogean karstic system, made of an intricate network of shafts and passages, among which the 200 m deep well of Abisso del Purgatorio is one of the most important caves of Sicily.

At the southern foot of Mt. Cofano is located the Grotta Mangiapane; a horizontal cave, 70 m high, 13 m large and 50 m long, where in the second half of the nineteenth century paleontological and archaeological surveys brought to light several prehistoric finds (tooth and bones fossils, artefacts in obsidian and flint, rupestrian paintings) dated at Upper Epigravettian. This cave, of karst origin, has been opened by marine erosion during the Middle Pleistocene.

Fig. 39.9 The Contrada Bufara doline near Custonaci

Thanks to the large dimensions, some rural houses have been built in the past into the Grotta Mangiapane cave. Starting from the last decade, during the Christmas period, the cave is used by the local people as a living nativity scene, whose evocative and natural location attracts a large number of tourists.

39.7 Human Activities and Protected Areas

On the whole, still nowadays, the distance from towns and the poor road connectivity have actually preserved the Capo San Vito peninsula territory from severe effects of high anthropogenic pressure, which elsewhere has compromised some coastal areas of Sicily. In fact, human impact, mainly consisting in the construction of rural country houses or small buildings, is limited to the surroundings of San Vito Lo Capo and Scopello. A very different scenario arises if focusing the analysis on the southernmost sector of the peninsula (Mt. Sparagio–Mt. Palatimone), where great marble quarries have substantially modified the calcareous slopes. At the same time, efforts to preserve the natural landscape resulted in the establishment of a number of geosites and two important Natural Reserves.

39.7.1 The Marble Basin of Custonaci

The southern slope of Monte Sparagio, in the Custonaci territory, has been since the fifteenth century affected by extraction of Cretaceous platform calcareous rocks commercially named Custonaci marbles. The technical and ornamental value of these rocks (the main type named "Perlato di Sicilia", with an ivory colour hosting dispersed patches of pure calcite), together with the presence of fault scarps, which expose large volumes of easily extractable blocks, have been responsible for the remarkable development of the quarrying activity in the area. Today, more than 200 active sites are recorded, involving an area of 3 km^2 and producing 1.5 million tonnes of rocks per year, employing near 3000 people with 100 million euros of sales volume.

In light of these data, the Marble Basin of Custonaci is the second in Europe for importance.

Such an impressive manufacturing activity has obviously resulted in intense modifications to the landscape, with high bare quarry fronts set at different heights on the slopes and great debris/scraps landfills, which result in uneven and ruiniform morphologies (Fig. 39.10). At the same time, in light of the great economic importance of the quarries, local people and the owner himself have been trying since long time to find a sustainable trade-off.

39.7.2 Protected Areas

Some of the most important protected areas of western Sicily area located in the Capo San Vito peninsula (Fig. 39.1): the Reserve of Zingaro and the Reserve of Monte Cofano, which were established with a regional law in 1981.

The Reserve of Zingaro was the first established natural protected area in Sicily, as an achievement of a great mobilization of the Sicilian people, culminated in a great march on 18 May 1980 for blocking the construction of an

Fig. 39.10 Quarry landscape at the southern slope of Mt. Sparagio

east-littoral road, which would have connected Scopello to San Vito Lo Capo, crossing the totally uncontaminated eastern coastal sector of the peninsula.

The restricted territory of the Reserve of Zingaro extends for 1600 ha, including a coastal cliff sector 7 km long, locally interrupted by some small sandy or pebbly bays. The reserve is an example of Mediterranean ecosystem, hosting a great variety of natural environments set on calcareous substratum. A great number of vegetable taxa (near 700) is present, some of which very rare and endemic, in addition to typical Mediterranean mammals and reptiles and nearly 40 different species of birds. A well-developed network of natural paths, 30 km long in total, allows the visitors to enjoy the summit landscape by trekking, as well as the sea, going to the bays.

The natural Reserve of Monte Cofano protects the calcareous promontory and its surrounding coastal areas. It was established on 1989 and extends for 537.5 ha. It is of great importance for the scenic coastal landscape as well as for the widespread occurrence of karstic epigean (dolines, sinkholes) and hypogean (caves).

39.8 Conclusions

The magnificent coastal, gravitational, karst and structural landforms of the Capo San Vito peninsula reflect an interplay between geomorphological processes, tectonics and Quaternary climate changes.

Broad wave-cut platforms, high abandoned structurally controlled sea cliffs, wide landslide scarps, large deformed rafting blocks, their position between sea and mountains, as well as weather and colours of Sicily, make the landscape of the Capo San Vito peninsula spectacular and wonderful. At the same time, the richness of the remarkable geomorphological features at the Capo San Vito peninsula makes it suitable both for geo-tourism and teaching. In fact, the geological and geomorphological situations and constrictions are very clear and easy to read/interpret.

From a scientific point of view, the set of the marine terraces, caves, wave-cut notches, and tectonic landforms, allow to reconstruct the geomorphological evolution of the Capo San Vito peninsula, highlighting morphogenetic, tectonic and climate events occurred during the Quaternary period in the central sector of the Mediterranean area.

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Landforms and Landscapes of Mount Etna (Sicily): Relationships Between a Volcano, Its Environment and Human Activity

40

Stefano Branca, David Chester, Emanuela De Beni, and Angus Duncan

Abstract

Mount Etna is the highest relief in Sicily and represents a unique environment because of its long-established and almost continuous eruptive activity, that has moulded its landforms and which has produced distinctive landscapes. Over the past 60 ka, both destructive and constructive geological processes have produced the principal morphological features of the volcano such as the wide Valle del Bove depression, monogenic scoria cones and extensive lava flow fields. Relationships between Etna, its environment and human activity began in the Neolithic Period within the mountain foot region and have developed over millennia. Even though there has been a rapid rate of resurfacing by lava during historic times, the impact on human activity has been short-lived, recovery has been rapid and society has adjusted to the ever present hazard in distinctive ways.

Keywords

Stratovolcano • Volcanic geomorphology • Human activity • Etna

40.1 Introduction

Mount Etna is one of the most famous volcanoes of the world due to its central location within the Mediterranean Sea and its almost continuous eruptive activity. Interrelationships between human activity and the volcanic environment have continued since the Neolithic Period. In fact, the favourable climatological, hydrological and pedological conditions of the lower flanks of Etna, named *mountain foot region* (0–1000 m a.s.l.), together with its strategic position as the connection between the Tyrrhenian district to the north and the Hyblean to the south, has allowed the development of both civilizing and cultural processes in this distinctive Mediterranean region. Mount Etna is delimited by the Simeto and Alcantara valleys which have been the main routes of communication since the Neolithic (Fig. 40.1). The oldest Greek colonies in Sicily are Naxos, founded on the lava promontory of Capo Schisò at the mouth of the Alcantara River in 734 BC, and the city of Katane (Catania), founded in 729 BC along the Ionian coast of Etna. After more than 2700 years about 900,000 people currently live in the mountain foot region.

The morphological setting of Etna volcano is the result of a complex geological evolution. It began about 330 ka years ago in a subaerial environment (Branca et al. 2011a), and was characterized by several changes in the shallow feeder system, eruptive style and shape and position of the numerous eruptive centres that contributed to the growth of this large composite volcano. In addition, the morphological features of Etna are influenced by the volcano's location within eastern Sicily, where several tectonic lineaments intersect (Favalli et al. 1999). In this area the interaction between volcanic and geological processes has led to the evolution of an extraordinary variety of environments,

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Fig. 40.1 Location of Mount Etna volcano in eastern Sicily. In the orthoimage of Etna (modified after Gwinner et al. 2006) the sterile lands formed by the lava flow fields of the last 400 years are clearly visible, as are forest regions and the highly urbanized lower eastern and southern flanks. *Inset* map **a** illustrates the major regional tectonic structures of eastern Sicily (modified after Azzaro et al. 2012)

landforms and landscapes, which are the result of a long and complex geomorphological evolution. Due to the uniqueness of its geological, volcanological and geomorphological characteristics, Mount Etna has been recently added to the UNESCO World Heritage List, in June 2013.

40.2 Geographical Setting and Land Use

Etna dominates eastern Sicily, being over 3300 m high and covering an area of *ca.* 1200 km^2. Geographers have described Sicily as '*an ugly picture in a frame of gold: the* *dry poverty-stricken core of the island contrasting vividly with the intensively-cultivated, irrigated coastal periphery*' (King 1973, p. 112). Etna is perhaps the 'frames' most singular region. Despite continuous cropping since the classical period, agricultural production has been maintained without significant soil erosion or yield reduction. There is a diversity of land use (Fig. 40.2), which reflects a delicate adjustment to both environmental and economic factors operating at varying heights within different sectors of the volcano.

Etna's climate is characterized by an increase in precipitation with height so that the summit area receives over 1200 mm; average annual temperatures are *ca.* 18 °C at the coast, but decline rapidly with height and heavy snowfall is the feature of the mountain's upper slopes; temperature contrasts occur between the warmer northern, northwestern, western and other sectors of the volcano affected by exposure to the Ionian Sea; and a persistent volcanic plume is deflected by predominantly westerly winds causing rainfall enhancement over the eastern and southeastern sectors. Irrigation exploits groundwater in permeable lavas, which are fed by winter rainfall and snow melt.

Soil variation on Mount Etna is primarily related to climate, but in many localities fertility reflects the nature, depth and age of soil-forming materials, local patterns mirroring the age and morphology of lava flows and the age/depth of tephra deposited on them. The most productive soils occur on old flows on the lowest slopes of Etna and are fine-textured, brown *cambisols* and *luvisols*. With the exception of rock outcrops, the poorest soils of Etna are

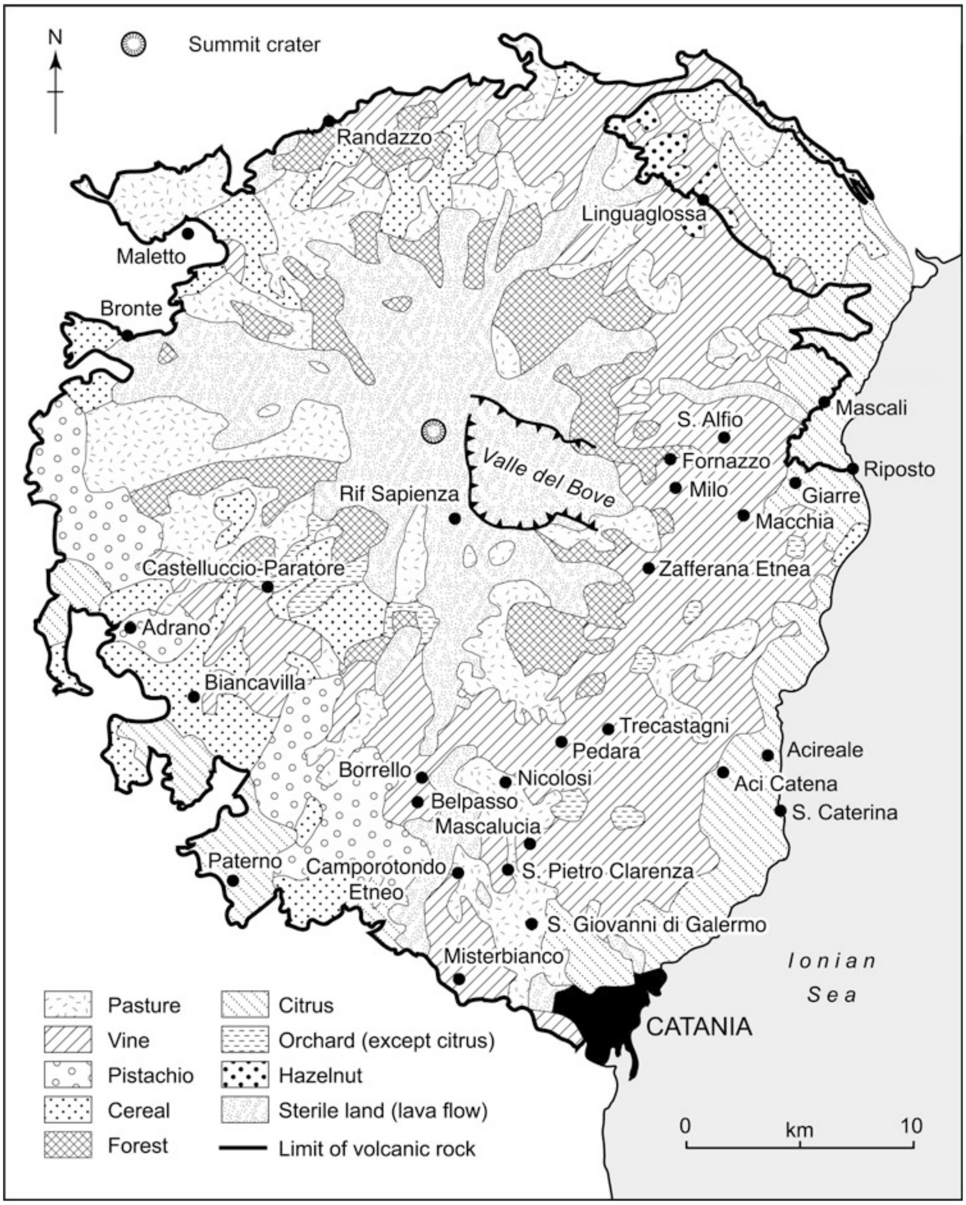

Fig. 40.2 Agricultural land use of the Etna region (modified after Chester et al. 1985). The *mountain foot region* stretches from sea level to 1000 m, the *regione boscara* from 1000 to 2000 m and the *regione deserta* is over 2000 m

young and eroded *lithosols*. *Regosols* are weakly developed in loose substrates, particularly on tephra.

Except at high altitude, the indigenous woodland of Etna has been cleared and the links between climate/hydrology/soils and land use are very strong, with the most intensive cropping taking place on the eastern, southeastern, southern and southwestern flanks, often under irrigation and within the mountain foot region (Fig. 40.1). Land-use intensity also reflects height (i.e. is more intensive at low levels) and proximity to Catania (population of the metropolitan area *ca.* 750,000), the principal port and city of the region. In recent years land around Catania is becoming progressively urbanized. On Etna yields within the mountain foot region were traditionally maintained by a combination of: (a) inter-cropping of cereals and vegetables, usually sown in association with tree crops; (b) lava-block terraces on steep slopes, that were well established by the thirteenth century and which reduce erosion; (c) wood-mulch which was widely used both to increase organic matter and reduce evaporation and (d) animals closely integrated into the farming system. As well as producing meat and other products, animals provided manure.

The maintenance of this distinctive agricultural system required large quantities of labour from farmers' extended families, but from the 1970s many terraces ceased to be cultivated. Abandonment bore witness to a reduction in the area being intensively cropped, especially towards the upper altitudinal limit of the mountain foot region. Investment by the Italian State and the *European Economic Communities* (later the *European Union*) was concentrated on larger units, mechanization and more modern techniques. On Etna the mountain foot region retains its agricultural particularity and the traditional system of intensive irrigated agriculture may still be recognized (Chester et al. 2011). The agriculture labour force continues to shrink, service employment to increase and many municipalities, particularly those near to Catania, are today's commuter settlements. Tourism is a major industry and the region is a location for many second homes. These developments are boosted by the region's designation as both a National Park and a World Heritage Site.

40.3 Geological Evolution

Submarine eruptions, representing the earliest volcanic events in the Etna region, occurred about 500 ka ago and products from this, the Basal Tholeiitic phase, are exposed along the coast, between the towns of Aci Castello and Aci Trezza, interlayered within Pleistocene marine sediments. The oldest subaerial volcanic products in the Etna region erupted about 330 ka ago within the paleo-valley of the River Simeto, forming a wide and thin lava plateau (Fig. 40.3). In this paleo-landscape, explosive phreatomagmatic activity also occurred at eruptive fissures, as recognized at Valcorrente and Motta S. Anastasia, due to the interaction between magma and groundwater located in the sediments of the paleo-Simeto alluvial plain (Branca et al. 2011a, b). Following a long *hiatus*, eruptive activity on Etna resumed about 220 ka. It became more continuous, developed along the present lower eastern flank and was associated with the Timpe faults system. This phase continued until about 130 ka. During that time effusive eruptions generated superimposed lava flows that formed Etna's earliest volcano structure. It is interpreted as a lava shield elongated for at least 22 km on a NNW–SSE alignment (Branca et al. 2011a, b). This lava succession is exposed discontinuously along the Acireale, Moscarello and Ripa della Naca fault scarps and a wide portion of the shield is below sea level (Chiocci et al. 2011). During this phase, which is named *Timpe* and is dated for about 129–126 ka years ago, effusive activity from fissure eruptions occurred for the first time in the central portion of the present Etna edifice in the area between Val Calanna and Moscarello.

Starting from about 110 ka, the path of magma ascent became more localized, an efficient plumbing system developed and this led to the construction of a central polygenetic volcanic structure in the area presently occupied by the Valle del Bove depression (Fig. 40.3). In particular, the change from fissure to central eruptive style produced the earliest polygenetic strato-cones: the so-called *Tarderia*, *Rocche* and *Trifoglietto* volcanoes (Branca et al. 2011a, b). The *Trifoglietto* volcano was characterized by steep slopes and reached a maximum elevation of around 2600 m, and represented the principal edifice constructed during this phase. Following the end of Trifoglietto activity, local shifting of the shallow eruptive feeder system generated several eruptive centres which not only covered the previous centres, but also produced a composite strato-cone formed by the superposition of several small central volcanic edifices.

The stabilization of the shallow plumbing system in its present position at about 60 ka allowed the main bulk of Etna's edifice to grow and produced the *Ellittico* volcano. This eruptive centre developed on the northwest flank of the Valle del Bove volcanic edifices because of a NNW shift of about 4 km in the position of the main eruptive axis. The Ellittico volcano was characterized by explosive and effusive activity both from summit vents and flank fissures, which generated steep slopes above a height of 1600–1700 m, forming the distinctive conical shape of the stratovolcano. This attained a maximum height of about 3600 m. The formation of lava flow fields during flank eruptions allowed for the gradual expansion of Ellittico's slopes on to the sedimentary basement, causing a radical modification of the paleohydrographic setting of the Simeto and Alcantara

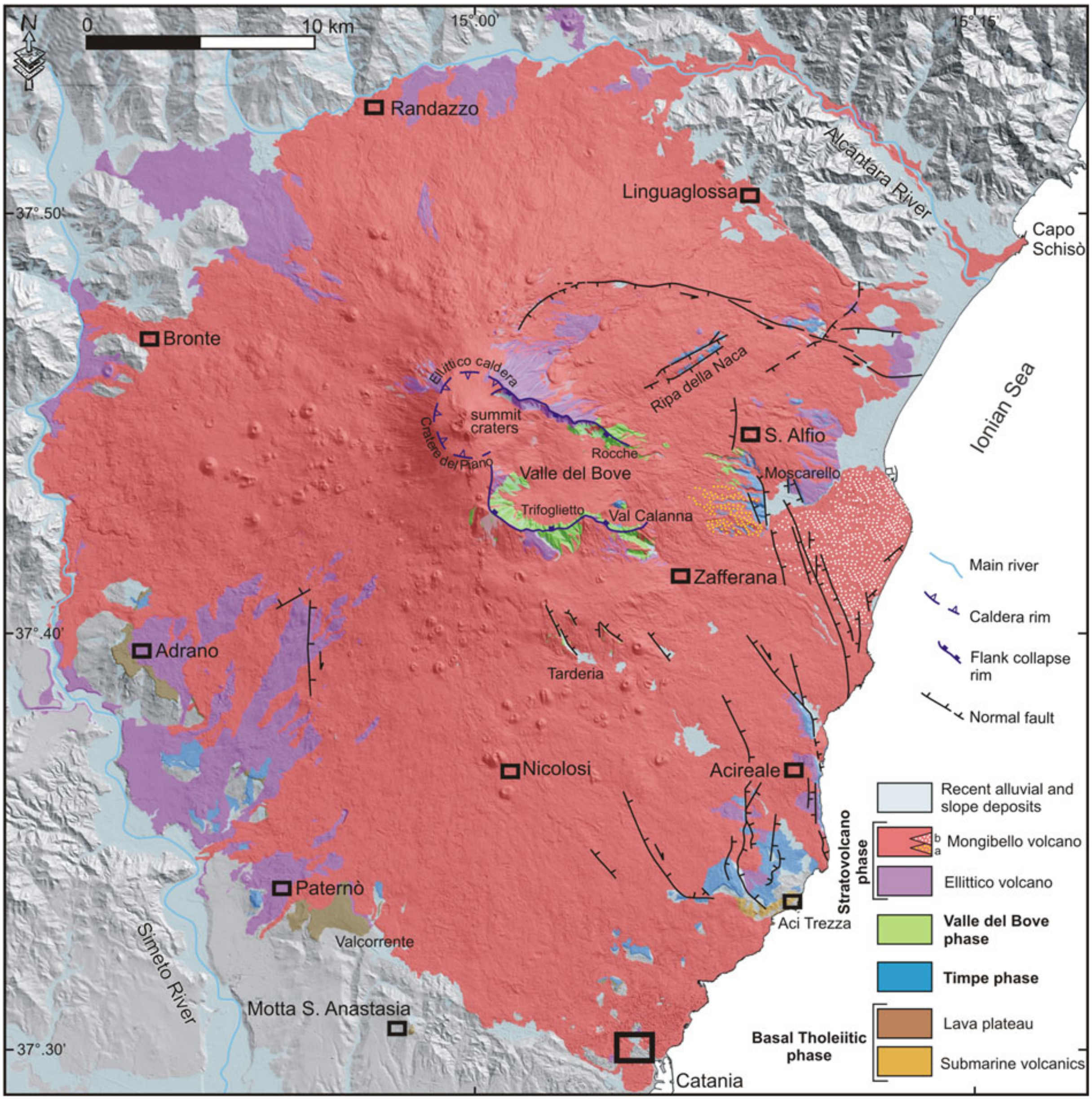

Fig. 40.3 Geological sketch map of the Etna volcano (modified after Branca et al. 2011a). Within the Mongibello volcano two units which relate to the formation of the Valle del Bove are represented: *a* the Milo debris avalanche deposit (*yellow dots*) and *b* the Chiancone debris-alluvial deposit shown by *white dots*

valleys between about 40 and 30 ka. In this period the paleo-valley of the River Simeto was invaded by lava flows which produced several dams within the paleo-watercourse. At the same time the Alcantara paleo-valley was totally filled with lava and this caused a northward stream diversion of the paleo-river bed to its present valley around 30–25 ka ago. Ellittico volcanic activity ended about 15 ka ago with a series of Plinian eruptions that caused the collapse of the summit cone from a height of about 3600 to 2900 m, forming the Ellittico caldera.

Finally, the eruptive activity of the past 15 ka belongs to the *Mongibello* volcano and has produced the present day morphology of Mount Etna (Fig. 40.3). In particular, lava flows from summit eruptions almost completely filled the Ellittico caldera, whereas lava flows generated by flank eruptions expanded the area of Etna. The eruptive fissures of the Mongibello volcano are spatially clustered indicating the presence of at least three main zones of weakness, the so-called NE, S and W rifts and these have been sites of repeated magma intrusion. Strombolian explosive activity along the eruptive fissures formed single and/or coalescent monogenic scoria cones and elongated spatter ramparts. At about 10 ka the morphostructural setting of the Mongibello volcano was drastically modified as a consequence of sector collapses that affected the eastern flank of the Etna edifice (Calvari et al. 2004). According to Guest et al. (1984), a number of large landslides generated the depression known as the Valle del Bove, producing the Milo debris avalanche deposit located at the end of the valley (Fig. 40.3). Subsequent processes of erosion and further minor collapses widened the depression and formed a large fan-shaped feature along the Ionian coast which is called the Chiancone. During the Holocene several intense explosive events from summit vents took place and in historical times the largest explosive eruption of Mongibello volcano occurred in 122 BC (Del Carlo et al. 2004). The 122 BC Plinian event produced a widespread pyroclastic fall deposit on the southeast flank, causing substantial damage to the ancient Roman city of Catania, the collapse of the summit cone and the formation of the caldera called Cratere del Piano. The effusive and explosive activity of the last 2 ka has completely filled the Cratere del Piano caldera, gradually forming the present summit region of Mount Etna with its associated craters.

40.4 Geomorphology and Landforms

The earliest volcanic landforms of the Etna region were formed during the *Basal Tholeiitic*, *Timpe* and *Valle del Bove* phases, between about 330 and 60 ka, and are almost totally masked by volcanic products from the Ellittico and Mongibello phases. The relicts of the oldest subaerial lava flows form a series of tabular terraced bodies along the left bank of the Simeto valley, dipping gently SSE, which crop out discontinuously from an elevation of about 550 to 250 m between the towns of Adrano and Paternò (Fig. 40.3). Conversely, the *Timpe* lava shield morphology is not recognizable since it is totally buried and in part rests offshore, close to the coast and near to the town of Acireale (Chiocci et al. 2011). The only preserved landforms of the earlier strato-cone morphostructures of the Valle del Bove phase belong to the *Tarderia* eruptive centre whose southeast flank is located to the south of the Valle del Bove and which forms a morphological belt of steeper land stretching from Tarderia to the town of Zafferana (Fig. 40.4) (Chester et al. 1985; Branca et al. 2011b).

The main landforms of Etna's edifice were formed during the activity of Ellittico and Mongibello volcanoes during the last 60 ka and were generated through both constructive and destructive processes (Azzaro et al. 2012). They are represented by steep slopes which form the conical shape of the Ellittico's strato-cone along the western and northern flanks of Etna, above a height of 1600–1700 m, and by the wide depression of the Valle del Bove—Val Calanna along its eastern side. The Valle del Bove—Val Calanna is a complex landform related to large-scale flank failures that have resulted in a typical horseshoe-shaped depression, about 7 × 6 km wide, which is characterized by steep-sided break-away scarps up to 1000 m high (Fig. 40.4). The summit area of Etna, instead, shows a broadly planar morphology at a height of about 2900 m which is bounded by the rim of the Ellittico caldera to the north and that of the Cratere del Piano caldera to the west and south. Conversely a typical tectonic landform represented by a series of high and prominent rectilinear morphological scarps, locally named Timpe, characterizes the lower east flank from Acireale to S. Alfio (Figs. 40.3 and 40.4) (Azzaro et al. 2012).

Overall, about 85% of the Etna flanks are formed by monogenic volcanic landforms such as pyroclastic cones and lava flow fields mainly generated during the eruptive activity of the past 15 ka (Branca et al. 2011a). More than 300 pyroclastic cones are widely distributed along Etna flanks above an altitude of about 500 m (Azzaro et al. 2012). These landforms of basaltic volcanism are related to the explosive activity which occurred along the fissures of flank eruptions. The morphological features of the pyroclastic cones can vary from larger spatter ramparts elongated according to fissure orientation to single scoria cones of different size and elevation and a series of coalescent scoria cones (Fig. 40.5). The scoria cones show a conical shape ranging from symmetric to asymmetric and reaching heights up to 200 m. Sometimes they are characterized by a breached side.

Lava flows are formed by both simple and compound fields showing different morphological features (Chester et al. 1985). As a rule, the simple lava fields are characterized by typical *aa* morphology, with a clinker and rubbly surface, whereas the compound fields show more complex morphologies due to the presence of both *aa* and *toothpaste flow* units with slabby surfaces (Guest and Stofan 2005). The simple lava fields can also be characterized by the presence of prominent features such as the *levées* of the flow channels with lengths ranging from several hundred metres to several kilometres (Figs. 40.6 and 40.7). Compound lava fields show several secondary surface textures such as tumuli and pressure ridges whose dimensions are generally decametres. The presence of compound lava fields characterized by *pahoehoe* morphology is rare on Etna. One of its best examples is the 1614–24 lava field, which covers an area of over 20 km^2 on the upper northern flank. This lava flow is characterized by several different surface textures such as ropy flows, squeeze-ups, tumuli, and driblet cones of entrail and toey lava. Sometimes the *pahoehoe* flow fields show the presence of large tumuli, having basal diameters ranging from several hundred metres up to 1 km.

Over time, the original morphology of the lava fields was gradually modified by pedogenesis (Chester et al. 1985).

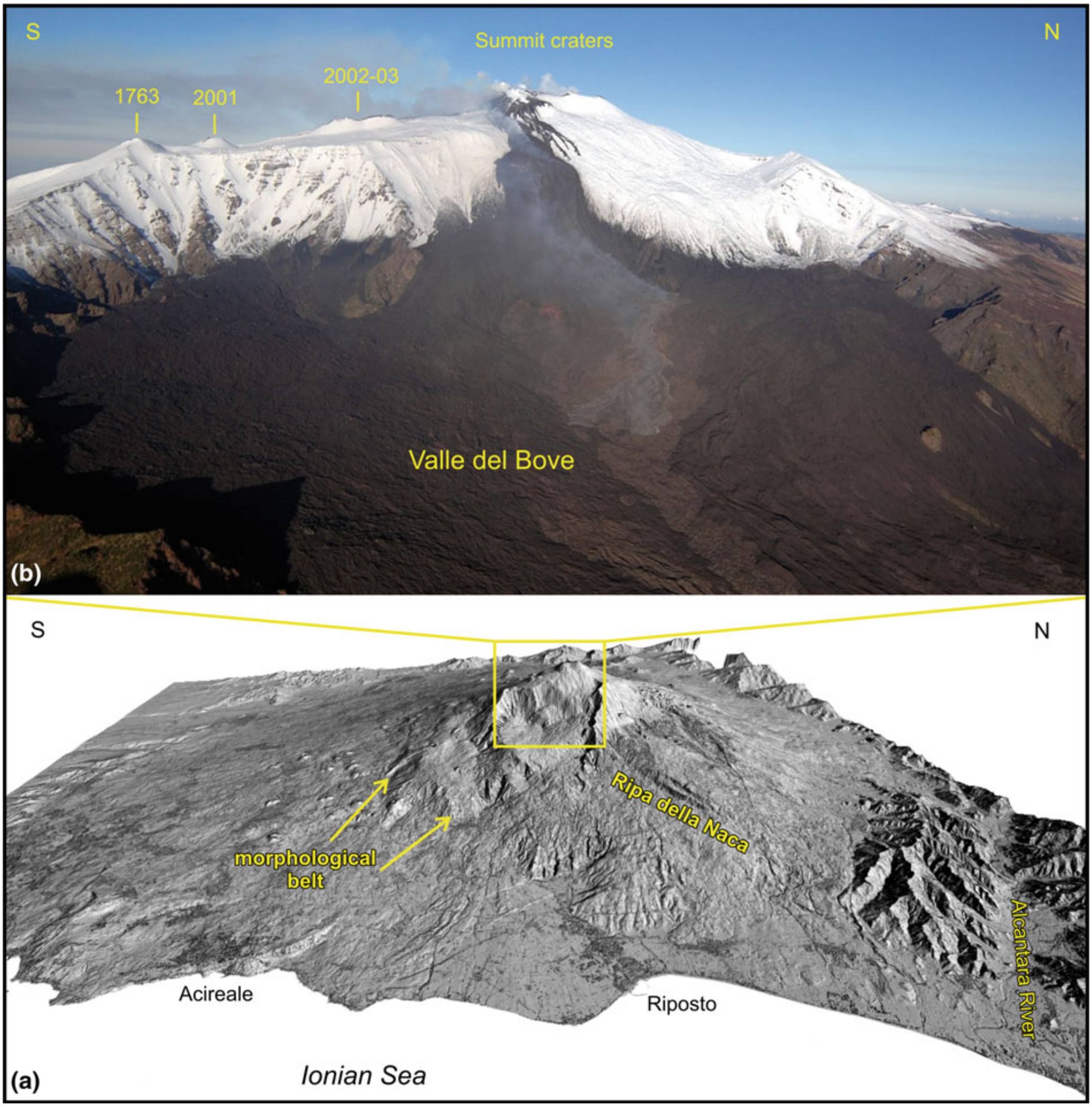

Fig. 40.4 **a** Oblique DEM-derived east view of Etna (modified after Gwinner et al. 2006) showing some of the principal landforms of the volcano such as the Valle del Bove; the morphological belt belonging to the early Tarderia eruptive centre and the rectilinear fault scarps from Acireale to the Ripa della Naca and **b** aerial view from the east taken in November 2006 showing typical landforms of the summit region and of the Valle del Bove. Large historic scoria cones located on the upper southern flank show the year of eruption

These processes are more intense in the mountain foot region where the formation of soil is more rapid, with its thickness varying from a few tens of centimetres to a few metres. Historical lava flows (i.e. those erupted over the past 2400 years) show a well-preserved morphology which in some cases can be covered by a soil which varies according to the location on the volcano's slopes. On prehistoric lava flows, the main morphological features are rarely unchanged, being covered by soil and/or pyroclastic and epiclastic deposits. Another important factor modifying the original morphology of the lava fields is intense human activity. This has affected the mountain foot region since before Roman times. In fact, the gradual development of agriculture led to the construction of terraces which have been built using lava blocks. A typical example is represented by the lava field of the 1408 eruption, whose intense agricultural exploitation in the area between Pedara and Trecastagni has masked most of its original morphological features. Reforestation has also

Fig. 40.5 Aerial view of the western flank which is characterized by eruptive fissures formed by scoria cones and spatter ramparts. In the *foreground*, two scoria cones formed during the 1974 eruption (Mts. De Fiore) should be noted. In the *background*, there are several scoria cones of prehistoric age

Fig. 40.6 A lava flow channel of the 2004–2005 eruption

Fig. 40.7 Panoramic view of the 2004–2005 lava flow field located along the western wall of the Valle del Bove

contributed to the acceleration of soil development which can make the state of preservation of historical lavas similar to those of prehistoric age.

40.5 Interactions with Human Activity

Throughout most of its history the Etna region has been a traditional self-contained agricultural society and has coped with eruptions using largely indigenous methods. Although there are examples of State involvement, such as the provision of troops to maintain law and order, comprehensive intervention only dates from the 1928 eruption (Chester et al. 2012). Since prehistoric times, the cultivated area of Etna has been impacted by frequent lava invasions, on occasion settlements have been totally and partially destroyed and the population has suffered distress. Major eruptions are known from the classical period (e.g. 122 BC), and medieval times (see Tanguy et al. 2012), but from the fifteenth century records are more comprehensive and show the following. The village of Pedara and its cultivated lands were destroyed in 1408; in 1537 Nicolosi was devastated; in 1646–47 a wide cultivated area on the north flank of the volcano was reported to have been wiped out; the 1669 eruption—the largest historical event—destroyed Nicolosi, Malopasso, S. Pietro Clarenza, Mascalucia, Comporotondo, S. Giovanni Galermo, Misterbianco, 14 smaller settlements and a part of Catania and agricultural land and dwellings were destroyed near to Macchia in 1689 (Fig. 40.1). In 1923, the small settlements of Cerro and Catena were severely damaged and in 1928 Mascali was destroyed by lava flows.

In the traditional economy of Etna region, the outskirts of towns and villages often comprise a *corona*, a roughly circular rim of particularly productive agriculture. For the period from the 1669 eruption to 1900, major losses to *coronas* occurred in 1651–1654—Bronte; 1792–1793—Zafferana; 1811–1812—Milo; 1832 and 1843—Bronte; 1852–1853—Zafferana; 1879—Passopisciaro; 1886 and 1892—Nicolosi. We estimate that between 1500 and 1900 *ca.* 8% of the total land area of the mountain foot region (Fig. 40.1) was effectively sterilized by lava (Chester et al. 2011).

When disaster strikes it is often assumed that people panic, but research on disasters in many countries and on Mount Etna shows this rarely to be the case. Though apprehension is noted in some documents, the vast majority of people remained calm, normal day-to-day activities continued and people still farmed their land and pursued their trades. On Mount Etna serious eruptions often occurred several times a century and people adapted to them. For instance, people frequently left their home villages to live with relatives, this being noted in 1843, 1883 and 1886. Sometimes farmers and their families were forced to convert small shelters on family plots into temporary accommodation and community relief committees featured in the process of recovery (e.g. in 1892).

On Etna a notable characteristic of loss-bearing was that, although cities, towns and villages could be badly impacted by lava flows, they quickly recovered. Nicolosi was, for example, devastated by lava in 1537, but seems to have been fully rebuilt by the time of the 1669 eruption (Chester et al. 1985). Lava flows normally advance slowly and residents

Fig. 40.8 The advance of the 1910 lava flow over cultivated land in an area of the *mountain foot region,* in the vicinity of Nicolosi (*photo* Archivio Fotografico Toscano di Prato, Fondo Gaetano Ponte)

know in advance if and when their village/home are about to be destroyed and there is evidence that people salvaged all they could. In 1928 newsreel films show that the removal of tiles, windows and doors was a well-established practice in the region and confirms earlier written accounts. Peasant agriculture involves maximizing family security over profit, and one feature is that cultivation plots are often owned in different localities (whether through inheritance and/or as a deliberate mitigation strategy is unknown), which means that a single eruption is unlikely to wipe out all of a farmer's land (Fig. 40.8). Pastoralism provided a valuable additional source of income in times of distress.

One distinctive feature of Mount Etna and southern Italy generally is that many people perceived and continue to see the divine hand in natural disasters, and eruptions have been associated with well-developed liturgies of divine appeasement, comprising the procession of sacred relics and saintly images, and intercessory prayer. One important aspect of this response is that it has not produced a fatalistic attitude and inhibited people either from protecting themselves or, more latterly, from accepting help from authorities and/or instruction from the State and its agencies.

The Etna region is also exposed to tectonic and volcano-related earthquakes, the former caused major localized damage in Catania in 1169 and 1693, whereas the latter produced major damage and fatalities near Macchia in association with the 1865 and 1911 eruptions (Chester et al. 2012). Indeed the only time when the region's resilience was almost overwhelmed by its vulnerability was during the second half of the seventeenth century, when in less than 25 years after the 1669 eruption, the 1693 earthquake caused a decline in agricultural production and much destruction. Recovery was not complete until well into the eighteenth century.

Mount Etna remains as one of the world's most active volcanoes. There have been a number of major eruptions over the last 50 years which have had significant impacts on human activity. Notable eruptions include those of 1971, 1983, 1991–1993, 2001 and 2002–2003 (Fig. 40.9). The eruption of 1971 acted as a catalyst for modern volcanological research on Mount Etna and study on Etna has played a major contribution to understanding the factors that control the morphological evolution of basaltic lava flows. In addition, since initial interventions during the 1983 eruption, work on the volcano has played a major part in the development of intervention techniques to divert and limit the spread of lava flow fields to minimize impact.

40.6 Conclusions

Mount Etna is one of the largest and most active continental volcanoes in the world and is arguably the dominant landscape feature in Southern Italy. The typical landforms of Etna volcano have developed during the past 60 ka in a period in which the main bulk of the stratovolcano structure was formed. In particular, the main morphological features have been produced during the Mongibello phase of activity in the Holocene. During this time interval, the wide horseshoe-shaped depression of the Valle del Bove formed, and intense eruptive activity generated numerous simple flows, compound flow fields and scoria cones on Etna's

Fig. 40.9 Aerial view of 2002–2003 eruption. In the foreground the lava flow destroys the pine wood forest of Linguaglossa. In the background is the upper northeast flank with the summit craters showing degassing activity and the ash column generated by the 2002–2003 eruptive vent located in the upper south flank

slopes. Though frequent eruptions have led to a high rate of resurfacing, the volcanic morphology of the mountain foot region has been significantly modified by human activity. This modification results from agricultural development, quarrying and, in the environs of Catania, urbanization. During recent historic times and apart from the major 1669 eruption which was followed by the devastating 1693 earthquake, the impact of eruptions on human activity has been short-lived.

Throughout much of the historic period responses to eruptions on Etna were local in scale and character. Since the 1928 eruption each successive eruption has, however, seen a greater State intervention in the process of hazard planning, particularly through the efforts of the *Istituto Nazionale di Geofisica e Vulcanologia*. Whereas this has enhanced overall disaster resilience, much of the traditional resilience that has been so typical of pre-industrial times has been reduced (Chester et al. 2011). Today responses to volcano and volcano-related emergencies in Italy are the responsibility of central government, through the Department of Civil Protection (*Dipartimento della Protezione Civile* which was founded in 1982). The *Dipartimento della Protezione Civile* can use the expertise and resources of local authorities (*comuni*) and scientific bodies, such as the *Istituto Nazionale di Geofisica e Vulcanologia* in Catania. The volcano is monitored by an array of geophysical techniques, but additionally proactive planning uses hazard mapping and land-use zoning.

The Etna region today, particularly on its southern and eastern flanks and in the vicinity of Catania, is the location of many second homes and large numbers of people commute each day to the city. The region as a whole is a tourist destination and much of the historic Sicilian way of life and the distinctive character of its settlements have largely disappeared, though some features are still to be found in the more isolated settlements of western and northwestern sectors.

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Pantelleria Island (Strait of Sicily): Volcanic History and Geomorphological Landscape

41

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Abstract

Pantelleria is a volcanic island located in the Strait of Sicily, 95 km far from the Sicilian coastline and 67 km from Cape Bon (Tunisia). The volcanological history of the island begins approximately 324 ka BP and the last eruptive event was a submarine eruption that occurred on 1891 A.D. Eruptive activity was characterized by seven very intense explosive events, the latest being the Green Tuff (44 ka). They have all produced ignimbrite sheets that covered large sectors of the island. The landscape of the island mirrors the variety of the eruptive styles and their interplay with volcano-tectonics. The most evident geomorphological features are represented by: (i) the mantle-like distribution of the Green Tuff ignimbrite; (ii) the arcuate remnants of the two large caldera collapses, and (iii) the intracalderic scoria cones, lava domes and lava fields. A very dense distribution of dry walls, built since Roman times, perfectly integrate the volcanic landscape, preventing from erosion and rock falls.

Keywords

Volcanic island • Ignimbrites • Caldera • Pantelleria • Strait of Sicily

41.1 Introduction

Pantelleria is a volcanic island located in the central portion of the Strait of Sicily Rift System, a domain of thinned continental crust with abundant submarine and subaerial magmatism (Rotolo et al. 2006; Civile et al. 2008). The NW–SE elongation of Pantelleria, coincident with the main axis of the Rift, reflects the influence of regional tectonics, also evident in the distribution of volcano-tectonic features (eruptive centres and fissures, exhalative areas; Catalano et al. 2009).

The most prominent morphostructural features of the island are the remnants of the two *nested calderas* (Mahood and Hildreth 1986): the older one is named *La Vecchia caldera* and its collapse is dated 140–145 ka (Rotolo et al. 2013); the younger one is named *Cinque Denti (or Monastero) caldera* and its collapse is associated with the Green Tuff Plinian eruption (Civetta et al. 1984; Mahood and Hidreth 1986). Caldera rims are preserved only at places (Fig. 41.1) being largely eroded or covered by younger eruptions. The traces of the two calderas are roughly concentric with a maximum offset of 1 km in the south (Serra Ghirlanda area), while they are apparently coincident in the north and east sectors of the island.

From the compositional viewpoint, the erupted volcanic rocks are mostly pantellerites (i.e. peralkaline rhyolites), less commonly trachytes and subordinately basalts. Although an ample variety of eruptive products is represented (ignimbrites, pumice falls, lava flows), explosive volcanism largely dominated the volcanological history of the island.

Finally, it is worth of note the interaction of human activities with the geological context. Since the Roman age, the central area of the island which is dominated by poorly consolidated tephra, was the most fertile and densely cultivated. However, cultivations are diffuse also in very rough areas, such as lava fields or steep volcano flanks, where dry

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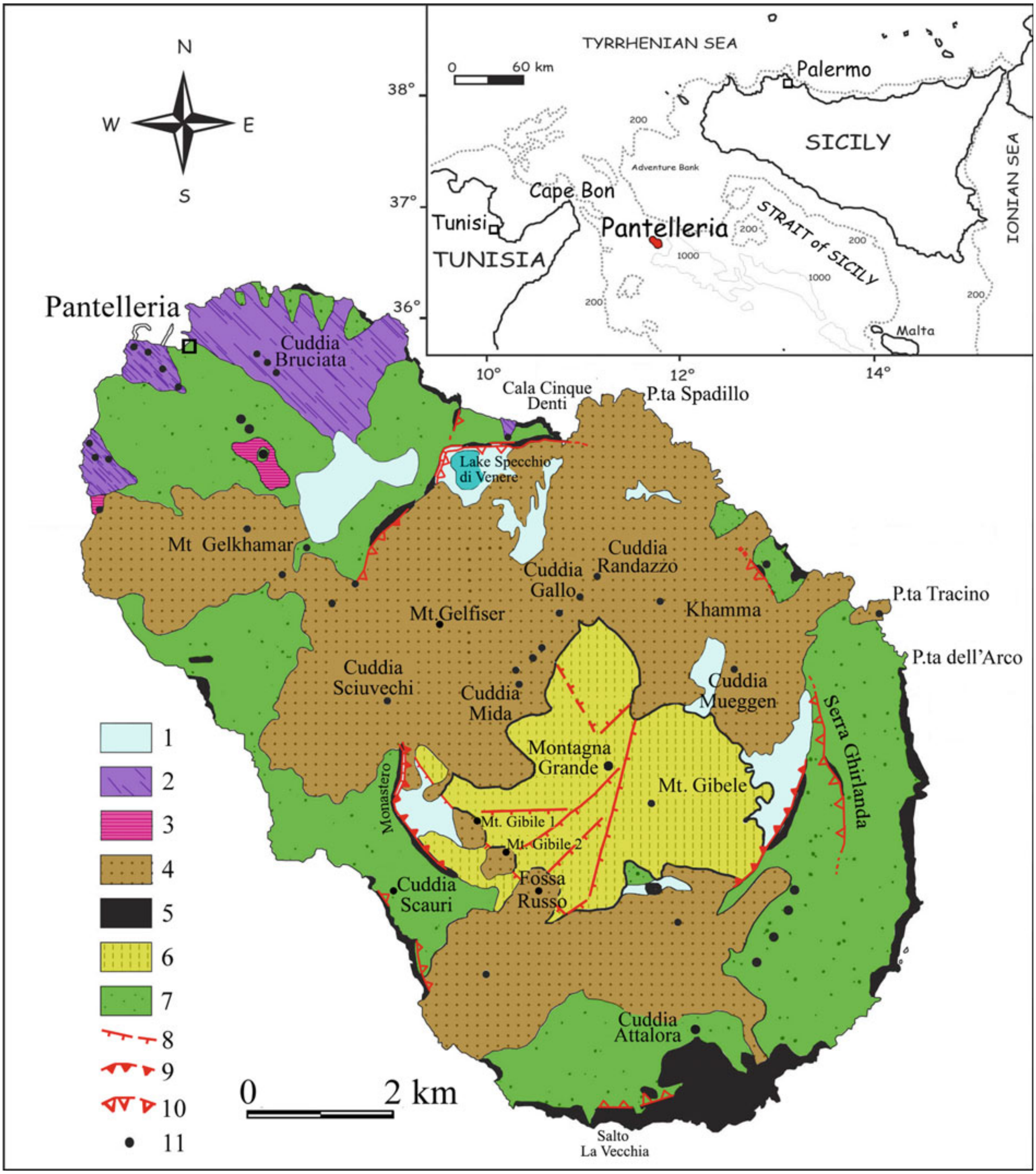

Fig. 41.1 Location of Pantelleria and simplified geological map of the island (modified after Rotolo et al. 2007). *1* Alluvium and fill; *2* Post-Green Tuff basalts; *3* Pre-Green Tuff basalts; *4* Post-Green Tuff pantelleritic pumice falls and lava flows; *5* Pre-Green Tuff pantellerites; *6* Trachyte lavas; *7* Green Tuff; *8* Faults; *9* Cinque Denti caldera rim; *10* La Vecchia caldera rim; *11* Principal eruptive vents

walls are used to form narrow terraces. The dry walls, mostly made of pantellerite lava, represent together with the ubiquitous hollow towers (called "*Pantelleria gardens*" and built to protect lemon trees from the wind), the typical markers of the man-made landscape of Pantelleria, perfectly integrated in the geological scenario.

41.2 Geographical Setting

Pantelleria is rising from a water depth of 2000 m below the sea level (Agnesi and Federico 1995) and extends for 83 km^2 between the latitudes 36°44′03″N and 36°50′20″N and the longitudes 11°57′13″E and 12°03′30″E, being

95 km (51 nautical miles) far from the Sicilian coastline and 67 km (36 nautical miles) from Cape Bon (Tunisia) (Fig. 41.1).

Pantelleria is the fifth Italian island, after Sicily, Sardinia, Elba and Sant'Antioco. It has the shape of an irregular ellipse oriented approximately NW–SE, whose length and width are around 14 and 8 km, respectively. Its perimeter is 51.5 km.

From the morphological viewpoint, two sectors of the island can be clearly distinguished: a mountainous sector which occupies the southeast portion of the island and a hilly sector located in the northwestern zone (Fig. 41.2). The first one, which is larger, includes the highest peak of the island, Montagna Grande (836 m a.s.l.), in addition to the mounts of Mt. Gibele (700 m) and Cùddia (an arabic word standing for hill) Attalora (560 m). Conversely, the northwestern sector is characterized by the reliefs of Mt. Gelfiser (394 m) and Mt. Gelkhamar (247 m).

The northern sector of the area is characterized by a low and rocky shoreline that is interrupted by numerous bays and small beaches; on the other hand, the southern coast presents hard rock cliffs, locally exceeding 200 m of elevation, which are also fragmented by small bays.

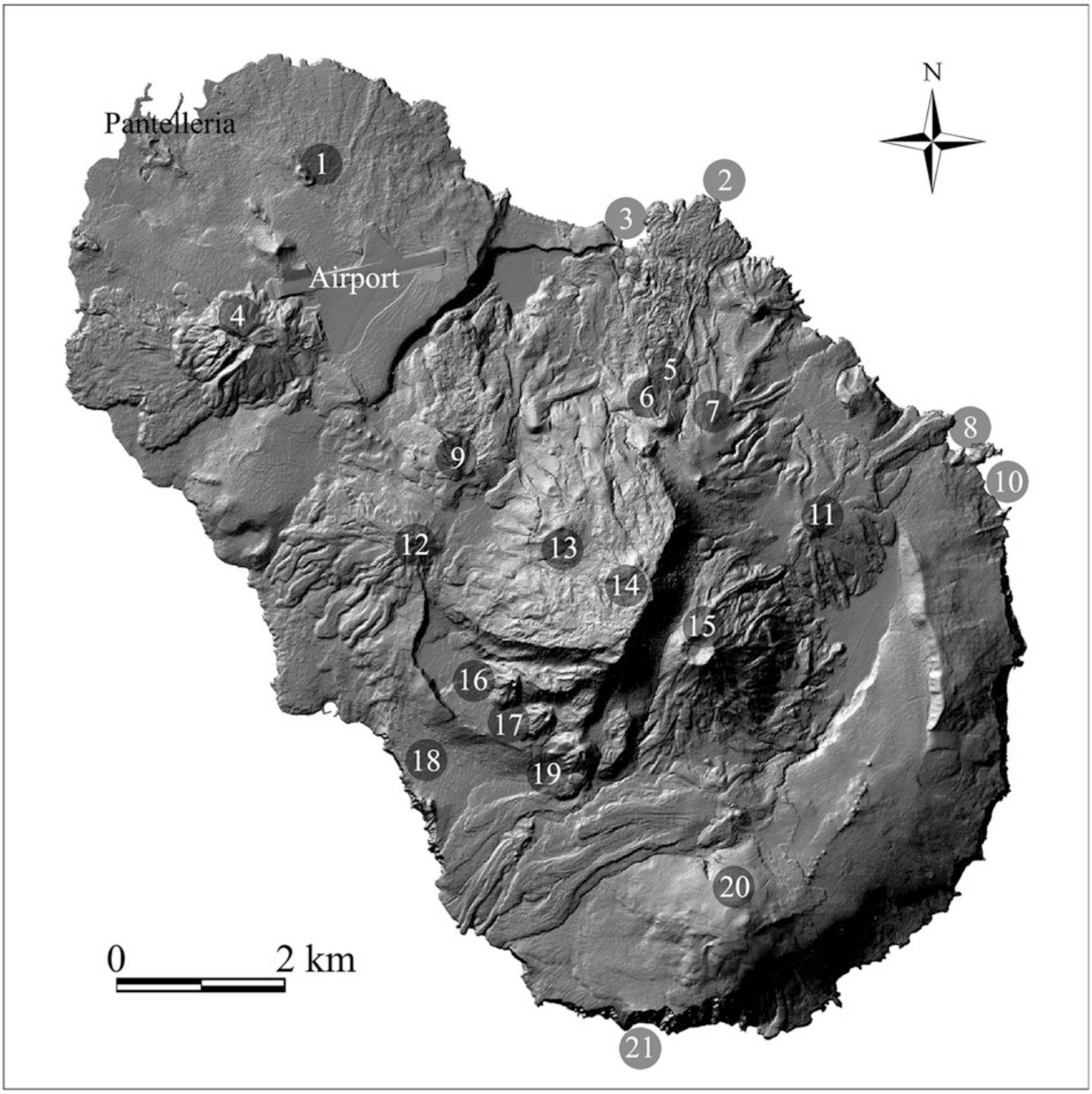

Fig. 41.2 Hillshade map of Pantelleria. *1* Cùddia Bruciata; *2* Punta Spadillo; *3* Cala Cinque Denti; *4* Mt. Gelkhamar; *5* Cùddia Randazzo; *6* Cùddia Gallo; *7* west of Khamma; *8* Cala Tramontana; *9* Mt. Gelfiser; *10* Cala Levante; *11* Cùddia Mueggen; *12* Cùddia Sciuvechi; *13* Cùddia Mida; *14* Montagna Grande; *15* Mt. Gibele; *16* Gibile 1; *17* Gibile 2; *18* Cùddia Scauri; *19* Fossa Russo; *20* Cùddia Attalora; *21* Salto La Vecchia

The position of Pantelleria generates climatic conditions typical of a transitional environment, with the peculiar characteristics of both the southern sector of Italy and the coastal region of North Africa.

The mean annual precipitation measured at the climatic station of the meteorological service of the Italian Air Force (191 m), calculated for the period 1971–2000, is 502 mm. November is the wettest month (mean rainfall 89.0 mm), whereas July is the driest one (mean rainfall 1.9 mm). Precipitation concentrates in the autumn/winter season, during which around 80% of total annual rainfall occurs, with maximum concentration in winter.

The mean annual temperature recorded in the same time interval is 20.7 °C, whereas the mean monthly temperatures range between 13.9 (January) and 29.0 °C (August).

41.3 Geological Evolution

The eruptive history of the island can be divided in two distinct periods: before and after the Green Tuff eruption (44 ka).

(i) *The old period* (300 to 44 ka) was dominated by medium to high-energy explosive eruptions, with seven (including the Green Tuff) very powerful eruptions that covered large sectors of the island with ignimbrite sheets (*ignimbrite* is the rock deriving from emplacement, cooling and welding of pyroclastic flows). More in detail, the two oldest ignimbrites were emplaced at 181 and 175 ka (Mahood and Hildreth 1986) in the south sector of the island, burying some old volcanic centres (e.g. Cùddia Scauri). A later eruption (dated 140–145 ka; Rotolo et al. 2013) caused the first caldera collapse ("*La Vecchia*" *caldera*) whose rim is visible in a superb exposure at Salto La Vecchia. Volcanism younger then 140 ka partly filled the La Vecchia caldera: one ignimbrite erupted at 125 ka was emplaced in the NW to NE sectors of the island, while two other ignimbrites (105 and 85 ka) covered almost all the island and are well visible in the vertical coastal cliffs (exceeding 200 m in height) west and south of Scauri village (Fig. 41.3), or at Salto La Vecchia, where these ignimbrites lap onto the La Vecchia caldera wall. The last high-energy eruption was the *Green Tuff* (age 44 ka,

Fig. 41.3 Cliffs of the southwestern sector of Pantelleria (2.5 km south of Scauri). From *bottom* to *top* three pantellerite lava flows, and five piled ignimbrite units. The ages (ka) of ignimbrites are from Rotolo et al. (2013)

Scaillet et al. 2013) to which the second caldera collapse was related, the “*Cinque Denti*” *caldera* (Mahood and Hildreth 1986) or “*Monastero*” *caldera* (Civetta et al. 1984).

The *Green Tuff* represents the most powerful eruption on the island (Plinian) (Lanzo et al. 2013) and produced a low aspect ratio ignimbrite (i.e. height/diameter ratio), impressive in its mantle-like distribution all over the island.

The Green Tuff has a very variable thickness: it thins out to 1 m in the lee-side of reliefs (with respect to the direction of the propagation of the pyroclastic flows) and thickens to 20 m in paleovalleys. This behaviour, typical of pyroclastic flows, results in a general flattening of the pre-existing topography.

(ii) *The young period* is related to the restart of activity after the Green Tuff eruption. Volcanism was much less explosive and was centred almost exclusively within the Cinque Denti caldera. The caldera was filled for around two-thirds with acidic (trachyte to pantellerite) magmas that formed pumice cones, lava flows and lava domes.

The first eruption after the Cinque Denti caldera collapse was the voluminous eruption (3 km^3) of trachyte lavas that now form the Mt. Gibele—Montagna Grande complex (age 35–28 ka, Mahood and Hildreth 1986). As first proposed by Mahood and Hildreth (1986), Montagna Grande represents a tilted block that was separated by the Mt. Gibele source vent by a trapdoor fault running NE–SW. Along the fault-hinges bordering the Montagna Grande tilted block, pantellerite magmas found a way to the surface, building a number of volcanic structures: (i) low-volume lava domes in the western side (Fossa Russo and the two Mt. Gibile), (ii) pumice cones and lava domes in the northern sector (Cùddia Mida, Cùddia Sciuvechi, Cùddia Gelfiser, Cùddia Gallo, Cùddia Randazzo) and (iii) a shield volcano (Cùddia Mueggen) in the east side.

Cùddia Gallo is also the youngest eruption of this sector with an age of 6–8 ka (Rotolo et al. 2007; Speranza et al. 2010; Scaillet et al. 2011). The most recent volcanic event was the 1891 submarine eruption that occurred 5 km off the NW coast of the island (Washington 1909) and produced floating basaltic scoriae, steam columns, but also earthquake swarms and the uplift of 1–2 m of the northern coast of the island (Riccò 1892).

41.4 Landscapes, Landforms and Human Activities

The complex volcano-tectonic history of Pantelleria strongly controls the island morphological evolution. Two main morphological sectors are evident on the island and witness the progressive migration of volcanism from southern to northern sectors. The present-day landscape is mainly controlled by gravitational and coastal processes and is markedly influenced by increasing human activities. In order to illustrate the geomorphological variety of the island, we identify the following morphological elements, representative of the different landscape types.

Fig. 41.4 The Randazzo volcanic centre (*centre-left*); note the pumice ring encircling a broken dome

Fig. 41.5 The Khaggiar lava field, view from the summit of Cùddia Randazzo

Fig. 41.6 A view of the southeastern sector of the island (looking NW). At the *centre left* Mt. Gibele, whose trachyte lava flowed in the young caldera plain. On the very *background* it is visible the summit of Montagna Grande, the highest relief of the island (836 m). A small portion of Mueggen pantellerite lava shield volcano is barely visible at the *extreme right* of the photo

Cùddia Randazzo complex—The Randazzo volcanic centre (age 7–8 ka BP; Speranza et al. 2010; Scaillet et al. 2011) consists of (Fig. 41.4): (i) a pumice cone of 400–500 m in diameter; (ii) a later pantellerite lava dome intruded in the core of the pumice cone. The dome is ruptured with a V-shape, opened towards NE; (iii) the break-up of the dome originated the *Cuttinar-Khaggiar* pantellerite lava field (Fig. 41.5) that extends up to Punta Spadillo, 2.5 km from the source vent of Cùddia Randazzo. In the very abrupt morphology of obsidianaceous pantellerite lavas, it is still possible to recognize traces of old man-made terraces and a Roman path that leads to the seaside.

Cùddia Mueggen—Mueggen is a young (age 18 ka, Scaillet et al. 2011) pantellerite shield volcano located in the eastern sector of the island, between Montagna Grande to the west and the La Vecchia caldera rim (at Khamma-Serra Ghirlanda) to the east (Fig. 41.6). Mueggen lavas flowed down to the sea, NE of the village of Khamma, in a narrow lava flow. Shield volcanoes are usually fed by poorly viscous mafic magmas, able to expand at 360° and maintaining a low aspect ratio, while are very uncommon in rhyolite magmas (very viscous). The exception of Mueggen is due to the relatively fluid behaviour of some alkali-rich pantellerite magma, with respect to the "normal" alkali-poor rhyolites.

The intra-caldera Lake Specchio di Venere (Fig. 41.7)—The Lake *Specchio di Venere* (literally Venus mirror) is a subcircular endhoreic lake, 450 × 350 m wide, with a maximum depth of 13 m (Bocchi et al. 1988) and the water table just one metre above the present-day sea level. The north margin of the lake is coincident with the north side of the young caldera wall, and the substratum of the lake is composed of the caldera debris and the Green Tuff. The water of the lake is a result of mixing of meteoric, hydrothermal and sea water (Aiuppa et al. 2007). The southwestern shoreline is characterized by several CO_2-rich hydrothermal springs.

The human activity in Pantelleria since the Phoenician age (fourth–third century BC) has produced a particular landscape characterized by the presence of dry walls, man-made terraces and circular towers. The dry walls have a height generally in the range of 1–2 m (Fig. 41.8a), and can be found all over the island, although they are rather more common in sectors close to lava fields, whose rugged morphology required the use of the dry walls to form small terraces. The latter constitute portions of land surface suitable for agriculture activities, the main of which is viticulture, largely related to the production of the *Zibibbo* grape (whose name derives from the Arabic word *zabib* = raisins). This grape is used to produce the sweet wine named *Passito*,

Fig. 41.7 The intra-caldera Lake *Specchio di Venere* (looking east)

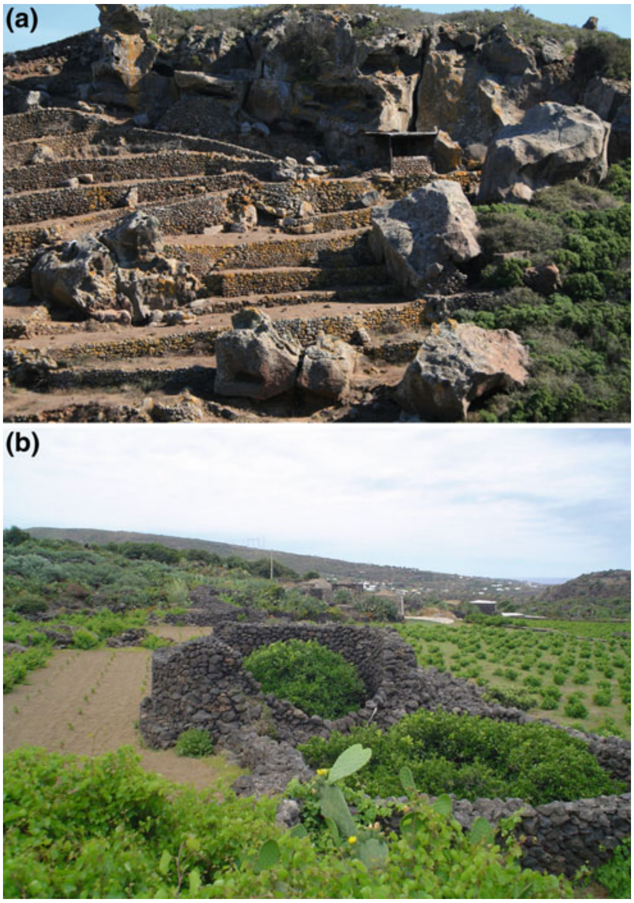

Fig. 41.8 **a** The characteristic dry walls; **b** the circular towers, *Pantelleria gardens,* built to protect lemon trees from strong winds

which is one of the principal high quality productions of the island.

The circular towers (Fig. 41.8b), which are locally called "*jardino pantesco*" (Pantellerian garden), are built to protect lemon trees (typically one or two) from strong winds that blow on the island in any season. They are circular structures (diameter 5–8 m, height 3–6 m, wall thickness ≤ 1 m), roofless and made of stones. These structures have a single narrow opening for access at the base. The thick walls retain moisture, helping to keep a particularly mild microclimate inside the garden. Unlike lemon trees, caper plants need windy exposures which particularly occur in the southern sector of the island.

41.5 Conclusion

During its early lifetime, Pantelleria experienced a series of ignimbrite-forming eruptions that culminated with a caldera collapse at 140–145 ka. The magnitude of the eruptions reached a peak with the Green Tuff (44 ka) eruption, related also to a second caldera collapse. The volcanism younger than the Green Tuff was much less explosive in comparison with the older period and was also punctuated by numerous pantellerite lava flows.

The complex interplay of tephra distribution and volcano-tectonic events created a landscape dominated by: (i) the ubiquitous mantling of the Green Tuff; (ii) the younger caldera depression and, only at places, the barely visible traces of the older caldera; (iii) young pumice and scoria cones, lava fields and lava domes, concentrated mostly within the young caldera.

The most recent eruption (1891 AD) was submarine, 5 km offshore, while the youngest onshore eruption was a low-energy Strombolian pumice fallout at Cùddia Gallo with an age of 6-8 ka. Although the island is rated with a low probability of unrest, the composition and temperature of thermal waters and CO_2 concentration of some well-known exhalating areas, are periodically monitored.

Due to the richness of flora, fauna and the uniqueness of landscapes that still preserve the typical ecosystem of the Mediterranean shrub, about one-third of the island is protected (*Riserva Naturale Orientata Isola di Pantelleria*) and connected through a dense network of footpaths; some of them are very ancient and scenically cross lava domes or lava fields. The presence of a Museum of Volcanology at Punta Spadillo, with illustrated geological itineraries, makes the Island a perfect site for geotourism, given the superb quality of exposures, the variety of volcanological scenarios and the perfect integration of volcanic landscapes with human activities. The ubiquitous occurrence of dry walls remodeled the topographic surface preventing erosion and rock falls. In addition, it increased the availability of areas for the cultivation of Zibibbo grape, used for the production of the famous *Passito* wine.

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Part III

Geoheritage

Geoheritage in Italy

42

Maria Cristina Giovagnoli

Abstract

The geoheritage of a country is one of the expressions of its geodiversity and Italy is a rich country in both of them. Nevertheless, Italy is still far from having a national geoheritage conservation strategy. In Italy, there is no national protection law about geoheritage which is protected only indirectly by the Cultural Assets Code and the national Law on Protected Areas and by only three regional laws strictly connected with geoheritage. In the Italian Geoparks of the EGN, European Geoparks Network, the geoheritage is protected and enhanced. Four Italian sites are in the UNESCO World Natural Heritage List, which has the aim of sharing with the whole world the responsibility of preserving these sites of outstanding properties.

Keywords

Geodiversity • Geoconservation • Geopark • European Geoparks Network • World Heritage Site

42.1 Introduction

The wide range of the Italian peninsula landscapes and their uniqueness are strictly connected with its rich geological variety, with its geodiversity. The geological diversity has also largely influenced land use and the distribution of habitats and location of human settlements. However, in the last years the relevance of the geological component is slow to be widely accepted by the Italian public opinion, unlike the growing awareness of the importance of preserving ecosystems and biodiversity. Geologists and geomorphologists started using the term geodiversity in the 1990s with slightly different meanings in different parts of the world, and in general it stands for the natural range of geological (rocks, minerals, fossils) and geomorphological (landforms, processes) and soil features of a territory and, according to Gray (2004), it includes their assemblages, relationships, properties, interpretations and systems. The geoheritage of a country is one of the expressions of its geodiversity, a term which implies the complexity and variety of geology and which is used to describe the variety within abiotic nature, whereas biodiversity means biological diversity.

Geoheritage includes sites or areas—the geosites, which have a special role in the reconstruction of the Earth's history and which show different geological characteristics: rocks, fossils and minerals recording how life evolved or how volcanism, sea level changes, erosion and other geomorphological processes have shaped the landscape and are continuing to shape it today. All the geosites of a territory represent its geoheritage.

42.2 Geoconservation and Geoheritage Protection in Italy

In the mid-1990s, a general discussion about geological heritage started in the Italian scientific community (Panizza and Piacente 1993; Brancucci et al. 1999) in the wake of a burgeoning of activities in Europe, but while in most European countries the interest in geoheritage had been

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determined by an environmental preservation policy, in Italy a geoheritage legislation has yet to be formulated.

As a matter of fact, in Italy the Code of Cultural and Landscape Assets (Law N. 42 of 2004) is the only national law that regards geological heritage. It deals with both cultural and environmental assets but not with geoconservation. This law refers to the territory as the result of the interaction between human and natural factors and states both that geological peculiarities (geosites) are under protection, if they are included in the town-and-country planning, and that some of them must be comprised therein. This is the reason why, in the last few years, local authorities in Italy have developed regional inventories of geosites.

Some Italian regions, as a result of this law, have developed an interest in geoconservation and have issued regional laws dealing specifically with geological heritage such as Emilia-Romagna in 2006, and Liguria and Apulia in 2009. In 2012, Sicily also issued a law about geosites but not directly dedicated to geological heritage and merely concerning the inventory of Sicilian geosites; however it may be a first step towards a geoheritage conservation project for the Island.

Another national legislative instrument which provides, although indirectly, an effective protection of geoheritage is the Framework Law on Protected Areas N. 394/1991. This law also takes into account the geological characteristics of a territory which are listed among features of relevant environmental importance legally required to establish an Italian Protected Area (national, regional, etc.). The geosites which are inside a protected area are protected by all the rules which regulate a park, a reserve, etc.

A specific national law dealing with geoheritage is still eagerly awaited for, while national activity of inventorying started at the beginning of the third millennium, with the aim of getting to know Italian geoheritage.

At the beginning of the 2000s, the Italian Geological Survey started a project on geoheritage, with the aim of producing a systematically compiled inventory of the most valuable sites of geological interest in Italy. The inventory was intended to be an instrument for gaining understanding of the Italian geological heritage. Sites were selected on the basis of information from published resources and data and only a very small part of them came from adequate research or site visits undertaken. The entire Italian coverage was selected from scratch, in a relatively short time (about two years). The implementation was not based on a pre-established geological framework but it was approximately based on geological domains such as geomorphology, palaeontology, stratigraphy, mineralogy, etc. Data collected for each geosite were related to general and geological characterization, illustrations, references and additional characteristics. The results of this first part of the project were then collected in a database. The second part of the activity was conducted sharing national and local experience about geosites and modifying the national format for the geosite collection, taking into account local geological situations, administrative use and touristic purposes.

Currently, the general characterization of each geosite includes: (i) geosite identification, (ii) geographical and administrative identification, (iii) access, (iv) legal protection, vulnerability and risks of degradation.

The geological characterization describes the geosite and validates its inclusion in the Inventory: (i) scientific interest (i.e. geological context) and its assessment: palaeontology, mineralogy, geomorphology, etc., (ii) rare, representative or illustrative, (iii) related interest: cultural, naturalistic, geotouristic, etc., (iv) scientific relevance: local, regional or national, (v) geological content: main lithologies, geochronology, a brief geological description, (vi) illustrations: pictures, excerpts of geological maps, geological sections, etc., (vii) references: pdf of scientific and informative literature and any other published document about the site.

As a result of this activity, the Italian Geosites Inventory is today a geodatabase published on the ISPRA website (Italian Institute for Environmental Protection and Research, which includes the Geological Survey of Italy) and it can be freely consulted (http://sgi.isprambiente.it/geositiweb/). At the moment the geodatabase contains data about approximately three thousand geosites and half of them are geomorphological sites. Geosites are important for their particular geological, scientific features but certainly the scenic impact of coastal cliffs and foreshore, U-shaped valleys and cirques, clints and grikes, dolines, lakes, canyons, badlands, etc., lends geosites an impact that cannot be underestimated.

Inventorying geosites is also a way to disseminate the knowledge of geoheritage and to bring it closer to the general public. Knowledge is, in fact, the first and perhaps the best way of preserving geoheritage. The best protection comes when people have a hand in it, when they feel that a geosite is something that belongs to them.

42.3 Italian Geoparks

In the last 20 years, the general interest in geoheritage has grown in Italy and a new approach to the geological study of an area, taking into account also the social, cultural and economic life has developed.

This kind of approach has been perfectly put into practice by the Geoparks of the European Geoparks Network (EGN). A Geopark, in fact, plays an important role in the economic development of its territory enhancing the geological heritage of the area through community involvement, aiming at the economic development of the region.

The EGN was born on the initiative of four European regions: Haute Provence (France), Maestrazgo/Teruel (Spain), Lesvos Island (Greece) and Vulkaneifel (Germany), which sensed the economic potential of their geoheritage and the importance of developing projects involving both the naturalistic and the cultural richness of their territories. Their joint analysis of the characteristics, perspectives and problems of their respective terrains resulted in the definition of a common development strategy focused on geological sustainable development and on geotourism in particular.

Any region that wishes to be part of the EGN, must complete a strict procedure in order to achieve high quality standards in Geoparks (UNESCO 2006, 2008) and the membership is limited to a period of 4 years after which it can be renewed following a revalidation process.

It should be remembered that a Geopark is not a protected area according to the legal significance that Italian law applies to this term. Therefore there are no legal restrictions applicable to a Geopark in order to protect its geoheritage.

At the end of the 2014, there were 111 Global Geoparks and their number is constantly changing. Currently there are nine Geoparks in Italy (Fig. 42.1), Italy being the second largest group in Europe, after Spain, whereas China is by far the first one in the world.

The Italian Geoparks (Aloia and Burlando 2013) are also natural regional parks, protected areas, with the exception of

Fig. 42.1 Map of Italian Geoparks (*red circles*) and World Heritage Sites (*blue stars*)

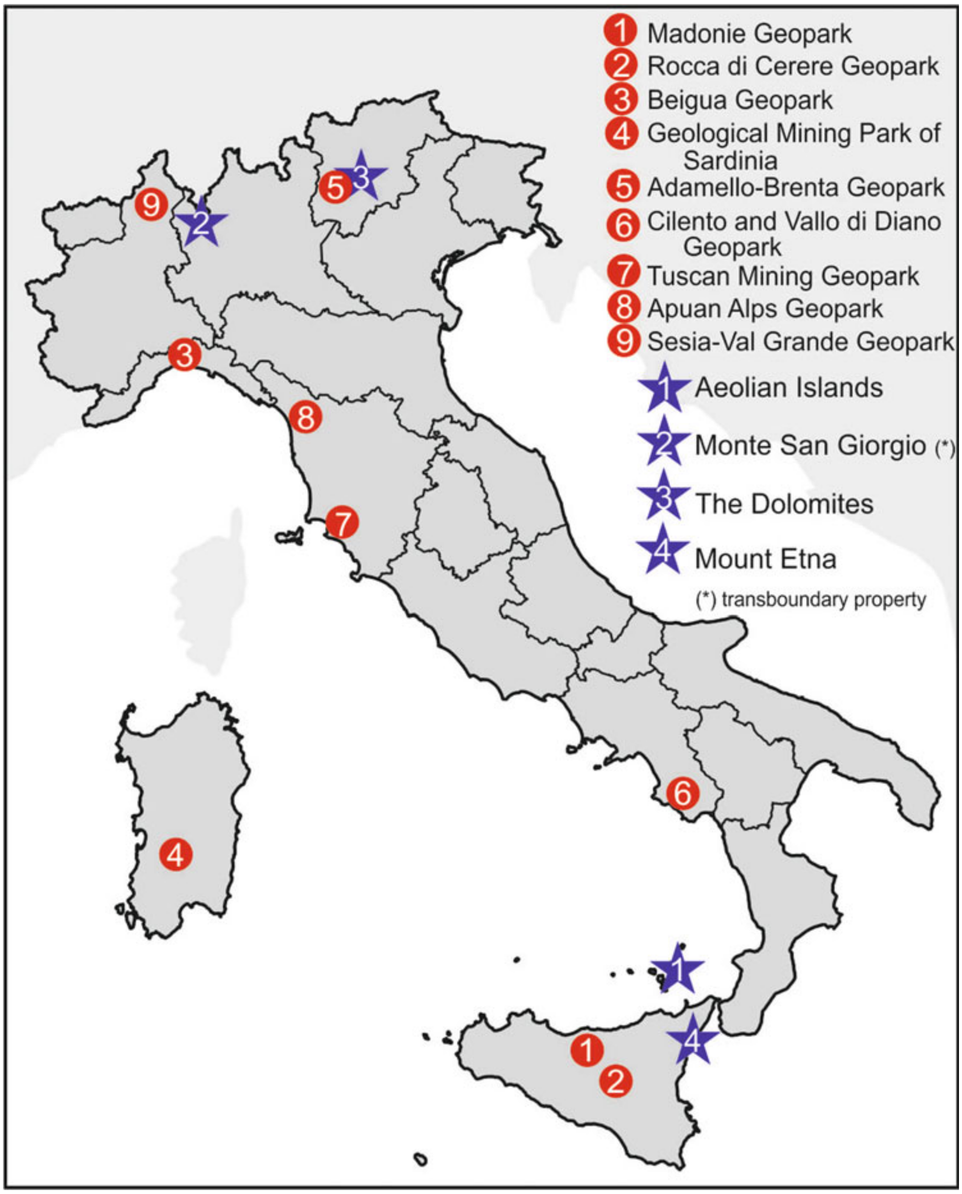

Fig. 42.2 Madonie Geopark, Sicily: the Carbonara tableland, a plateau situated on Pizzo Carbonara at an elevation between 1500 and 1979 m a.s.l. (*photo* P. Li Puma)

the Rocca di Cerere Geopark. The Tuscan Mining Geopark and the Geological Mining park of Sardinia are also mining parks.

The *Madonie Geopark* in northern Sicily (Fig. 42.2) was the first Italian Geopark, joining the network in 2001. The Madonie Mountains are a region of extraordinary interest, both geological and botanical and cultural: rocks from Triassic to Pleistocene age outcrop in the area and are grouped in units whose relationships are extremely complicated by tectonics (Catalano and D'Argenio 1982). The geomorphological aspect of the Madonie is the result of the morphogenetic processes acting on different lithologies outcropping and of the interaction of these processes with the tectonic and neotectonic evolution of the region, as well as the climatic variations that continued during the Quaternary Period. The karst areas, a large plateau carved by hundred of sinkholes, 1600 m above sea level, are among the most impressive landscapes in the Madonie.

The *Rocca di Cerere Geopark* (Fig. 42.3) is located in the central zone of Sicily (Lentini et al. 1987). The name has been chosen because of the ancient consecration of this territory to the chthonian deities. The area of the Geopark is characterized by the presence of a gypsum-sulphurous plateau arisen during Messinian salinity crises (between 5.96 and 5.33 Ma ago) due to the drying up of the Mediterranean Sea with the consequent deposition of evaporites. The numerous, now closed down mines, with their significant archaeological industrial settlements, are connected to the Messinian deposits outcropping in the area.

The *Beigua Geopark* (Fig. 42.4) is located in Liguria (northwestern Italy) and covers an area of particular interest in reconstructing the evolution of the Alpine mountain chain and its relationship with the Apennines, where extensive exposures of ophiolites represent a fragment of the original Jurassic ocean basin (Rovereto 1939). Geomorphological processes in a periglacial environment have strongly affected the landscape influencing the origin of a gentle morphology, with accumulations of large block deposits like block streams and block fields. Water effects on the Beigua Geopark landscape are visible both as fluvial landforms, as in the Valle Gargassa canyon, as well as in the contemporary coastal settings in the form of cliffs and beaches. Relict marine terraces and beach deposits are also present.

The *Geological Mining Park of Sardinia* (Fig. 42.5) consists of eight different areas, each one identified by its mineralogical and mining activity and by the historical and human aspects related to mining (Zoppi 1888). It occupies one-sixth of the total area of the Sardinia Island and is characterized by spectacular landscapes and unique geological heritage. In Sardinia the oldest rocks in Italy outcrop, dated to the Lower Cambrian. In fact, the island was part of the paleo-European margin until its counterclockwise rotation during Oligocene-Early Miocene. The important processes of metallogenesis and minerogenesis occurred during millions of years, resulting in the most significant mineral deposits in Italy, and Sardinia was in the past the first mining district in Italy. The almost total abandonment of mining at the end of the twentieth century left an extraordinary

Fig. 42.3 Rocca di Cerere Geopark, Sicily: Gresti Castle on Numidian Flysch (Late Oligocene—Early Miocene) (*photo* G. Amato)

Fig. 42.4 Beigua Geopark, Liguria: the Valle Gargassa, a spectacular canyon which has been shaped in Valle Gargassa conglomeratic formation (*photo* M. Saettone)

heritage of mining archaeology to be preserved and transmitted. Combined with the natural and archaeological heritage, this makes this Geopark truly unique.

The *Adamello-Brenta Geopark* (Fig. 42.6) covers a key-area in northwestern Trentino, characterized by the presence of tectonic border between the Austroalpine and the Southern Alps, and the history of the geological units outcropping in the area began in the Lower Paleozoic (Castellarin and Vai 1982). Gorges, alluvial plains, fans, landslides and detrital strata result from fluvial and gravity-driven erosional and depositional processes which occurred after the Last Glacial Maximum (LGM). In the Brenta Dolomites, the carbonatic rocks have been intensively carved by karstic processes which have obliterated or erased glacial morphologies. Even hypogean karstification is well developed and caves, cavities and karstic wells make the Brenta Dolomites a very important karstic aquifer. On Mount on the other hand, due to the plutonic origin of the rocks, glacial morphologies dominate.

The *Cilento, Vallo di Diano and Alburni Geopark* (Fig. 42.7) located in the south of Campania (southern Italy) is characterized by very dissected morphology with hilly landscapes and deeply engraved valleys and a costal sector with cliffs and limited coastal lowlands (Valente et al. 2017). The Cilento landscape took shape mainly during the Quaternary and was strongly influenced by both tectonic evolution of the area and climatic changes during this period. On the Mesozoic carbonate succession, karstic processes have

Fig. 42.5 Geological Mining Park of Sardinia: the coastal dune of Piscinas

Fig. 42.6 Adamello Brenta Geopark, Trentino Alto Adige: the geosite of Cima Vagliana (*photo* G. Alberti)

Fig. 42.7 Cilento and Vallo di Diano Geopark, Campania: Calore Gorges near Felitto (*photo* A. Aloia)

Fig. 42.8 Tuscan Mining Geopark, Tuscany: a mining deposit geosite known as "le Roste" (*photo* R. Cinelli)

produced plateaus showing sinkholes and poljes, limited by slopes and dissected by deep gorges and canyons.

The *Tuscan Mining Geopark* (Fig. 42.8) in southwestern Tuscany coincides with the territory of the Colline Metallifere, the most important mining district in the Italian peninsula (Lazzarotto et al. 2003). Geodiversity of this region results from the long and complex geological evolution of southern Tuscany, mainly related to the formation of the Apennine chain. These geological processes were accompanied by intrusive and effusive magmatic activity which has produced geothermal systems, as well as a widespread hydrothermal circulation responsible for sulphide mineralization (mainly in the Colline Metallifere district). At present, the Larderello and Mt. Amiata geothermal fields are active and exploited for production of geothermal energy, for heating domestic and industrial structures. Several recent surface manifestations of the southern Tuscany thermal anomaly occur in the Geopark territory, mainly as gaseous emissions, hydrothermal springs, hydrothermally altered rocks and travertine deposits, which have influenced the history, economy and culture of the territory of the Geopark.

The territory of the *Apuane Alps Geopark* is situated in northwestern Tuscany. The Apuan mountains were named "Alps" due to the presence of high peaks, different from those of the Northern Apennines (Carmignani and Kligfield 1990). The "Alpine" morphology is more evident on the coastal side of the region whereas the inland side has similar characteristics but with a slightly more gentle profile. Apuan stones, often grouped together under the trade name of Carrara marbles, have always been famous. Quarrying activity began in the sixth century BC and continues today. The complex geological history of the area is responsible for its high geodiversity: 19 mineral species have been discovered and described here for the first time, most of which are exclusive to this area.

The youngest Italian Geopark in the EGN to date is the *Sesia—Val Grande Geopark*. The name comes from two alpine valleys which share the same geological heritage and have decided to join in a single Geopark. The area is located in northeastern Piedmont (northwestern Italy), where it sits astride the Canavese segment of the Insubric Line, a 1-km-thick mylonite belt that is a major tectonic boundary of the Alps (Fountain 1976). Accessible outcrops display the effects of dramatic geological processes that shaped the continental crust at a wide range of crustal levels, from high-grade metamorphism, magmatism, anatexis and ductile deformation at depths as great as 25–30 km, to the explosive eruption of a "supervolcano" 282 million years ago.

42.4 The World Heritage List

The main purpose of the UNESCO—Convention Concerning the Protection of the World Cultural and Natural Heritage is to increase the States' awareness on issues related to knowledge and conservation of their own heritage. In particular, the Convention establishes a List that includes the most important and representative examples of heritage, either natural or cultural, which are considered to have values that are essential for the whole of mankind, no matter where they are located. The concept of "outstanding universal value" is the peculiarity of this List. The sites selected are the best examples of cultural and natural heritage on a world basis or specific to certain geographical areas and within a specific category of properties. The purpose of the List is to identify properties of outstanding value and to share with the whole world the responsibility of preserving them for future generations. Currently there are 49 Italian sites of outstanding universal value. Four of them (Fig. 42.1) are natural properties: the Aeolian Islands (since 2000), Monte San Giorgio (2003, extended in 2010), the Dolomites (2009) and Mount Etna (2013).

The *Aeolian Islands* are the emergent portions of large volcanic edifices rising *ca.* 2000–3000 m above the seafloor and are the most active volcanic structure in the Mediterranean area (Lucchi et al. 2017). Stromboli and Vulcano are presently active, Panarea and Lipari are dormant, whilst Salina, Filicudi and Alicudi are extinct volcanoes. The Aeolian Islands volcanism has entirely developed during the Quaternary, starting from *ca.* 1.3 Ma in the submarine areas (Beccaluva et al. 1985) and *ca.* 270–250 ka in the emergent portions. All the Aeolian Islands are polygenic composite volcanic edifices resulting from the interplay of successive eruptive sequences and volcano-tectonic collapses through time. Implications for volcanic hazard and risk assessment are primarily related to the currently active volcanoes of Stromboli and Vulcano.

The Italian *Dolomites* have been recognized by UNESCO as a World Heritage Property in 2009. They are located in northern Italy, in the southeastern sector of the Alpine chain but, from the geological view point, they belong to the Southern Alps and are a segment of the African margin. The outcropping rocks are mainly of sedimentary origin and were deposited in a warm tropical sea during the middle Triassic and in a vast tidal flat during the late Triassic, when the most famous and spectacular geological formation of the Dolomites, the *Dolomia Principale*, was formed. During the middle Triassic the region was characterized by intense volcanic activity. The superb landscapes of Dolomites are the result of geomorphological processes which acted during the Quaternary and particularly since the LGM, on rocks with very different geomechanical behaviour. Hence, the variety of landforms which makes the Dolomites a unique place in the world (Panizza 2009; Soldati 2010).

The latest Italian site on the List was *Mount Etna*, inscribed in 2013. Etna is one of the largest continental volcanoes in the world, characterized by an almost continuous eruptive activity. It dominates eastern Sicily, being over 3300 m high. Its typical landforms have developed during the past 60 ka in a period in which the main bulk of the stratovolcano structure was formed and they were generated through both constructive and destructive processes (Azzaro et al. 2012). Interrelationships between human activity and volcanic activity have continued since the Neolithic. Except for a few hiatuses, volcanic activity has never stopped to this day and there have been a number of major eruptions over the last 50 years which have had significant impacts on human activity. At present it is interesting to observe how the impact on human activity has always been short-lived, recovery has been rapid, and the society has showed a strong resilience to disasters.

In 2010 UNESCO approved the extension of *Monte San Giorgio*, Switzerland, to include the portion of Monte San Giorgio located in Italy, on the basis of natural criteria. The site is listed as: "transboundary property". The property encompasses the complete Middle Triassic (240–230 Ma) outcrop of Monte San Giorgio, one of the most famous fossil-bearing outcrops and the most important in the world in terms of marine vertebrates. The fauna is characterized by an exceptional state of conservation and an extremely high number of findings which have led to the identification of about 30 species of marine and terrestrial reptiles, about eighty species of fish, more than one hundred invertebrate species, and several plants. Reptiles are the most spectacular, some specimens being more than six metres long. Sauropterygians, a taxon of aquatic reptiles, is the most represented one in the outcrop while the land-based fauna is more restricted and includes a complete skeleton of *Ticinosuchus* (Krebs 1965), the first to be discovered in the northern hemisphere. A continuous scientific study of the site has been carried out in the last 75 years by Zurich, Switzerland, and Milan, Italy, research teams.

The popularity that derives from being included in the List certainly brings with it immediate economic effects and makes local communities aware of the value of the place where they live. In general, the action of the Convention has focused attention on issues related to conservation and protection of the heritage and it has recommended each State party to the Convention to identify innovative tools for managing heritage, combining conservation and protection with sustainable development, which would also aim at improving the socio-economic situation and the quality of life of the population. Being on the List is a great opportunity but not a direct instrument for preserving natural heritage and consequently, the geological one too.

42.5 Conclusions

As the EGN Network experience shows very effectively, geological heritage can become an economic resource. In the same way, as Geoparks have developed successfully throughout Europe, geotourism and geological focused sustainable tourism could be a new economic strategy which would offer an indirect protection to geosites. Enhancement projects, exploring strategies for attracting tourists and providing them with positive experience, are on the way and in the next years we will see if projects focused on geoheritage have got off the ground in Italy. The positive side effects of these activities should be better awareness of geoheritage and consequently public cooperation in its protection. Participation in protection would be the most efficient solution, while awaiting a law dedicated to the safeguarding of the Italian geoheritage that at present is still only the subject of debate among experts.

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43

Geomorphodiversity in Italy: Examples from the Dolomites, Northern Apennines and Vesuvius

Mario Panizza and Sandra Piacente

Abstract

Following the concept of *geomorphodiversity* (Panizza 2009), the extrinsic and intrinsic peculiarities of the geomorphology of the Dolomites, Emilia-Romagna Apennines and Vesuvius volcano are outlined. The Dolomites show an exceptional beauty and unique landscape. The inclusion in the UNESCO World Heritage List is an important scientific achievement, owing mainly to their geomorphological importance. The Emilia-Romagna Apennines, a candidate for enrolment in the European Geopark Network, show a multifaceted and complex image from the geomorphological point of view. They constitute an educational example to illustrate geomorphic evolution, gypsum karst phenomena and morphodynamic peculiarities. The Vesuvius volcano shows geomorphodiversity mainly referred to the type of eruptions, with some exemplary processes inserted in international volcanic nomenclature. It makes up an important geoheritage site that can be considered a field laboratory for volcanic geomorphology research. As for the management of these mountains, a conceptual path is suggested and illustrated, following the phases of knowledge, communication, awareness, protection and appraisal.

Keywords

Geomorphodiversity • Geoheritage • Dolomites • Emilia-Romagna Apennines • Vesuvius

43.1 Introduction

Starting from the definition of *landscape* (European Landscape Convention, Florence 2000), *geoheritage* (see EU Manifesto on Earth Heritage and Geodiversity, Strasbourg 2004) and *geodiversity* (Sharples 1995; Dixon 1996; Gray 2004; Zwolinski 2004; Reynard and Coratza 2007; Erikstad 2013), *geomorphodiversity* was defined as: "*the critical and specific assessment of the geomorphological features of a territory, by comparing them in a way both extrinsic and intrinsic and taking into account the level of their scientific quality, the scale of investigation and the purpose of the research*" (Panizza 2009).

This concept of geomorphodiversity cannot be univariate. The whole set of geomorphological data of the study territory should be critically assessed, compared with that from other territories mainly in an extrinsic way and analysed within the territory itself mainly in an intrinsic way in order to evaluate geomorphological characteristics and, therefore, geomorphodiversity of the area. The scale of the investigations should be taken into the right account and the level of their scientific value assessed. Practically, it is a matter of carrying out original research, finalized each time towards well-defined purposes, by avoiding statistical elaborations, even with mathematical indexes and formulas: in fact this procedure does not constitute a scientific research, but a mere statistics, which are only an end in themselves; see difference between geology (γή-λόγος) and geometry (γή-μέτρον).

This concept of geomorphodiversity can be usefully applied to the description and assessment of geomorphological

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Fig. 43.1 Location of Dolomites (1), Emilia-Romagna Apennines (2) and Vesuvius volcano (3)

heritage. Three examples of this application in Italy are presented: the first one concerns the Dolomites, the second one focuses on the Emilia-Romagna Apennines, the third one deals with the Vesuvius volcano (Fig. 43.1).

43.2 The Dolomites

On June 26 2009 the Dolomites were included in the World Heritage List because of their exceptional beauty and unique landscape (criterion vii), as well as in the recognition of their scientific importance from the geological and geomorphological viewpoint (criterion viii). In particular, with reference to criterion viii and to geomorphology specifically, it was stated that

> The Dolomites are of international significance for geomorphology, as the classic site for the development of mountains in dolomite limestone. The area presents a wide range of landforms related to erosion, tectonics and glaciation. The quantity and concentration of extremely varied carbonate formations is extraordinary in a global context, including peaks, towers, pinnacles and some of the highest vertical rock walls in the world. Taken together, the combination of geomorphological and geological values creates a property of global significance.
> (UNESCO, General Assembly, Valencia, Spain, June 2009)

The area is located in the northeastern sector of Italy and it is a part of the Southern Alps. Out of the Dolomite range, nine different "systems" were chosen to represent an organic series of exceptional aesthetic and scientific values. The nine systems, contained in an area of approximately 142,000 hectares, are integrated and complement one another. In fact, they constitute a serial property, as they represent a unified whole, albeit dislocated and complex, both in terms of geography and landscape and from a geological and geomorphological standpoint (Gianolla et al. 2008).

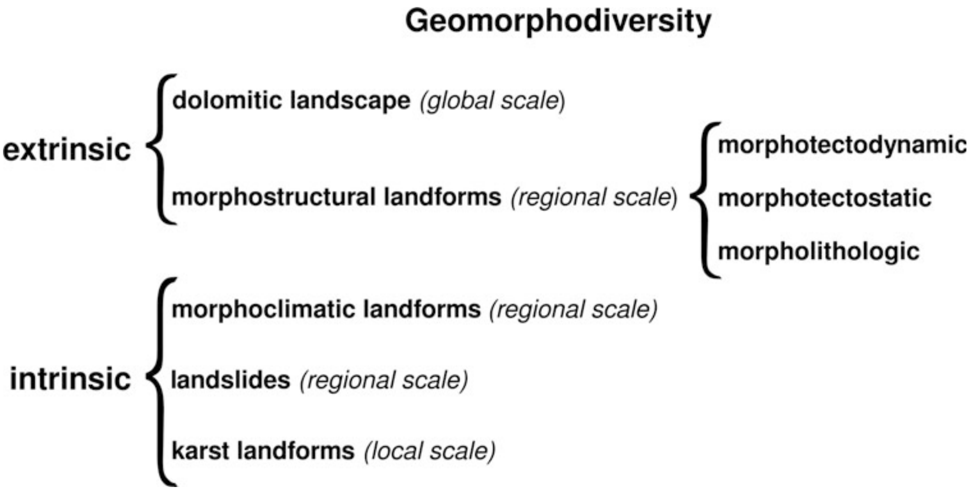
From an aesthetic point of view these mountains present exceptional, monumental, original and spectacular features. It is here that nineteenth century travellers found inspiration for the "romantic" landscape, and the Dolomites still provide a fundamental reference point for defining the modern concept of natural beauty. We should remember the painters who have been inspired by these mountains for their works: from Titian to the romantics (Fig. 43.2), from the expressionists to the futurists and onwards to contemporary artists, in addition to writers, poets, musicians and other artists who have felt stimulated and called to immortalize the aesthetic values of this range.

The geological importance of the Dolomites is due to the extremely detailed and continuous manner in which they represent a large part of the Mesozoic Era, bearing witness to a tropical sea which existed here between 260 and 200 million years ago. It is possible to reconstruct the geological history of this period as if reading from the pages of a gigantic stone book (Gianolla et al. 2008).

In order to acquire correct geomorphological understanding of these mountains, the concept of geomorphodiversity has been applied (Panizza 2009) (Fig. 43.3). First of all, they have monumental, original and spectacular qualities (Fig. 43.4) which distinguish the Dolomites from all other mountains in the world (extrinsic geomorphodiversity on a global scale). Furthermore, in the context of the alpine environment, they offer a particularly varied, complex and emblematic range of morphological features (extrinsic geomorphodiversity on a regional scale), with structural forms causally linked with movements of the Earth's crust both in the past and at present. On account of their variety and complexity, these landforms are superimposed on other forms which offer an almost complete educational and scientific case study within the Dolomites (intrinsic geomorphodiversity at regional scale). The contemporary morphology partly reflects the present-day climate conditions whilst partly it records processes taking place during recent geological periods (cf. Soldati 2010). Thus, we can observe vestiges from the pre-glacial and inter-glacial times right up to the present day, including, above all, erosional and depositional landforms left by ancient glaciers (Fig. 43.5). These glaciers occupied the

Fig. 43.2 Landscape in the Dolomites: general view of Catinaccio. Oil painting on canvas by J. Gilbert (1862) after Audisio and Guglielmotto-Ravet (1982)

Fig. 43.3 Geomorphodiversity of the Dolomites



valleys of the Dolomites until only a few thousand years ago, leaving only the highest peaks emerging above the ice surface, and reaching as far as the edge of Po Plain. On a local scale, another example of intrinsic geomorphodiversity is offered by a wide range of karst formations, both epigene and hypogene.

In conclusion, we can assert that the Dolomites represent a kind of high altitude, open air laboratory of geomorphological heritage of exceptional global value, clearly one among the most extraordinary and accessible in the world, and ideal for researching, teaching, understanding and developing Earth Science theories.

Fig. 43.4 Croda da Lago (on the *left*) and Nuvolau (on the *right*) in the Dolomites (*photo* H. Kostner). Croda da Lago is made up of Norian dolomites, Nuvolau is made up of Ladinian-Carnian dolomites: they are both examples of high extrinsic geomorphodiversity on a global scale

43.3 The Emilia-Romagna Apennines

Concerning the Emilia-Romagna Apennines, a dossier is being prepared to present a part of these mountains as a candidate to the European Geoparks Network (Gentilini and Panizza 2012). The area is located in northern Italy, south of the Po Plain, where it extends in NW–SE direction. The regional administrative framework is the Emilia-Romagna Region, but the territory examined covers only a portion of it, including mostly the Bologna Apennines. It can be considered representative of the Emilia-Romagna Apennines' geological characteristics.

The importance of the region in geology dates back to the introduction of the very name of the discipline which occurred for the first time in 1603 in Bologna by Ulisse Aldrovandi (Gentilini and Panizza 2012). Before Aldrovandi, Leonardo da Vinci, while crossing the Romagna Apennines, described the succession of strata he encountered (Leicester Codex 1506–1510) and drew a synthetic view of fluvial geomorphological knowledge in the Imola Map (1503). Later, the Emilia and Romagna geological research reached international relevance and recognition in stratigraphy and micropaleontology, marine geology, sedimentology of clastic (the concept of "turbidite" was born in the Northern Apennines), carbonate and evaporite rocks, tectonics, sedimentation, applied geomorphology, speleology. On this sound scientific basis, it was possible to establish and promote different areas as geological heritage. The physical characteristics of the territory reflect the geological background of the mountain chain. In particular, they are strictly controlled by geological-structural factors, such as the outcrops of the Tuscan Units (Oligo-Miocene arenaceous Flysch), overlying the mostly clayey Ligurian Formations. The valleys descending from the mountain crests in certain places have the shape of dug-in grooves, with bare steep slopes. Vast areas are characterized by landform homogeneity and correspond to the zone where the so-called "Argille Scagliose" (historical name) crop out. The prevalence of pelitic formations has favoured erosional processes along the valley floors and on the slopes, with widespread mass wasting processes and the development of "calanchi" (badlands). A lower geomorphological unit corresponds to the outcrop area of the Plio-Pleistocene sands and silty clays, showing badland erosional landforms between sandy bluffs. Along the border between the Bologna and Ravenna provinces the "Vena del Gesso" (literally "Gypsum Vein")

Fig. 43.5 Late Glacial moraine arc which blocked the Chedùl valley (Upper Badia Valley, Italian Dolomites), leading to the origin of a small, now extinct lake. Example of intrinsic geomorphodiversity on a regional scale (*photo* M. Panizza)

crops out, with its spectacular epigene and hypogene gypsum karst morphology.

Also for this area the concept of geomorphodiversity has been applied (Fig. 43.6). In the case of extrinsic geomorphodiversity, the area of the prospective geopark can be considered as an exemplary case in the Apennines owing to its typical geological features. It is in fact an educational example to illustrate tectonic evolution, stratigraphic and sedimentological sequences and lithological peculiarities of this chain and to compare with other mountains in the world. Gypsum karst phenomena, though, remain the most important and interesting geological characteristic of this area (Gentilini and Panizza 2012). From the surface viewpoint, individual landforms such as large sinkholes, blind and closed valleys, lapiez fields and deep dissolution furrows attract most attention. Among subterranean karst systems, it should be noted that in the province of Bologna there is one of the most widespread gypsum cave system in the world (Fig. 43.7).

On the other hand, intrinsic geomorphodiversity is mainly at regional scale and concerns first of all the complexity and variety of geomorphological features, including Last Glacial Maximum (LGM) glacial landforms, fluvial landforms, spectacular badlands, and mud volcanoes (“salse”), which create a very peculiar morphology (cf. Castaldini and Coratza 2017). A characteristic of the Emilia-Romagna mid-Apennines is given by the high frequency of mass wasting phenomena in both time and space. A large part of the slopes is indeed affected by gravity movements of various types (Fig. 43.8). This is mainly due to the prevalently clayey nature of the rocks as well as jointing, tectonic setting and climate characteristics, with intense precipitation in the spring and autumn. Finally, human intervention should not be ignored since various anthropogenic activities in the past have caused instability situations on extensive slope surfaces, such as deforestation or slope cuts for engineering works. Owing to all these characteristics and processes, the Emilia-Romagna Apennines are to be considered among the most landslide-prone regions in the world.

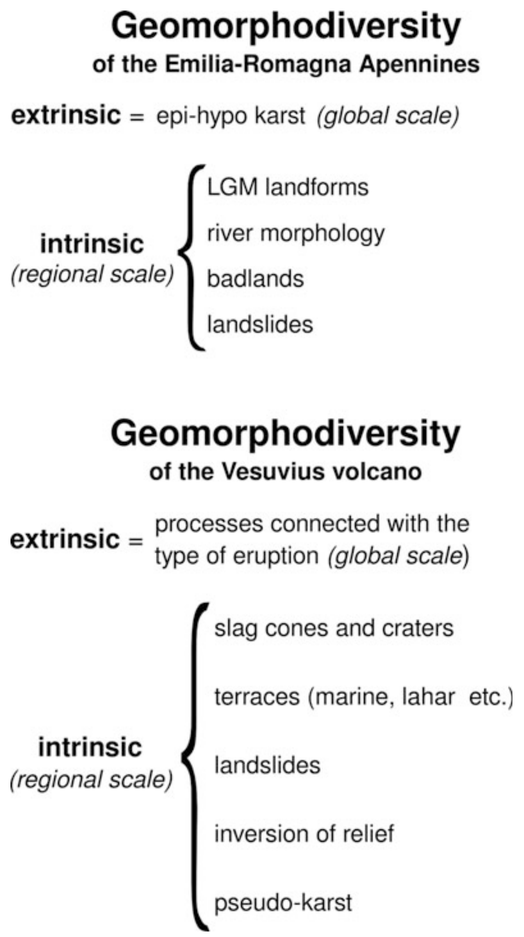


Fig. 43.6 Geomorphodiversity of the Emilia-Romagna Apennines and of the Vesuvius volcano

43.4 The Vesuvius Volcano

A third example is given by the Vesuvius volcano, one of the Italian National Parks, which is about to be also proposed as a candidate for the European Geoparks Network.

Mt. Somma-Vesuvius (Fig. 43.9) is a composite central stratovolcano made up of a more ancient structure, which has been affected by numerous collapses and now constitutes the caldera rim of Mt. Somma, and a more recent volcanic cone—Vesuvius—which was formed inside the ancient caldera. The cone grew and collapsed several times owing to constructive volcanic activity during the inter-plinian extrusive phases and destructive activity during plinian and sub-plinian type explosive eruptions (cf. Luongo 2012; Aucelli et al. 2017).

The beginning of volcanic activity in this area goes back to some 400,000 years BP. The first plinian eruption identified in the field is dated for 18,000 years BP and was named as the Basal Pumice Eruption. It was followed by other plinian eruptions: the Mercato Eruption (8700 years BP), the Avellino Eruption (3700 years BP), and the Pompeii Eruption (79 AD). All these volcanic activity phases were interspersed with many sub-plinian eruptions which were characterized by the same mechanisms as in plinian eruptions, but at lower energy levels. Among these, the most recent ones were the 472 AD Eruption and the 1631 Eruption. The latter initiated a long period of persistent activity which ended with the 1944 Eruption. At present, the endogenic dynamics of Vesuvius is represented by slow ground movements, low-energy seismicity and low-intensity fumarole activity from the bottom of the crater. All these phenomena are being recorded by the INGV—Vesuvian Observatory in order to monitor the hazard level of the area (Lirer et al. 2009; Luongo 2012; Aucelli et al. 2017).

Also for the Vesuvius the concept of geomorphodiversity has been applied (Fig. 43.6). From the geomorphological standpoint, extrinsic geomorphodiversity mainly refers to the type of eruption, with exemplary processes reflected in the international volcanic nomenclature. For example, morphological features of tephra connected with the plinian eruptions (Fig. 43.10), or surface runoff erosion and typical forms which developed from the ashes of “Vesuvian” eruptions. At a regional scale, intrinsic geomorphodiversity includes the examples of landforms and processes linked to volcanism, such as slag cones or craters, which have considerable educational value. Of further interest is marine terraces (Fig. 43.9) and other terraced forms, whose origin is related to the occurrence of lahars. Also the phenomena of relief inversion may be observed in the area. They generally originate through the geomorphic evolution after a lava flow filled a valley and has progressively emerged in the form of a terrace or ridge resulting from differential erosion affecting the surrounding slopes. Other landforms specific to the area are those typical for pseudo-karst topography, pseudo-dolines of phreato-magmatic or outgassing origin, or resulting from minor explosions. Other cases are represented by the cavities on Mt. Somma, in correspondence with eruption fractures or joints between two adjacent layers, or caves and tunnels due to lava flows or, less frequently, gas bubbles trapped within flows. Typical are the caves found in the municipalities of Ercolano, Torre del Greco and Terzigno.

Around Vesuvius there are archaeological parks of the ancient Vesuvian cities buried by the volcanic ejecta of the 79 AD Eruption. Among these are the excavations at Pompeii, Herculaneum, Oplontis and Stabiae. From the summit of the northern rim of Vesuvius crater, a magnificent panorama of the Gulf of Naples and the surrounding islands, as far as the Pontine Islands, can be admired.

Fig. 43.7 The Tanaccia cave (Emilia-Romagna Apennines), one of the largest epigenetic gypsum caves in the "Vena del Gesso", Ravenna province (*photo* P. Lucci). It is an example of high extrinsic geomorphodiversity on a regional scale

Fig. 43.8 The Morsiano earth flow, made up of the clayey Helmintoyd Flysch and "*Argille Scagliose*" (*Auctt*) formations, in the Emilia-Romagna Apennines (*photo* G. Bertolini). It is an example of intrinsic geomorphodiversity on a regional scale

Fig. 43.9 The Mt. Somma-Vesuvius (*photo* U. Leone). It comprises the caldera rim (Mt. Somma, on the *left*) and a more recent volcanic cone (Vesuvius, on the *right*), which was formed inside the caldera. In the *foreground* the Tyrrhenian coast showing marine terrace formed by the tephra of the Pompeii eruption of 79 AD: near Herculaneum the progression of the coastline towards the sea was about 400 m

43.5 Landscape Management

The values of the landscapes of the Dolomites, Emilia-Romagna Apennines and Vesuvius reside in their geodiversity, biodiversity, geomorphodiversity, scenic qualities and cultural heritage. All these values should be considered as inter-related and inter-dependent elements within a holistic conception, including also social components and strategies (Erikstad 2013). These are not fixed or immutable values but rather dynamic ones, in agreement with the evolution of the society itself (Panizza and Piacente 2014). A holistic approach that integrates these different values is essential since landscape character is the result of the action and interaction of both natural and human factors. Therefore, the knowledge of the landscape is achieved by searching for all the causes that have contributed in space and time to its formation. All the landscape features should be analysed from various standpoints related to different cultural and disciplinary backgrounds in order to build an integrated and holistic understanding of the landscape. This type of integrated approach has also been advocated elsewhere (Henriques et al. 2011; Prosser et al. 2011; Gordon et al. 2012). Therefore, the landscape is increasingly becoming a basis for research and for our awareness facing global change (Hijort and Luoto 2010).

In order to carry out a thorough territorial analysis, it is therefore of paramount importance to first choose the goals of investigations and, consequently, the most appropriate conceptual and methodological path for management purposes.

As for the management of the mountain areas described in this chapter, a conceptual path is suggested and illustrated, following the phases of knowledge, communication, awareness, protection and appraisal.

Knowledge should be based on a detailed analysis of the specific aspects of the Dolomites, of the Emilia-Romagna Apennines and of the Vesuvius. Such knowledge should be articulated into: (i) a strictly scientific interdisciplinary research; (ii) an accurate interpretation, within an integrated holistic-type synthesis. Subsequently, analytical–descriptive approaches are to be followed by systemic-developmental ones, which envisage the landscape as a set of interacting elements, closely connected to socio-cultural development.

Communication must be comprehensible in order to enrich knowledge, and based on scientific rigour. Specific communication skills are needed, together with a clear cultural and social aim. The two main aspects of communication should be popularization (by means of meetings, folders, articles, books) and education and training (school and lifelong learning).

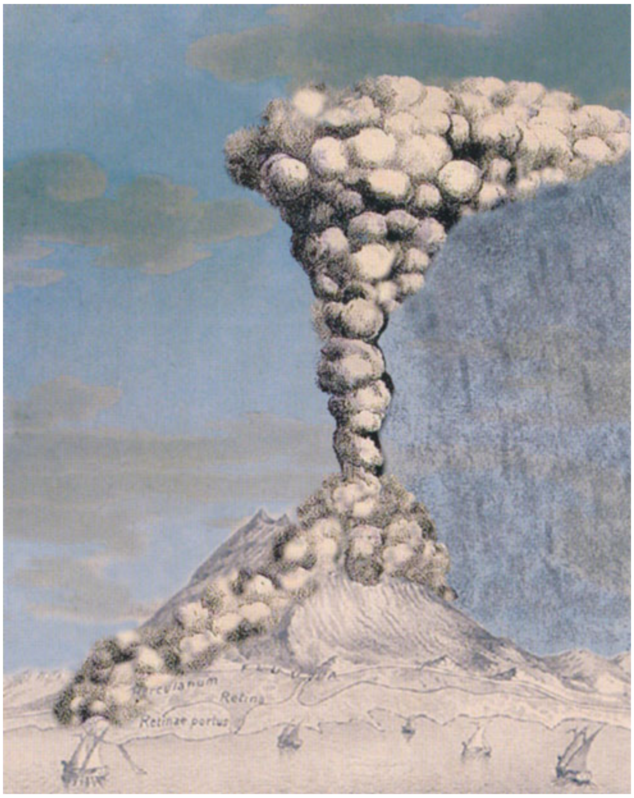


Fig. 43.10 Pyroclastic flow deposits on the slope above Herculaneum, laid down during a phase of 79 AD plinian eruption of Vesuvius (after Lirer et al. 2009). They are examples of extrinsic geomorphodiversity on a global scale

Awareness: any landscape can become common heritage and therefore a cultural asset in all its values only if communication leads to shared awareness; not only would this allow participation but would also support territorial management choices. It is obvious that, besides the above quoted specific characteristics, the strategies for involving and awakening public opinion could result also from the perceptions and expectations of diverse territorial realities, taking into account previous local experiences. A project thus conceived would involve the experience and responsibility of administrators, operators and beneficiaries at different levels.

As for protection and appraisal, the idea is "not planning in order to protect and protecting in order to manage" but "planning in order to disseminate knowledge and develop awareness in order to appraise and self protect" (Panizza and Piacente 2014).

Management: not a top-down planning (passive approach) but a bottom-up planning (active approach) with community involvement. Therefore, this sort of management must be linked to an "open network", intended as a cultural network of all the physical, biological and cultural elements of the territory.

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Goethe's Italian Journey and the Geological Landscape

44

Paola Coratza and Mario Panizza

Abstract

Over 220 years ago Johann Wolfgang von Goethe undertook a nearly two-years long and fascinating journey to Italy, a destination dreamed for a long time by the great German writer. During his journey from Alps to Sicily Goethe reflected on landscape, geology and morphology of "Il Bel Paese", sometimes providing detailed descriptions and acute observations concerning the great and enduring laws by which the earth and all within it are governed. In the present chapter an attempt is made to reproduce Goethe's *ante litteram* geotourism itinerary through Italy, which is considered one of the most attractive tourist destination worldwide thanks to its rich cultural and natural heritage and the outstanding aesthetic qualities of its complex landscape.

Keywords

Italian landscape • Geology • Goethe

44.1 Introduction

Johann Wolfgang von Goethe (28 August 1749—22 March 1832)—considered the greatest German literary figure of the modern era—in 1786 set out on a fascinating journey to Italy: a journey to a distant, warm and sunny land, a dream longed for a long time. Goethe's journey across Italy lasted nearly two years, from September 3 1786 to June 18 1788: exactly one year, nine months and fifteen days. Most of this time was spent in Rome, where he first stayed for four months and later on for nearly ten months. During his stay in Italy, he wrote many letters to a number of friends in Germany, which he later used, enriched with afterthoughts and reminiscences, as the basis for his famous book "Italian Journey" (original title: *Italienische Reise*) published in 1816–17.

The present chapter refers to the journey of the great writer as an example of perception and description of an "integrated" landscape, taking into account its natural and human components (geology, biology, climate, history, architecture, literature, etc.). From the Brenner Pass to Sicily, Goethe reflected on landscape, contrasting morphologies, the genesis of territories, providing detailed descriptions useful for reconstructing land use conditions of the late eighteenth century (Fig. 44.1). The "Italian Journey" is a kaleidoscope of images, documents, notes, impressions and ideas of life lived in pleasant situations or problematic ones. Goethe was an observer, with the eye of a geologist and landscape painter, as he himself stated, and therefore he had a 360° view of the Italian landscape (Panizza and Coratza 2012).

44.2 Goethe in Italy

In the eighteenth and nineteenth centuries, the Grand Tour of Italy—in search of art, culture and the roots of western civilization—became an almost compulsory step, a sort of rite of passage, in the education of European upper-class young men, who were expected to acquire experiences that would complete their traditional and classical education.

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Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Fig. 44.1 Goethe's journey across Italy

Travelling in the eighteenth century was dangerous, since highwaymen could attack on any road. Furthermore, coaches could easily break down due to poor state of the roads. As regards travelling in another country, very few people could speak a foreign language. Journeys were slow and long. In a week, no more than 500–600 km could be travelled and only very rich people could afford the expenses of such long journeys.

In 1786, Goethe was already the acknowledged leader of the Sturm und Drang literary movement, when he set out on his journey to Italy to fulfil his personal and artistic quest and to find relief from his responsibilities and the agonies of unrequited love. The journey was a kind of escape, prepared in secret, since his work as minister at Weimar had stifled his creativity. On September 3 1786, at three in the morning, Goethe slipped away from the Bohemian spa of Carlsbad and travelled by post coach to the Brenner Pass and down through South Tyrol to Verona, without saying goodbye to anybody (Fig. 44.1). The urgency of his first journal entry shows his desire to leave without notice: "*I slipped out of Carlsbad at three in the morning; otherwise, I would not have been allowed to leave. Perhaps my friends, who had so kindly celebrated my birthday on 28 August, had thereby acquired the right to detain me, but I could wait no longer*" (Goethe 1786–1788: 23).

Goethe made this journey in Italy mainly to discover himself as an artist: "*My purpose in making this wonderful journey is not to delude myself but to discover myself in the objects I see*" (Goethe 1786–1788: 57), "*Now my attention is fixed on the architect, the sculptor and the painter and in them too, I shall learn to find myself*" (Goethe 1786–1788: 155). He travelled through Italy with the desire to see with his own eyes art and architecture that he had only read and heard about before, especially from his father. He described the draw of travelling as "*an irresistible need*" (Goethe 1786–1788: 128). In 1788, he returned from his famous travels in Italy profoundly transformed as a man, humanist and scientist. What Goethe was looking for in our country was not so much the Italy of Michelangelo, Leonardo and the great Renaissance and Baroque paintings. He was searching for Greek and Roman antiquities, and when he saw a real Roman monument for the first time in Verona—the Arena—he was overjoyed.

The “Italian Journey” is a journal full of fascinating observations on geology and botany, climate, art and history, and the character of local people he encountered. Goethe brought back home about one thousand sketches and drawings and also started to write and became creative again. Within the field of geology and mineralogy, he showed a keen interest in rocks. His studies and remarks led him to take the side of the Neptunists, who were convinced of the importance of water in the slow process of formation of all kinds of rocks, against the Plutonists, who, on the contrary, favoured the igneous origin of many rock types.

44.3 Walking in Goethe’s Footsteps: From Brenner to Sicily

On September 3 1786, Goethe travelled as rapidly as he could by coach to the Brenner Pass and down through South Tyrol to Verona, Vicenza, and Venice (Fig. 44.1). On September 8 1786, he stopped in Brenner at the “Post Hotel”. Goethe described “*the limestone Alps through which I have been travelling so far are grey in colour and have beautiful irregular shapes, even though the rock is divided into level strata and ridges. But since folded strata also occur and the rock does not weather equally in all places, the cliff and peaks assume bizarre shapes*” (Goethe 1786–1788: 33). Goethe could not see the Dolomites directly, as he had come from the valleys of the Adige and Isarco rivers and travelled mostly at night. However, he referred to the morphology and differential erosion of “*limestone*” and to the high mountains of Tyrol (Fig. 44.2).

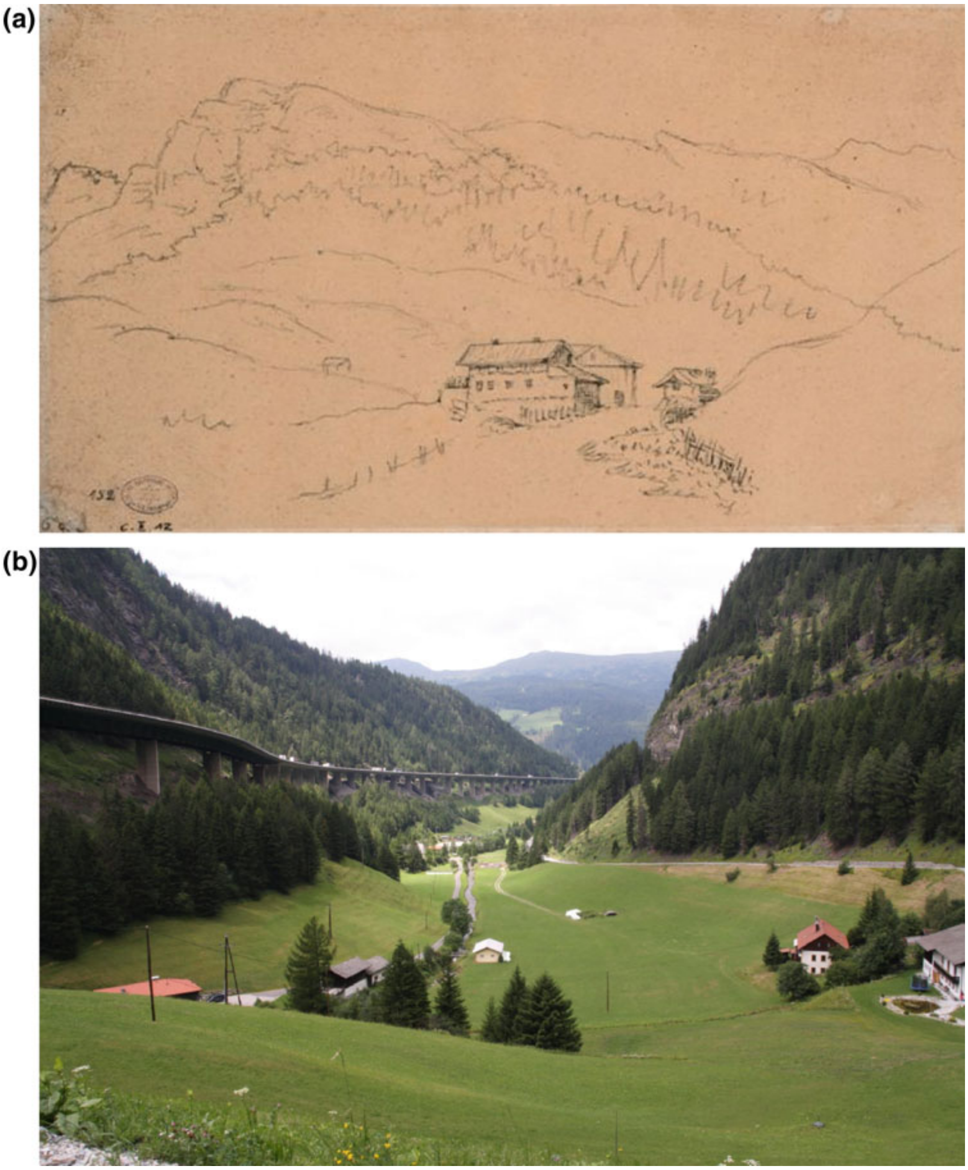

Fig. 44.2 **a** Brenner Pass in an original drawing by J.W. Goethe (1786); **b** Brenner Pass nowadays (*photo* Sönke Kraft aka Arnulf zu Linden, Wikimedia Commons under CC BY-SA 3.0)

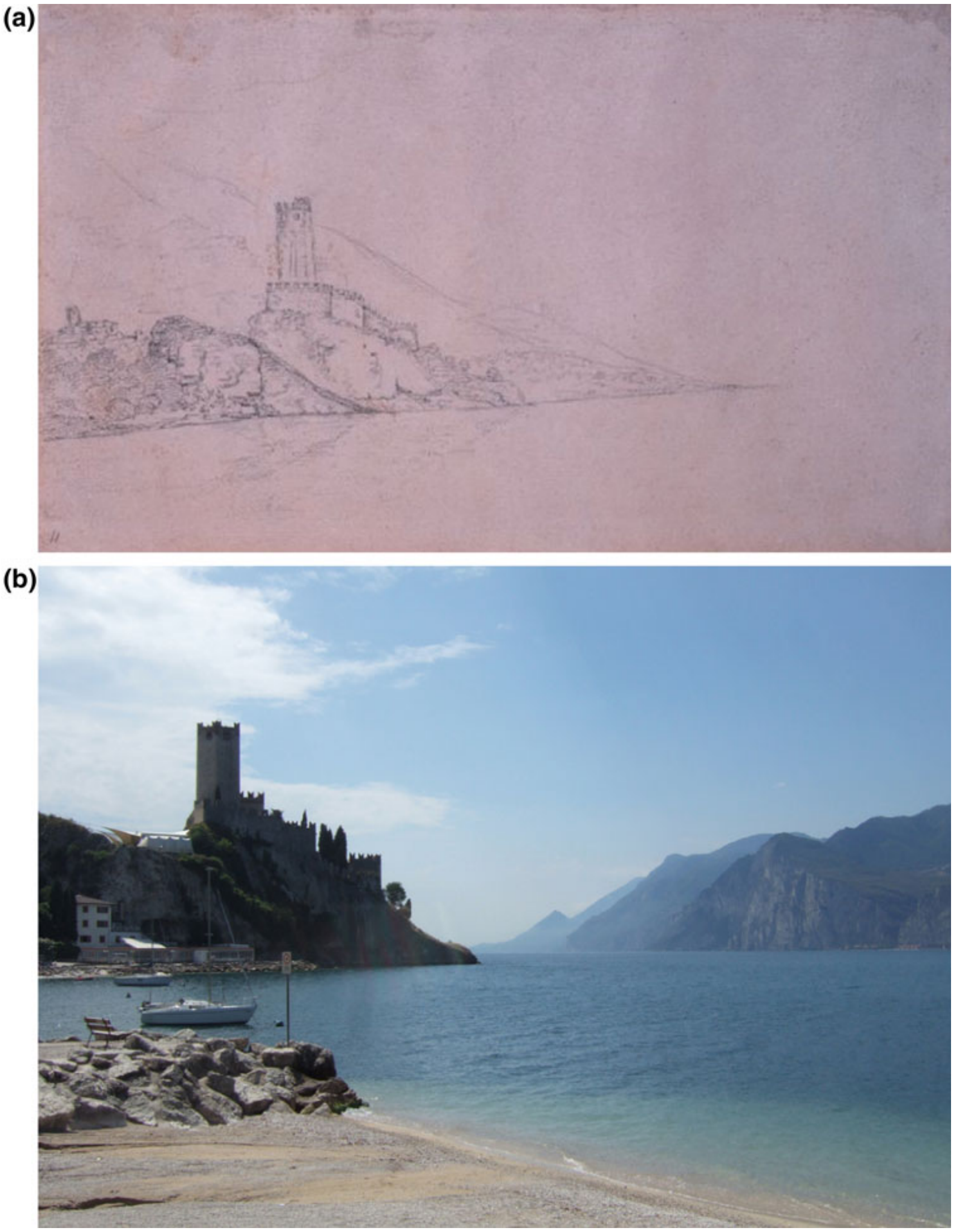

Fig. 44.3 **a** Drawing of the castle of Malcesine (1786) by J.W. Goethe; **b** Malcesine nowadays (*photo* degreezero 2000, Wikimedia Commons under CC BY-SA 2.0)

Continuing his journey towards Rome, Goethe was fascinated by the scenery around Lake Garda: “*I could have already been in Verona this evening, but I was close to a magnificent product of nature, a splendid spectacle, Lake Garda. I did not want to miss it, and I was repaid for my detour*” (Goethe 1786–1788: 41). He described the unique natural landscape of this lake, the open spaces and the majesty of the mountains surrounding it (Fig. 44.3). They fascinated him as he followed the road across the moraine hills which border the lake in its southern part. He described the moraine amphitheatre of Lake Garda, a very complex structure resulting from several glacial advances including those of the Last Glacial Maximum (Baroni 2017), as a “*gigantic dam of gravel*” whose origin is related to glacial and fluvio-glacial morphogenetic processes. It is important to realize that in Goethe’s time the theory of glaciation had not yet been developed and therefore the correct explanation of the genesis of these landforms was unavailable to him. He described this area as a land of plenty, “*a new country*”, in which “*the people lead the careless life of a fool’s paradise*”, living in homes where “*the doors have no locks*” and “*the windows are closed with oil paper instead of glass*” (Goethe 1786–1788: 42). What he enjoyed most of all was fruits. For the first time he mentioned lemons, figs and pears that he loved (Fig. 44.4).

In his diary unexpected attention is given to the agricultural landscape, and in particular to vineyards. Sometimes Goethe showed particular interest in the growing of crops,

Fig. 44.4 The lemon house of Castel: remnants of the florid past of lemon cultivation in Limone (Garda Lake) (*photo* Wikimedia Commons under CC0 1.0 Universal Public Domain)

the characteristics of the soil and farming practices, providing detailed descriptions useful for understanding and reconstructing the agricultural landscape of the late eighteenth century. Proceeding from Verona to Vicenza, the journey took place from the wide valley of the Adige River to the hills of volcanic origin of the Berici Mountains, passing by the calcareous hills of the Lessinean Mountains. These are landforms characterised by various lithological sequences which are explicitly mentioned by Goethe. The country traversed was defined as "*a vast plain… across which we drove on a wide, straight and well-kept road through fertile fields. There trees are planted in long rows upon which the vines are trained to their tops. Their gently swaying tendrils hang down under the weight of the grapes, which ripen early here. This is what a festoon ought to look like*" (Goethe 1786–1788: 63).

On September 28, he arrived in Venice (Fig. 44.5), where he saw the sea for the first time in his life and gazed across the lagoon from the top of the St. Mark's bell-tower. The view of the vast expanse of water beyond the Lido and the view of the Alps to the north and east was an extraordinary experience: "*The lagoons are covered at high tide, and when I turned my eyes in the direction of the Lido, a narrow strip of land which shuts in the lagoons, I saw the sea for the first time*" (Goethe 1786–1788: 79). During his two-week stay in Venice much emphasis was given to the architecture and particularly on how it stands as a human construct in relationship to the water of the lagoon. The Lagoon of Venice—the largest in Italy with an area of about 550 km^2—is influenced by the tides of the Adriatic Sea and constitutes the unique result of natural and anthropogenic changes which have occurred since its formation, about 6000 years BP. From a geomorphological standpoint, the lagoon is characterised by a complex system of mud-flats, salt marshes, shallows and brackish ponds, together with a network of channels and tidal creeks, formed by "*the interaction of tides and earth*". The Lagoon of Venice has undergone continuous modifications mainly due to mean sea-level changes, and in more recent times, to human activities, that directly and indirectly induce the complex morphodynamic changes occurring in the lagoon (Bondesan 2017). Goethe gave a very exhaustive description of this landscape: "*The lagoon is a creation of nature. The interaction of tides and earth, following a gradual fall in level of the primeval ocean, formed an extensive tract of swampland at the extreme end of the Adriatic, which was covered at high tide but partly exposed at low*" (Goethe 1786–1788: 97). In Venice and its lagoon nature and history are intimately linked: "*Human skill took over the highest portions of ground and thus Venice came into being as a cluster of hundreds of islands surrounded by hundreds of other islands*" (Goethe 1786–1788: 97). The detailed description given by Goethe is useful for understanding the complex environmental system of the lagoon: its integration into the wider system of high-Adriatic lagoons, the presence of human activities on the original environmental matrix, the connection with the sea through the beaches, the action of the tide and the system of internal channels, the ongoing process of landfill and therefore, the hydrological connections with the mainland, human intervention and the problems of maintenance (Bondesan and Rossetto 2012). "*All that intelligence and hard work created in times past, intelligence and hard work have now to preserve*" (Goethe 1786–1788: 97).

Goethe's interest in rocks is also evident in the description that he gave of the badlands of Paderno, in the Bologna Apennines, which he visited on horseback on 20 October. Goethe dedicated a few passages of his diary to the description of rocks and landscapes that he encountered along his path. The most beautiful lithological description concerns the rock complex on which the Paderno badlands were formed. He compared the *Argille Scagliose* (scaly clayshales —"*schist*" in Goethe's definition) to "*… finely laminated schists… that glitter like bituminous coal",* pinpointing their main features. He did not even miss their typical jointing and the contrasting appearance of intact clayshales compared with weathered clayshales. Obviously he must have picked up a sample and crushed it into fine fragments, noticing that the rock does not lose its typical scaly texture. By quoting "*… conchoidal surface…",* he probably observed the rock concave–convex scaly surfaces, whereas when he described it as "*… spotted with white particles and sometimes with yellow…"* he referred very likely to salt and limonite efflorescence (the latter derived from the weathering of pyrite), which is frequently observed on the surface of these clayshales (Cazzoli 2012). Goethe also referred to the morphology of these places: "*The hill where the spar is found is not far from*

Fig. 44.5 **a** Lagoon of Venice in an original drawing by J.W. Goethe (1786); **b** Aerial view of the old town island of Venice and its surrounding lagoons. Canal Grande in the *centre* of the photo (*photo* Wikimedia Commons under CC0 1.0 Universal Public Domain)

a brick kiln and a stream formed by the conjunction of a number of brooks…" (Goethe 1786–1788: 114). This is indeed the situation found on the valley floor of the Torriane and Strione streams, which collect water from many ditches and rivulets and make up the typically patterned hydrography of the badlands of the northern Apennines. There are very evocative short passages, which in their extreme synthesis convey a clear view of the badland environment, the visible erosion of the autumn rains on the slopes (Goethe's visit took place in October) and their instability, due both to falls which affect the sub-vertical faces of the badlands and mud flows which spread about as far as the valley floors: "*By ascending along the gorges of the brittle and decaying mountain, washed up by the latest rain… in various points of recently formed landslide bodies*…" (Goethe 1786–1788: 114). Although the Paderno badlands, unlike other areas of Emilia (Canossa, Monteveglio, Passo dell'Abbadessa etc.), do not show on the whole spectacular morphological features, they are articulated into different small basins with rugged and twisted morphology which makes the landscape unique. Thanks to the roads running along their margins, these landforms are visible from several panoramic points, with striking perspectives from the valley floor to the mountain crests and vice versa (Cazzoli 2012). The final part of Goethe's description was dedicated to "*… the so-called Bolognese heavy spar*…", which is the main goal of his investigations in Paderno. In fact, this mineral was already known to the German writer when he was 22 years old, as demonstrated by the account given in his famous "best-seller" *The Sorrows of Young Werther*. The description of the samples he examined is extremely clear, with some remarks on the possible origin of these minerals: *"… One can see at once that they are not alluvial detritus, but to determine whether their formation was simultaneous with that of the schist, or a result of the tumefaction or decomposition of the latter, would require a more careful examination"* (Goethe 1786–1788: 114–115).

The journey continued south through "*a strange network of criss-crossing mountain ridges*", the Apennines: "*a curious part of the world*". Although Goethe described with great care the landscapes he came across, it is surprising that he paid little attention to places which have always been consecrated to religious and secular history, such as Florence, Perugia, Assisi and Spoleto, but the writer's mind is diverted by his eagerness to arrive in Rome, "*my heart's desire*". "*Across the mountains of Tyrol I fled rather than travelled. Vicenza, Padua and Venice I saw thoroughly, Ferrara, Cento, Bologna casually, and Florence hardly at all. My desire to reach Rome quickly was growing stronger every minute until nothing could have induced me to make more stops, so that I spent only three hours there. Now I have arrived, I have calmed down and feel as if I had found a peace that will last for my whole life. Because, if I may say so, as soon as one sees with one's own eyes the whole which one had hitherto only known in fragments and chaotically, a new life begins*" (Goethe 1786–1788: 128).

Fig. 44.6 Goethe in the Roman Campagna, the famous painting by his friend and painter J.H. Tischbein, his housemate in Rome

Goethe first stayed for four months and later for nearly ten months in Rome, which he described as "*the First City of the World*". He called on 1 November, when he arrived in Rome, "*the birthday of my new life*". Once he arrived in Rome, he felt immediately at home and behaved as if he had always lived in the city (Fig. 44.6). Goethe was an extraordinary observer and examined the landscape with extreme sensitivity. He was probably the first scholar to guess at the overlapping of Rome's "historical strata", that is, that the city's millenary history had an intrinsic relationship with the landscape, the morphology and lithological nature of Roman territory (Fig. 44.7). "*Here is an entity which has suffered so many drastic changes in the course of two thousand years… and this makes it difficult for one to follow the evolution of the city, to grasp not only how Modern Rome follows on Ancient, but also how, within both, one epoch follows upon another*" (Goethe 1786–1788: 133). The morphology and the particular geological features which characterise it have had a decisive role in the history of Rome (Del Monte 2017). The proximity to a large river which allowed easy access to the sea, the surrounding hills which favoured defence, the availability of practically inexhaustible territorial resources—in particularly excellent and plentiful building stones—and, even more important, abundant fresh and clean water from the Apennines slopes determined the fortune of this city destined to become over the millennia Republican and Imperial Rome, the city of the Popes and, finally, the capital of unified Italy (De Rita 2012).

In spring of 1787, after four months in Rome, Goethe decided to move on to Naples, as his father had done before. He arrived in Naples with his friend Johann Heinrich Wilhelm Tischbein on 25 February, and spent two months there (Fig. 44.8). The road passed "*between and over volcanic hills*," and "*Vesuvius was on our left all the time, emitting copious clouds of smoke*" as they made their way to the city. He climbed Vesuvius—"*a peak of hell which towers up in the middle of paradise*"—three times. In the description of the excursions, Goethe showed an extraordinary ability in

Fig. 44.7 **a** Imaginary Italian landscape in the moonlight with the Pyramid of Caius Cestius (Rome) in the *foreground* and a Roman aqueduct in the background (original drawing J. W. Goethe 1788); **b** Pyramid of Caius Cestius in Rome (*photo* Jimmy P. Renzi, Wikimedia Commons under CC BY-SA 3.0)

Fig. 44.8 The Bay of Naples with a view of Mt. Vesuvius in a drawing by C.H. Kniep, Goethe's friend and travel companion in Naples and in Sicily (Hildesheim 1755—Napoli 1825)

understanding volcanic processes and described them with great effect, penetrating the complexity of the phenomenon despite the lack of physical knowledge compared with our studies today (Luongo 2012). As a student in Freiburg, Goethe had attended lectures by Abraham Gottlob Werner, the leading German figure in geology, and convicted Neptunist. Because of his education, Goethe could not have been convinced about the centrality of volcanoes in earth formation, as he stated that volcanoes were "*the superficial result of localized combustion, having no geological significance.*" Notwithstanding this position, he was taken with the romance of Vesuvius and the description of his ascents reveals how Goethe was mesmerised by the phenomenon of its eruption: *"The Terrible beside the Beautiful, the Beautiful beside the Terrible, cancel one another out and produce a feeling of indifference,*" and "*The Neapolitan would certainly be a different creature if he did not feel himself wedged between God and the Devil*" (Goethe 1786–1788: 215). The final ascent, on 20 March, is filled with details and the German scientist described the canals formed as the lava flowed down the mountain slopes, with the molten material stiffening, "*while the dross floating on the surface is thrown down equally to the right and left. By this means a dam is gradually raised, on which the glowing river flows along as calmly as a mill stream. We walked beside the dam, which was raised to a considerable height, the dross regularly rolling down its sides as far as our feet. We could see the glowing stream from below through several holes in the canal, and from above as it flowed on down*" (Goethe 1786–1788: 214). Mt. Somma-Vesuvius is an active composite central stratovolcano made up of a more ancient apparatus, the caldera of Mt. Somma, that contains the younger cone of Mt. Vesuvius, which has remained in a dormant state since 1944 (Aucelli et al. 2017). Goethe during his ascent, may have seen spectacular flow features like breaks in the slope due to lava overflowing artificial walls, cracks or fractures, folds, lava blocks, ridges, lava levees, channelled flows, flow lobes and toe-like flows.

From Naples Goethe ventured into the deep south of Italy, and in March he set sail to Sicily—with the painter Christoph Heinrich Kniep—where he arrived after a four-day journey and spent a month and a half on the island (Fig. 44.9). In his journey across Sicily, which took place in April, Goethe was overwhelmed by the extraordinary variety of the landscape, turning from barren plains and hills to luxuriant spots. The view of the Monte Pellegrino promontory and the harmonious landscape between sea, sky and coast, when he was still on his boat in the harbour, is enriched by the striking scenery offered by vegetation, such as the "*mulberry trees in their freshest green, evergreen oleanders, hedges of lemon trees etc.*" (Goethe 1786–1788: 228) which made him define this island as a blessed land. "*I had completely recovered and was able to enjoy everything thoroughly… The delicate contours of Monte Pellegrino to the right were in full sunshine, and a shore with bays, headlands and promontories stretched far away to the left* ". The geomorphological features of the area around the Gulf of Palermo are characterised by coastal plains, isolated ridges and mountain groups. The plain of Palermo is a vast flat surface linked to sub-vertical cliffs through thick debris

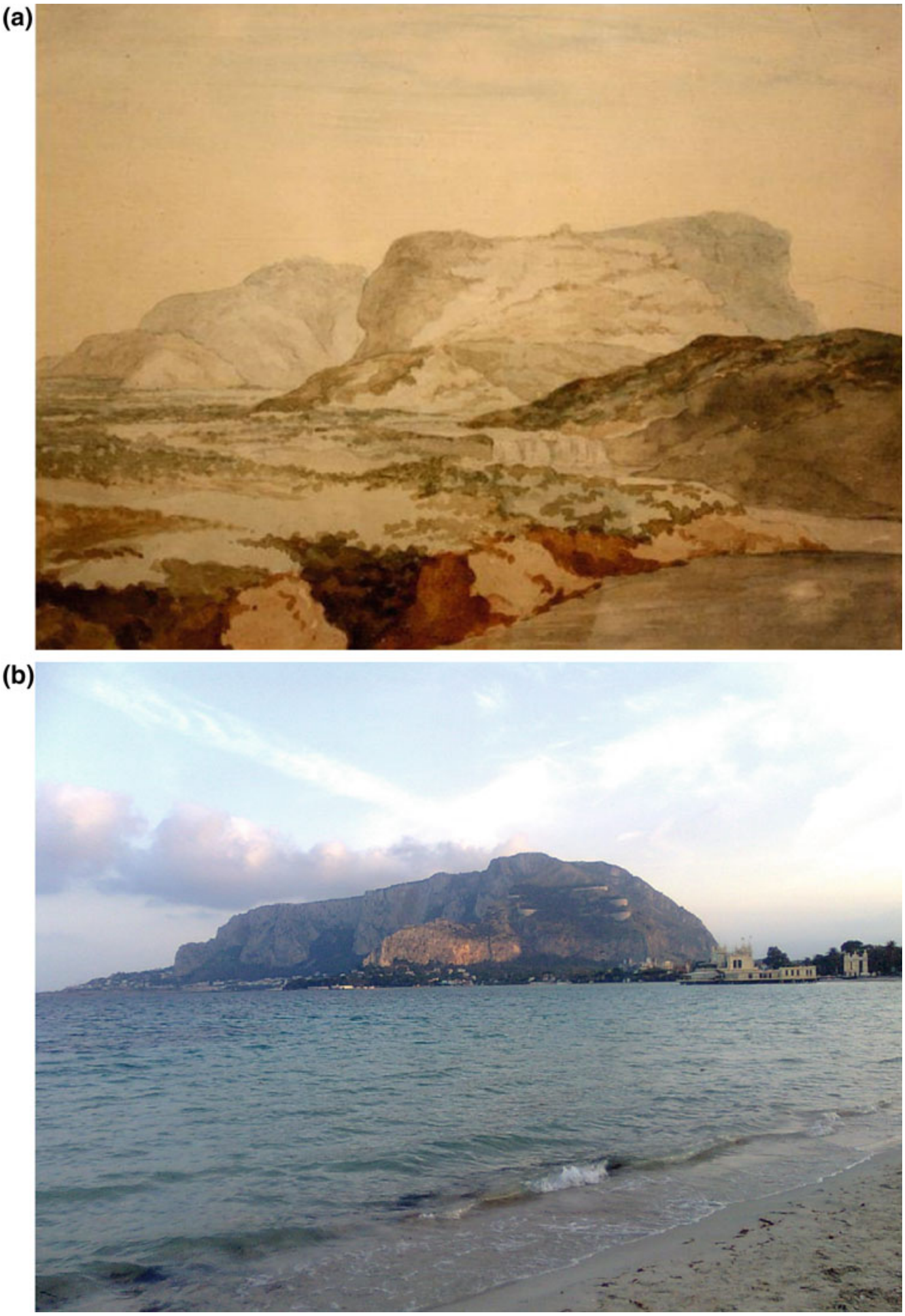

Fig. 44.9 **a** Sicilian landscape in an original drawing by J.W. Goethe (1786); **b** Panoramic view of Monte Pellegrino observable from the famous seaside resort of Mondello (*photo* Wikimedia Commons under CC0 1.0 Universal Public Domain)

cones. Typically, this geomorphological arrangement is controlled by the vertical tectonic movements of the last 4 million years, which has formed an alternation of horst and graben, the latter filled up with the prevalently calcarenite Pleistocene deposits (Nicchitta and Messina 2012).

Goethe much appreciated geological, climatic and gastronomic characteristics of Sicily, stating that "*To have seen Italy without having seen Sicily is not to have seen Italy at all, for Sicily is the clue to everything*" (Goethe 1786–1788: 246). He also considered the Sicilian food exquisite: "*The vegetables are delicious… The oil and the wine are also good, but would be even better if prepared with greater care*" (Goethe 1786–1788: 247).

44.4 Final Remarks

The roots of the modern tourism can be traced back to the seventeenth and eighteenth centuries when the Grand Tour became an institutional practice among aristocrats and literati, primarily, but not exclusively, for education and pleasure. Although the interest in the ancient classical world and its rediscovery in the forms of the Renaissance was the main motivation for the Grand Tour, also the natural environment with its sublime and picturesque scenery has been an "object of desire" for many tourists and especially for Goethe. In this perspective, even though the term "geotourism" came into common usage from the mid-1990s onwards (Hose 1995) in order to define a sustainable geologically based tourism, the Goethe's journey is an excellent example of early geotourism, related to landscape and its geological features.

Goethe was not only a great writer, but also a scientist and a geomorphologist *ante litteram*. His diary contains examples of landscape-scale analysis, where an appreciation of interactions between landscape compartments, sense of place, appreciation of diversity and difference, and associated insights into human relationships are highlighted. Goethe's Italian journey as revisited in this paper aims at stimulating interest in the "geological" component of the environment in which we live or travel by means of an "integrated" approach.

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Wine Landscapes of Italy

45

Vincenzo Amato and Mario Valletta

Abstract

The grapevine is present in Italy from the Alpine areas to the Mediterranean islands, according to geological, geographical, soil and climate features. The variety of wine landscapes of Italy is mainly due to the high degree of geodiversity of the Italian territories and second due to the complex relationships between landforms and human activities. Since it is impossible to outline all the wine landscapes of Italy in a single chapter of a book, we have chosen to describe only some best-quality wines and the connected typical landscapes, such as the well-known Chianti, and some smaller and unique terroirs connected with regional specific landscapes, such as those of Adriatic piedmont and hilly areas (Abruzzo Region), of southern Apennine inner valleys (Campania Region) and of mountains and volcanoes (Sicily Region).

Keywords

Italian terroir • Vineyard • Soils • Geodiversity

45.1 Introduction

Italy is one of the major worldwide producers of wines, not only in terms of quantity (more than 80 million hl) but also in terms of high quality and large variety. The main Italian quality wines are defined with different level of labels according to their area of production and in the respect of defined quality standards, as Controlled and Guaranteed Denomination of Origin (DOCG) and Controlled Denomination of Origin (DOC). Within these two levels, the wines are grouped in 92 "macro-areas", according to geological, soil, geographical and climatic features (Pollini et al. 2014) (Fig. 45.1). Moreover, many other wines are anyhow true "excellences". The grapevines are cultivated in a variety of environments, from high mountains to coastal areas, from hills to alluvial plains, from dry to marshy areas, with bedrock that range from granites to limestones, from conglomerates to schists and from volcanic and volcaniclastic rocks to marls and clays (Table 45.1). The wine production area is a very important variable influencing consumers' judgment, since it reflects the origin, quality and traceability of the wine. The landscape represents an important component of the wine origin and it summarizes several factors and attributes of the wine quality (e.g. climate and soil for grape quality, the local history for grape production traditions). The latter is the result of a combination of geology, geomorphology, pedology, climate, agrarian features which characterize the terroirs that make each wine so unique (Biancotti et al. 2003). A vineyard is one of the elements composing a landscape often becoming a revaluing and distinctive feature for those who study and appreciate the land and its scenery. In this way, the wine landscapes and the related terroirs are among the major elements supporting high quality of wine and have to be taken into account from the production to the choice, tasting and evaluation of a wine, both from the producers and oenologists and from the consumers and experts' point of view.

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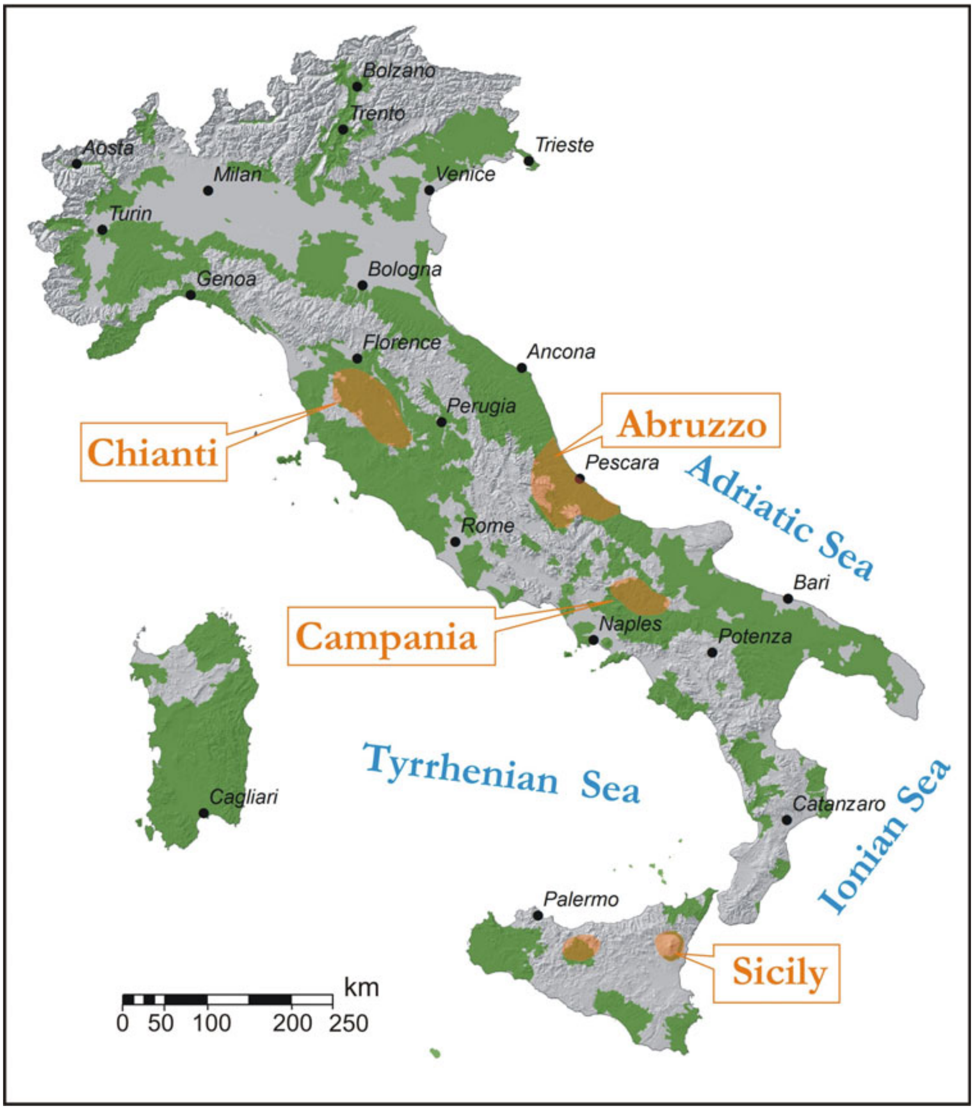

Fig. 45.1 Map of the main Italian areas of wine production (*green areas*) (original drawing by E.A.C. Costantini and R. Lorenzetti) and selected wine landscapes of Italy illustrated in this chapter (*orange areas*)

From the outstanding variety of the Italian terroirs and related high-quality wines (Biancotti et al. 2003; Cita et al. 2004; Colacicchi and Parotto 2006), some areas of Tuscany, Abruzzo, Campania and Sicily have been selected and described in this chapter. These areas may be considered as representative of the main wine landscapes of Italy. In addition, they present historical and cultural components as additional values to the wine landscapes. The Chianti district (Tuscany), representative of the Tyrrhenian Apennines hilly areas, is the most popular Italian wine production area in the world. The Adriatic coastal and hilly areas, represented by the Abruzzo Region, are one of the Italian areas of greater production of wine. The inner valleys of the Southern Apennines, represented by the Campania Region, having been affected by repeated and recent sedimentation of volcanic products, are the terroirs of the best high-quality wines of Southern Italy. The Island of Sicily, with alternating high mountains, hilly, coastal and volcanic landforms, is a special area where the wine landscapes are also widespread up to high altitudes. For these selected areas, in a journey through the Italian peninsula, the complex multifaceted relationships between landscape and terroirs (rocks, soils, geomorphology, climate, exposure) and grapevines are outlined, showing the main factors and elements composing the landscapes of wine. Several high-quality wines of the four selected areas are not described in the following paragraphs, but they are briefly synthesized in Table 45.2.

Table 45.1 Selected Italian wines and their relationships with geology and landscape features

Region	Terroir	Wine	Geology	Landscape and landforms
Piedmont	Monferrrato, Langhe, Asti and Alba	Nebbiolo, Barolo, Barbaresco, Barbera, Grignolino, Dolcetto, Brachetto, Moscato	Sandstones, marls, clays, sands, calcarenites	Hills and hillslopes
Piedmont	Canavese, Ivrea, Maggiore Lake	Erbaluce di Caluso	Glacial deposits	Intramoraine lake and gentle slopes
Val d'Aosta	Aosta valley	Petit Rouge, Red and White of the la Thouille	Metamorphites, glacial deposits	Valley flanks
Lombardy	Valtelllina	Sassella, Inferno	Glacial deposits	Stone wall terracing of mountain slopes
Lombardy	Oltrepò Pavese	Bonarda, Riesling	Clays, sands, conglomerates	Hills and hillslopes
Lombardy	Franciacorta, Garda	Terre di Franciacorta, Groppello, Lugana	Moraines	Gentle slopes
Trentino	Adige and Isarco valley, Rotaliana plain, Venosta valley	Schiava, Müller-Thurgau, Riesling, Sylvaner, Sauvignon, Lagrein, Moscato giallo, Nosiola, Traminer, Gewürztraminer, Blauburgunder	Ignimbrites, limestones, fluvial and glacial deposits	Well-exposed slopes and flat alluvial plains
Veneto	Soave, Valpolicella	Soave, Amarone, Recioto, Valpolicella	Marls, limestones, basalts, alluvial deposits	Hills and hillslopes bordering alluvial plains
Veneto	Marca Trevigiana	Prosecco di Conegliano, Valdobbiaddene	Alluvial deposits	Alluvial plains
Veneto	Gambellara, Breganze	Bardolino, Bianco di Custoza, Cartizze, Durello, Gambellara, Raboso	Marls and alluvial deposits	Hills and hillslopes
Friuli	Grave, Iudrio and Isonzo rivers	Picolit, Terrano, Collio, Ribolla gialla, Pinot bianco and grigio, Verduzzo, Tocai friulano, Refosco	Marls, red residual soils, sandstones	Alluvial plains and hillslopes
Liguria	Cinqueterre	Rossese, Pigato, Sciacchetrà	Marls, siltites, limestones	Terraces of coastal steep slopes
Emilia-Romagna	Colli Piacentini	Dolcetto, Barbera, Bonarda	Clays, sands, alluvial deposits	Alluvial plains and hillslopes
Emilia-Romagna	Romagna	Sangiovese, Albana, Trebbiano	Clays, sands and alluvial deposits	Alluvial plains, coasts, hillslopes and hills
Emilia-Romagna	Parma, Reggio Emilia and Modena	Lambrusco	Clays, sands and alluvial deposits	Hills and hillslopes, alluvial plains
Umbria	Central sector	Sagrantino di Montefalco, Rubesco di Torgiano	Clays, sands, conglomerates, marls	Alluvial plains, hillslopes and hills
Umbria	Orvieto	Classic Orvieto	Tuffs, ignimbrites	Intermontane basins and gentle slopes
Marche	Mt. Conero	Rosso Conero	Pelitic and pelitic-carbonatic deposits	Gentle and steep coastal slopes
Marche	Adriatic coast	Kurni, Verdicchio di Jesi, Verdicchio di Matelica	Sandstone and pelites	Coastal and valley slopes
Molise	Biferno and Trigno rivers	Pentro di Isernia, Biferno	Clays, sandstones	Hills and hillslopes
Molise	Adriatic coast	Tintilia	Pelites	Coastal and gentle slopes
Latium	Bolsena Lake and Latera basin	Aleatico, Est!Est!Est! di Montefiascone	Volcanic rocks	Gentle slopes and hills

(continued)

Table 45.1 (continued)

Region	Terroir	Wine	Geology	Landscape and landforms
Latium	Cesanese	Cesanese Comune, Cesanese d'Affile	Marls, sandstones and volcanic rocks	Gentle slopes and hills
Latium	Castelli Romani	Montefiascone, Frascati, Marino, Aleatico	Volcanic rocks	Gentle slopes and volcanic hills
Basilicata	Monte Vulture	Aglianico del Vulture	Tuffs, sandstones	Gentle slopes
Apulia	Murge	Castel del Monte, Locorotondo, Gioia del Colle, Gravina, Martina Franca	Red residual soils	Plateaux and gentle slopes
Apulia	Salento	Primitivo di Manduria, Salice salentino, Copertino	Clays and sands	Gentle coastal slopes
Apulia	Tavoliere	San Severo, Rosso di Cerignola, Cacc' e mitt' di Lucera	Clays	Plains
Calabria	Ionian coast	Cirò, Gaglioppo, Greco, Nerello	Pelites, sandstones, sands, conglomerates	Terraces of coastal slopes and valley flanks
Calabria	Aspromonte	Bivongi	Metamorphites, alluvial deposits, sandstones	Steep and gentle slopes, hills and alluvial plains
Sardinia	Nuoro	Cannonau	Granites, basalts, metamorphites	Gentle and steep slopes and hills
Sardinia	Campidano	Nuragus di Cagliari	Pelites	Hillslopes and plains
Sardinia	Gallura	Vermentino di Gallura	Granites	Gentle slopes and hills
Sardinia	NW coast	Malvasia di Bosa	Riolitic ignimbrites, pyroclastic deposits	Gentle and steep slopes and hills

45.2 The Chianti Hills: A Worldwide Famous Wine Landscape

The Chianti hills are one of the most well-known Italian examples of a territory whose name corresponds to a high-quality food: the Chianti wine. The Chianti Classico area is the historic core of the Chianti hills in Tuscany, which are intimately connected to a specific appellation of origin, the Chianti Classico DOCG. This connection gives paramount evidence to the linkage between landscape and wine lying under the "terroir" concept (Van Leeuwen and Seguin 2006; Goulet and Morlat 2011; Vaudour et al. 2015). The Chianti Classico highlights a secular awareness and a general acknowledgment of a "taste of land", which is also a cultural heritage (Costantini and Barbetti 2008). The beautiful Chianti landscape can boast a harmonious blend of features shaped by farmers, castles and villages with traditional rural architecture and medieval heritage (Fig. 45.2).

The Chianti Classico DOCG area extends to almost 72,000 ha and presents vineyards located at altitudes not exceeding 700 m a.s.l. The grape variety is typically Sangiovese, for a minimum of 80% of grapes, with the possible addition of other black berries of the area, not more than a 20%. Notwithstanding the linkage between the Chianti territory and the Chianti wine, the DOC area encompasses lands showing some common traits but also many local specificities, which give reason for the presence of many terroirs and wines with different qualities and styles (Priori et al. 2014).

The Chianti landscape can be described by nine landscape units, which enclose environmentally homogeneous areas at the reference scale of 1:250,000 (Fig. 45.3). Actually, the morphology of Chianti is quite variable, passing from the high and low mountains and hills to the east, where the vineyards are placed on the Chianti Classico Ridge up to 500–600 m a.s.l. (landscape 1), to the more gentle hills of Val di Pesa or Val d'Elsa to the west (landscapes 4 and 5). Average annual rainfall spans between 650 and 950 mm, with a gradient from the northeast to the southwest. The average annual temperature is 13–14 °C, with cold winters and hot summers and maximum temperatures often above 35 °C. The daily fluctuations are quite pronounced, especially at higher elevations. The different mesoclimatic conditions have a pronounced effect on wine acidity, anthocyanins and sugar content (Costantini et al. 2006).

Table 45.2 - Selected wines of the Tuscany, Abruzzo Campania and Sicily regions, and their relationships with geology and landscape features

Region	Terroir	Wine	Geology	Landscape
Tuscany	Montalcino hills	Brunello	Pelites, sands, sandstones, calcareous turbidites	Hillslopes and hills
Tuscany	D'Orcia and di Chiana valleys	Vino Nobile di Montepulciano	Clays and sands	Alluvial plains and hillslopes
Tuscany	Senesi hills	Morellino, Solaia	Arenaceous turbidites, pelites, sands	Hills and hillslopes
Tuscany	Vulsini volcanoes	Bianco di Pitigliano	Tuffs	Gentle slopes and volcanic hills
Abruzzo	NE sectors of Abruzzo-Molise Apennines	Pecorino, Passerina, Cabernet, Chardonnay, Merlot, Pinot Noir, Riesling	Clays, sands, conglomerates, marls, sandstones, limestones	Gentle slopes, hills, coastal and valley slopes
Campania	NW sector of Campanian Plain	Falerno del Massico	Limestones, tuffs, pyroclastites	Gentle slopes and coastal plains
Campania	Ischia Island, Phlegrean Fields	Per' e' palumm', Biancolella	Vulcanites	Gentle and steep slopes
Sicily	Palermo and Trapani provinces	Alcamo, Marsala	Sandstones, marls, limestones	Hills, gentle and steep slopes
Sicily	Pantelleria Island	Moscato o Zibibbo di Pantelleria	Basalts, pumices	Gentle coastal slopes
Sicily	SE coastal sector	Cerasuolo, Contessa Entellina, Monreale, Conte di Salaparuta, Moscato di Noto, Nero d'Avola, Syrah, Inzolia	Limestones, red residual soils, sands	Hills and gentle hillslopes

Fig. 45.2 An example of the landscape of the Chianti Classico area, sculptured by man throughout the centuries and millennia

Landscape 1 (NE Chianti area) geologically corresponds to the central part of the Chianti anticline, that is tectonically overlain by the Ligurian Unit, made up of Cretaceous to Eocene shales, limestones and marls. Sandstones of the Macigno del Chianti formation are also present south of Castellina in Chianti, in the upper valley of Arbia River (landscape 3). In these units the viticulture develops on sandy soils with locally high degree of stoniness. They have low

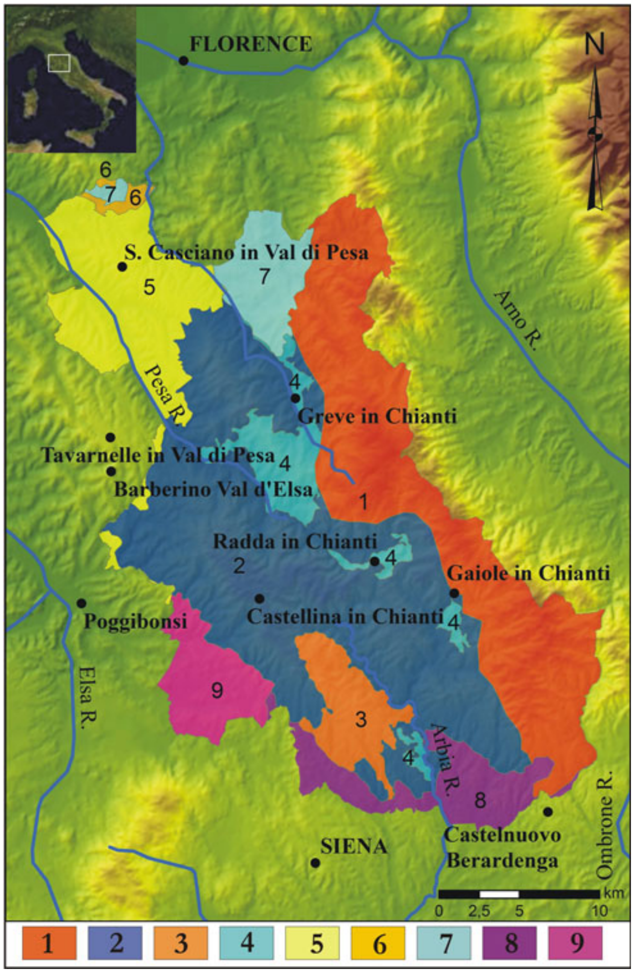

Fig. 45.3 Landscape unit map of the Chianti Classico area. *1* Low mountain and high hills with medium and high gradient on sandstone (Macigno del Chianti Formation); *2* Low mountain and high hills with medium and high gradient on limestone and marly limestone, sandstone and shale (Montemorello Formation); *3* High hills with medium gradient on sandstone (Macigno del Chianti Formation) and slope of the Flysch of the Chianti Formation; *4* High hills with medium gradient on predominantly marly clay and shale; *5* Low and medium hills with medium gradient on mostly calcareous conglomerates and gravels, with sand and clayey sandy; *6* Low and medium hills with medium gradient on sandstone; *7* Low and medium hills with medium gradient on marly clay and shale; *8* Low and medium hills with medium gradient on marine sand sediments; *9* Low and medium hills with medium gradient on marine clay sediments

water availability for plants, which can be an important limiting factor for grape production, but also a determinant of wine finesse. A thrust fault line marks the boundary between landscape 1 and landscapes 2, 4 and 7 (i.e. Greve in Chianti, Radda in Chianti, Castellina in Chianti) where the Ligurian Units outcrop. Soils have good fertility and moderate water holding capacity. The amount of the skeleton is also here the dominant functional character. The high limestone content can limit excessive vegetation, and be beneficial for the grape quality, concentrating the juices inside berries.

Landscape 5 includes low and medium hills of the Val di Pesa area, on mostly calcareous conglomerate and gravel, with sand and clayey sand. Here the soils are well drained and easily penetrated by roots. Good fertility may lead to an excessive plant vigour and depress wine quality. Landscape 8 belongs to the Siena Basin and landscape 9 to the Val d'Elsa area where marine conglomerates and sandstones of Early–Middle Pliocene are exposed (Coltorti et al. 2009). The sandy lithology determines well-drained soils, poor in skeleton, easily penetrable by plant roots. As a whole, the low-lying areas consist of soils formed upon alluvial materials with a deep rooting potential, dating from the Quaternary. Further uphill, on the Pliocene and Miocene marine sediments, the soils are mainly clayey and calcareous, but they are often rather thin due to severe water erosion. Chianti wine quality here is very much affected by climatic conditions of the year, since soils are not able to mitigate the excess or lack of available water.

Finally, the Chianti landscape and their soil features are the key for the wine quality. On the whole, the richness of the skeleton is the main functional soil characteristic in the Chianti region, since it regulates soil fertility and drainage of rainwater. Skeleton also induces a high root deepening, which favours slow and steady supply of water and nutrients to the plant, and an optimal ripening process of grapes. These soils are particularly suited to tree crops in general and wine in particular. The main Chianti grape varieties such as Sangiovese, which exert a low genetic control on their phenology, reach in stony soils of the Chianti hills very high-quality levels (Costantini et al. 2006).

45.3 The Wine Landscapes of the Adriatic Piedmont and Hilly Areas: Examples from Abruzzo

Moving toward the east and crossing the Apennines chain, the Adriatic piedmont and hilly areas slope down to the Adriatic coast, in a wide belt from the northern to the southern part of Italy, and are characterized by the widespread presence of vineyards placed from the coast up to 800 m a.s.l. "Blonde" golden hills separate the mountain range (to the west), from the Adriatic Sea (to the east). Here, in regions where vineyard cultivation and wine making has been well established for centuries, the Abruzzo hilly areas have been recently growing as "hills of wine" merged with large olive groves.

The Abruzzo piedmont and coastal hilly sector is an approximately 30 km wide, SW–NE trending belt between the coast and Apennines (Fig. 45.4), ranging from 100 to 1000 m a.s.l., with gentle slopes and wide alluvial plains. Climate is humid subtropical with an annual precipitation range between 600 and 800 mm (sub-coastal regime) and

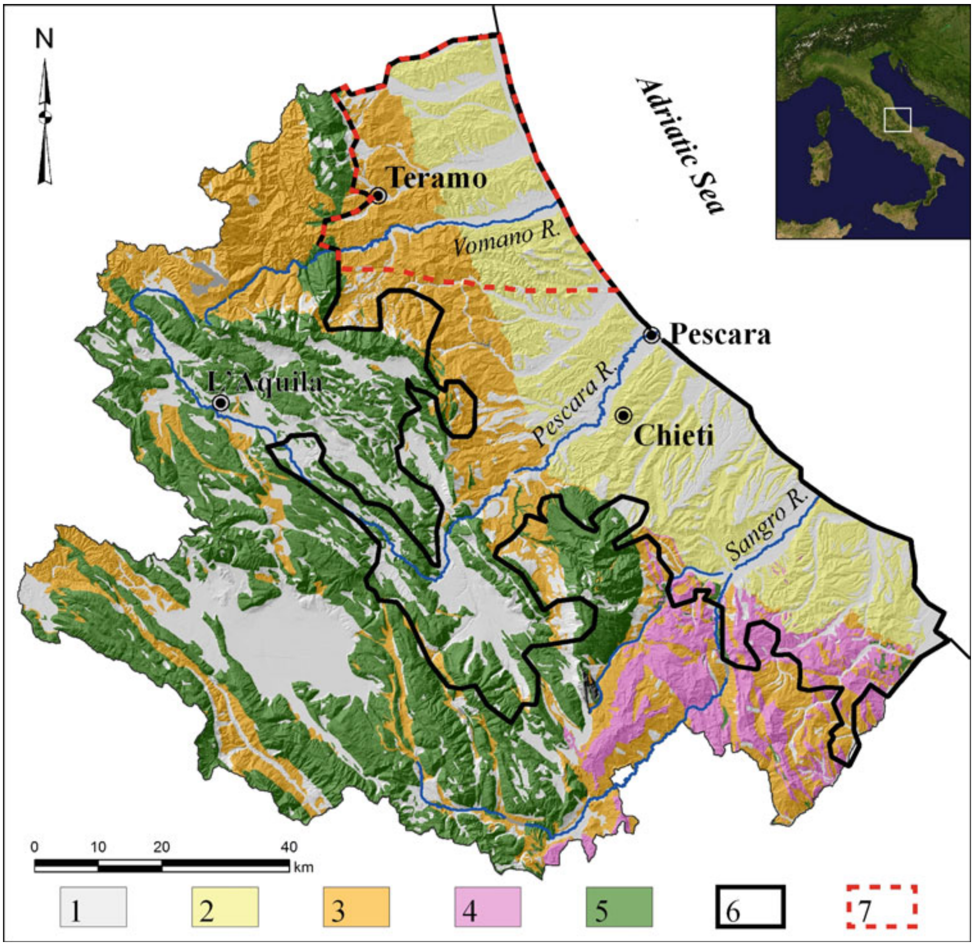

Fig. 45.4 Simplified lithological map of Abruzzo and main wine zones. *1* Gravel, sand and clay of Quaternary deposits; *2* Clay, sand and conglomerate of Pliocene-Pleistocene marine sequence; *3* Arenaceous and pelitic rocks of Neogene turbiditic sequences; *4* Calcareous and marly rocks of Mesozoic-Cenozoic marine carbonate platform, slope and pelagic sequences; *5* Clayey-marly-calcareous rocks of Mesozoic-Cenozoic Molise pelagic sequence; *6* Montepulciano d'Abruzzo and Trebbiano d'Abruzzo wine zones; *7* Controguerra and Montepulciano "Colline teramane" wine zones

average temperatures ranging between 8 and 10 °C in January and more than 25 °C in July and hence suitable for vineyards, although occasionally affected by spring frost due to northeastern winds.

The hilly landscape is the result of fluvial and gravity-induced geomorphological processes, which have affected marine sedimentary rocks (Pliocene-Pleistocene clays, sandstones and conglomerates; D'Alessandro et al. 2003) and have contributed to the formation of Quaternary continental sedimentary deposits (slope debris and colluvial deposits, fluvial sand, gravel and silt, beach sands) (Fig. 45.4). These recent terrains are covered by loose clayey, silty and sandy soils, rich in clay minerals, locally with a gravel skeleton. Soils are from permeable to moderately impermeable with skeleton content from high to low, with moderate water retention and good workability. They are particularly suited to tree crops, in general, and wine in particular (Fig. 45.5), being rich in clay minerals. Here, the vineyards found a favourable climate, landscape and lithological conditions, except for the alluvial and coastal plains, due to high humidity and possible water stagnancy.

A large terroir includes the Abruzzo hills and the Sulmona intermontane basin and produces well-known wine varieties, the Montepulciano d'Abruzzo (red grape) and the Trebbiano d'Abruzzo (white grape). These varieties were first developed in the higher part of the Pescara River valley, on pelitic-arenaceous terrains, and in the Sulmona intermontane basin (known since the times of the Roman poet Ovidio as being fertile and ideal for the cultivation of wheat and grapes), on lacustrine and alluvial deposits of a Pleistocene lake (Colacicchi and Parotto 2006). Later, they found suitable conditions for their development in the whole hilly landscape. Today, crops are installed on alive supports and mostly on artificial supports. The high-quality vineyards are grown at elevations between 150 and 500 m a.s.l. (up to 600 m for south-facing slopes), on hills with variable slope (mainly gentle and moderate, 10–20°, or on planar hilltops) and aspect (mainly south) (Figs. 45.5 and 45.6). The Rittochino vineyard arrangement is the most common (wine rows perpendicular to the slope) and induces a good soil drainage but increases soil erosion. Due to high sun radiation and low air humidity, the "awning" system is also common

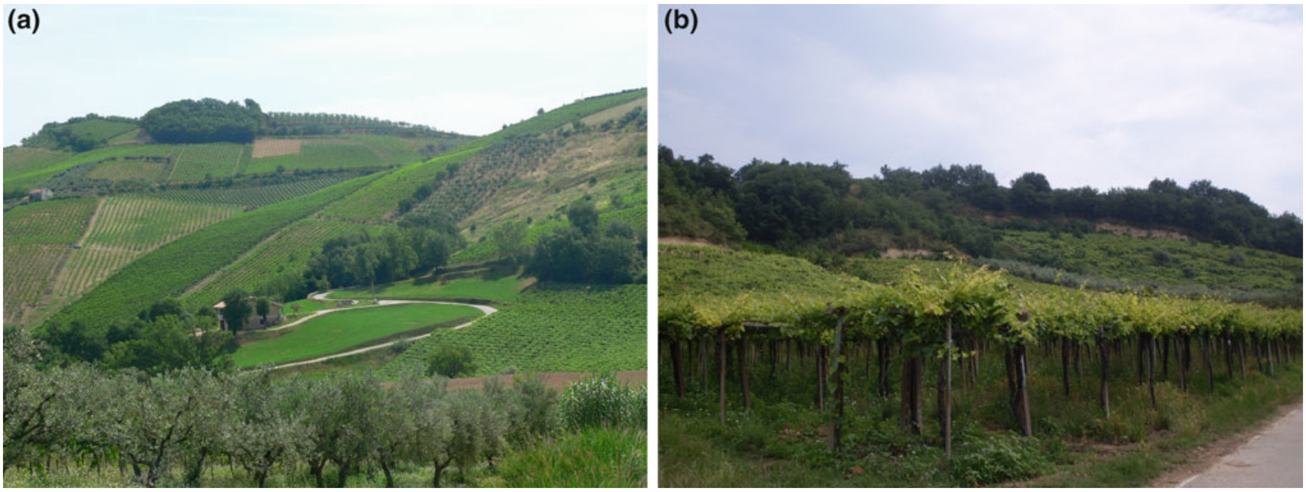

Fig. 45.5 **a** Expanses of vineyards in Central Abruzzo, with vine rows on clay slopes bordering the main rivers; **b** Vineyards cover clay slopes in central-southern Abruzzo, characterized by sandy and conglomerate tops and top scarps, providing a heterogeneous and well-drained soil on the clay bedrock

Fig. 45.6 Piedmont-hilly area of northern Abruzzo characterized by coloured gentle hills, with vineyards, merged with olive groves, along the slopes of fluvial valleys (**a**) and on coastal slopes (**b**)

(a vertical trunk with the fruiting canes originating a continuous coverage).

The quality of bedrock (moderately loose and rich in clay minerals) and soil (incoherent, heterogeneous, poorly sorted and well draining), together with appropriate solar irradiation, climate conditions and morphology define Abruzzo's Montepulciano terroir and result in the main features of the wine: from moderate to high alcoholic rate, an inviting intense ruby red colour, with an unmistakable aroma of red fruits, flowers and spices, and a dry and mellow flavour. According to historical documents, the Montepulciano has been present in the region since the mid eighteenth century and it has progressively become the 'true ambassador' of Abruzzo's wines (it represents over 80% of the total quality wines of this area). From the same landscape and the same grapes, but with a particular winemaking technique, a cherry-red colour rosé wine is produced, the Cerasuolo wine.

From the same landscape and terroir of Abruzzo's Montepulciano, but from white grapes, Abruzzo's Trebbiano wine, the second DOC of this area, is produced (Fig. 45.4). However, Trebbiano vineyards prefer the hilly areas closer to the seaside, characterized by higher temperatures and humidity, which provide the wine with its straw yellow colour and its organoleptic properties; this wine is very much appreciated for its pleasant flowery and fruity bouquet, its freshness, and its dry and harmonic flavour. A third DOC wine, typical of a small area in the northernmost hills of Abruzzo, at the border with the Marche Region, is the Controguerra wine (Fig. 45.4). It includes excellent types of white and red wines obtained from indigenous local grape varieties, expressing the age-old tie with the landscape (Pecorino, Passerina), together with international grape varieties (Cabernet, Chardonnay, Merlot, Pinot Noir, Riesling).

45.4 The High-Quality Wine Landscapes of the Campania Region

Moving south and crossing back the Apennines chain, the landscape of the Campania Region can be briefly summarized in two main geomorphological districts: the first, characterized by the mountains and hills of the Apennines chain and by wide and narrow fluvial valleys; the second, located in the western part, characterized by alternating high-rocky coasts, alluvial coastal plains and volcanic landscapes (Fig. 45.7). The vineyards are widespread in all geomorphological and lithological contexts, especially in the hilly, piedmont and alluvial-plain sectors of the Apennine chain. Among the latter, the Sannio and the Irpinia vineyards are the best examples of high-quality and high-amount wine production, particularly the territory between the Calore and Sabato river alluvial plains. Only here in the whole region, there are wines (Taurasi, Greco di Tufo, Fiano di Avellino and Aglianico del Taburno) classified as DOCG appellation. Wines of best quality are produced mostly in three little village territories: Castelvenere, Tufo and Taurasi.

The village of Castelvenere, situated in the southern-eastern flanks of the Matese Mts. (Fig. 45.7), was founded in the Middle Ages on the volcanic deposits of the Tufo Grigio Campano Formation (Late Pleistocene, 39 ka BP, De Vivo et al. 2001). Over 80% of the territory is occupied by vineyards, which are widespread in all the geological and geomorphological contexts. A key role for high-quality wines is played by low topographic gradients of vineyard surfaces that allow for the development of mature soil profiles and runoff or stagnation of shallow and deep waters and permit a good exposure to the sun's rays. The vineyards producing high-quality wines are generally located on slopes with gradients ranging 10–20°, with preferential SW and SE aspect. Among the native or semi-native grapes, the most common is the Falanghina del Sannio, an ancient white grape variety. In particular, the Falanghina

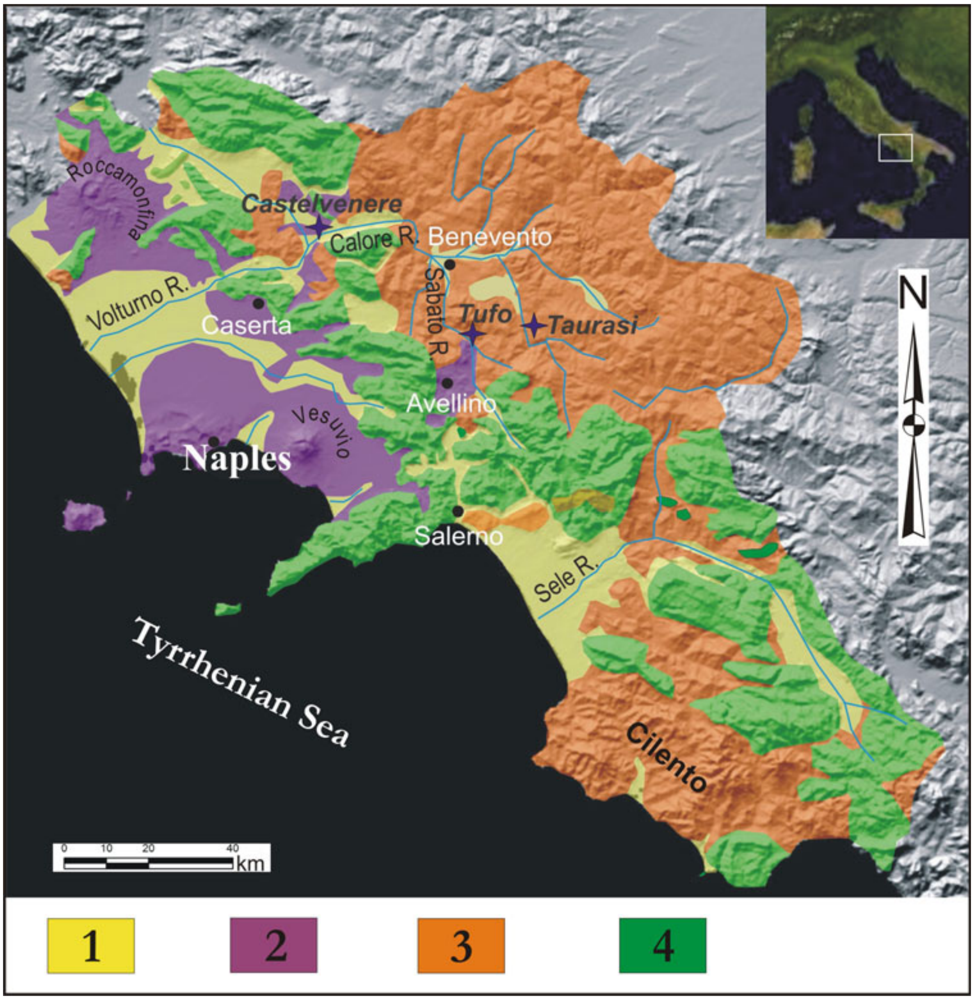

Fig. 45.7 Simplified geo-lithological map of the Campania Region showing the three high-quality wine selected areas (Castelvenere, Tufo and Taurasi). *1* Alluvial, coastal, palustrine-lacustrine and slope deposits (Quaternary); *2* Volcanoclastic deposits (Quaternary); *3* Basinal units (Meso-Cenozoic); *4* Limestones, dolomites and marls of carbonate platform units (Meso-Cenozoic)

vineyards, well adapting to the stagnant water, prefer planar or sub-planar surfaces, such as the alluvial terraces of the Calore River, the lacustrine-palustrine terraces and the erosional surfaces located at the top of the hills (Fig. 45.8a, b).

The village of Tufo is the spearhead of the winegrowing production zone of Sabato River valley. The main lithologies outcropping in the valley flanks and in the hills, which reach 600 m a.s.l. at maximum, are constituted by Miocene-Pliocene sandstone, conglomerate and clay with intercalations of gypsum and sulphur layers. Here, in the last twenty years, relevant works of terracing have been done for vineyard cultivations, converting the slope profiles into long sequences of terraces. The vineyards are widespread over all lithologies, although gentle slopes on sandstone and

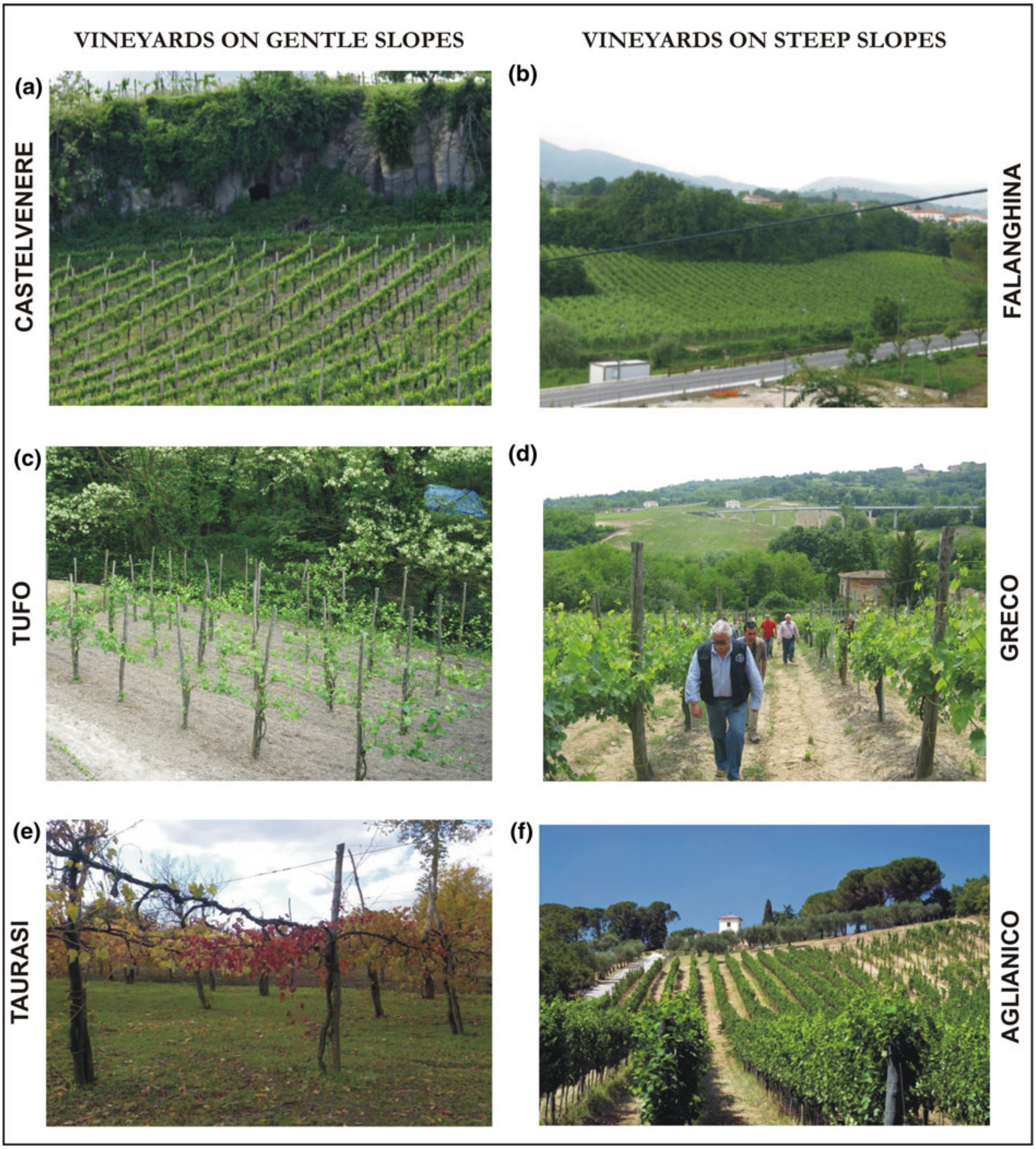

Fig. 45.8 The main wine landscapes of Castelvenere (**a** and **b**), Tufo (**c** and **d**) and Taurasi (**e** and **f**) villages. **a** Falanghina vineyards on Tufo Grigio Campano Fm. terrace; **b** Falanghina vineyards on Calore River valley flanks; **c** Greco vineyards on alluvial terrace; **d** Greco vineyards on sandstones with gypsum-sulphur layers; **e** Alberata Taurasina vineyards; **f** Aglianico vineyards on erosional glacis truncating Miocene sandstone

silty-clay deposits—especially those with SW–SE aspects—and alluvial or tuff terraces, generally characterized by well-drained soils, very rich in volcanic and fluvial assemblages, are preferred (Fig. 45.8c, d). High-quality wines are produced in the vineyards cultivated close to the gypsum-sulphur layers of the Miocene-Pliocene succession. In fact, the great amount of sulphur in the soils and rocks inhibits the formation of harmful pathologies and reduce the annual numbers of chemical and phytosanitary treatments. This peculiarity of the Tufo territory has been the driving force to the development of the Greco grape since the Greek-Roman period.

The Taurasi village is located in the central sector of the valley of the Calore River (Fig. 45.7). Taurasi wine is the first wine of the region that achieved the title of DOCG, with the appellation "red wine obtained mainly by the Aglianico vineyards and secondly by other black grapes that cannot exceed the 15%". The production guidelines indicate that cultivation must follow traditional techniques and must prefer hilly landscapes with good exposure to the sun's rays, while the vineyards within the alluvial plains and over the planar and sub-planar surfaces are not recommended, being characterized by high humidity and not sufficiently sunny. High-quality wines are produced on soils improved both by polygenic clasts derived by fluvio-aggradational processes and high amount of volcaniclastic and clayey fraction (Fig. 45.8e, f). The combination of geological factors enhances both the vegetative activity of the wines and the winegrapes, promoting lignification processes and organoleptic characters of the wine, giving an intensity of aromas, good structure and balance. The widespread and specialized presence of vineyards over the last millennia in the Taurasi village area gave rise to the development of a typical vineyard farming system, known as "Alberata Taurasina" or "Antico sistema taurasino", dating back to the Etruscan school (3.0–2.5 ka BP) (Fig. 45.8e). Today, the landscape of vineyards made of Alberata has almost disappeared because the modern viticulture prefers the less laborious espalier vineyards.

45.5 The Wine Landscapes of Sicily: The Examples of Mount Etna and the Madonie Mountains

The journey through the wine landscapes, passing the Messina Strait, ends in Sicily which, according to Cita et al. (2004), is "a puzzle of different lithospheric pieces in motion relative to each other" resulting in a mosaic of different landscapes. Mountainous chains, developing along the northern coast, include Saccense, Imerese and Panormide complexes, Madonie Mts. and Peloritan-Calabrian arc (Fig. 45.9). The southeastern sector belongs to undeformed foreland. A wide deformed area, including marine deposits of Quaternary-Neogene age and Messinian evaporites, occupies an area comprehended between the two sectors. Mt. Etna characterizes the eastern coast of the island. With this geodiversity of Sicily, a great number of wine landscapes is associated, from high mountains over the 1000 m a.s.l to the coastal landscapes, including gentle or steep slopes, hills, alluvial plains, flat areas of plateaux, etc. Some of them are peculiar, particularly in terms of connection between landscape and geological features, such as the Mt. Etna, with special cultivars widespread up to over 1000 m a.s.l., and the Madonie Mts., representative of Tyrrhenian coastal and mountain areas which bear traces of the whole geological history of the island.

45.5.1 Mount Etna

Mt. Etna, one of the most active volcanoes of the world—the largest active in Europe—is the highest mountain of Italian islands (3323 m a.s.l.). It is a complex stratovolcano, composed of overlapping various volcanic structures active during different periods (Branca et al. 2011; Branca et al. 2017). Its products overlap partially allochthonous Cretaceous to Pleistocene rocks (Fig. 45.9). The fertile soils developed on volcanic products and the propitious climate, with different climatic–environmental zones according to altitude and distance from coast, contribute to the high-quality wines. Vineyards are placed mostly along the northern and eastern slopes and reach an altitude of over 1000 m a.s.l. (northern slope, Alcantara River valley). One of the most important areas for the grape-growing extends from the village of Randazzo (to the west) to Passo Pisciaro (to the east). This area is delimitated, at the northern side, by river terraces, especially suitable for grape-growing, formed on barrages produced by lava flows. Where the slopes are steeper, dry-stone walls contain earth platforms where vineyards are planted (Fig. 45.10). The Etna DOC region covers over 1828 ha in the Catania area on the eastern slopes of the volcano. The most produced wines are red, together with a typical white wine (Etna Bianco and Etna Bianco Superiore) made from two very ancient autochthonous cultivars: Carricante and Catarratto comune. The vineyards grow on volcanic terrains of Na-alkaline-basaltic composition, generally light due to the presence of ash and lapilli. The Carricante cultivar is native of Sicily: the name means abundant, constant yield. This wine has a particular flavour of Marsala, and is used as base for production of many vermouths. Etna Rosso or Rosato is a very popular red wine produced on the slopes of Mt. Etna from the autochthonous Nerello Mascalese and Nerello Mantellato variety. Etna's Minnella Bianca is a very rare white wine, typical and exclusive of Mt. Etna. It is produced in extremely small

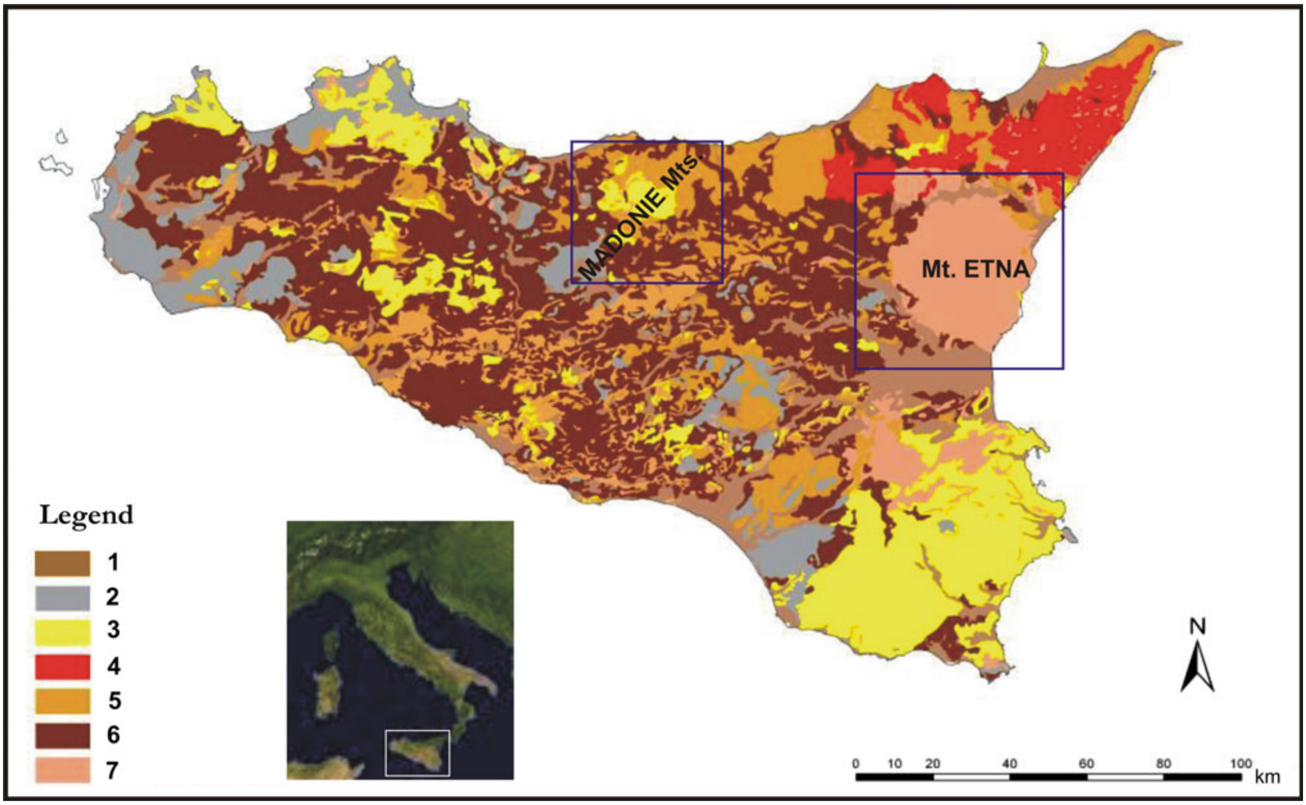

Fig. 45.9 Simplified geological map of Sicily showing the two high-quality wine selected areas: Mt. Etna and Madonie Mts. *1* Alluvial, coastal and slope deposits (Quaternary); *2* Sandstones and siltstones (Cenozoic); *3* Limestones (Meso-Cenozoic); *4* Metamorphic rocks (Mesozoic); *5* Sandy clays and arenaceous rocks (Cenozoic); *6* Clays (Cenozoic); *7* Volcanic rocks and sediments (Quaternary) (modified after Fierotti et al. 1988)

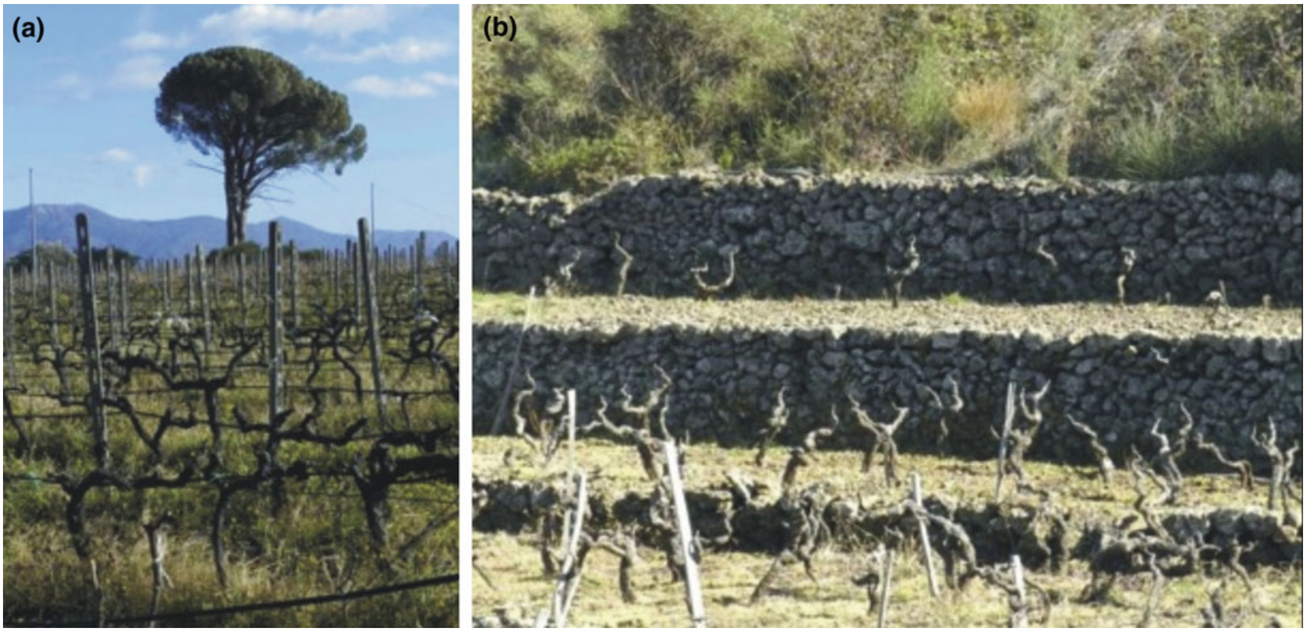

Fig. 45.10 Mt. Etna vineyards: in the areas of Passo Pisciaro (**a**) and on artificial terraces (**b**)

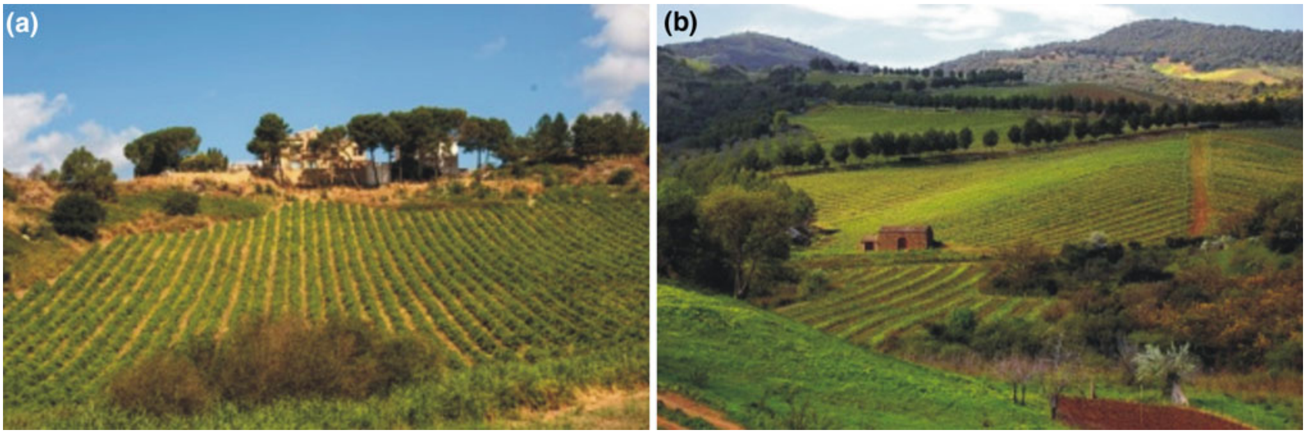

Fig. 45.11 An overview of the Madonie Mts. vineyards: **a** gentle slopes underlain by pelitic and pelitic-arenaceous sediments; **b** gentle slopes underlain by the Numidian Flysch

quantities and is named from a cultivar characterized by long bunches and oblong (rather than round) grapes with thick skins.

45.5.2 Madonie Mountains

The wine production area in the Madonie mountains is resulting only from little cultivations mainly of red wines with a high alcoholic strength. These are located on the northern slopes of the Madonie Mts., in an area in the northern part of EGN/GGN Madonie Geopark, the first Italian Geopark. Geologically, the massif consist of carbonatic, carbonatic-marly and silico-clastic sediments of the Mesozoic-Cenozoic age (Imerese, Panormide and Sicilide tectonic units), in addition to Numidian Flysch (Fig. 45.9). The Trubi Formation, mainly consisting of terrigenous and carbonatic-marly deposits, rests unconformably on pelitic sediments of the Sicilidi tectonic unit. Great part of the vineyards, and consequently the wine landscape, are on gentle to steep slopes of hills made of pelitic and pelitic-arenaceous sediments (Fig. 45.11a). Some small vineyards are on red residual soils generated by karstic processes on the carbonatic rocks and on quartz-arenitic deposits, generally affected by intense and concentrated weathering. The best high-quality wines are produced in the Castelbuono village territory and extend especially in the foothill and hilly areas toward the Tyrrhenian Sea. The best wines are produced on the soils genetically connected to Numidian Flysch, since they have a medium mixture (sandy-silty clays) with a siliceous skeleton (Fig. 45.11b). Vineyards extend especially in the areas with northern aspect and elevation from 200 to 500 m a.s.l. The red, white and rosé wines result from the union of native grapes varieties, as Grillo or Nero d'Avola, and international ones, as Cabernet Sauvignon, Merlot, Sauvignon Blanc and Chardonnay. Biological and biodynamic wines are Montenero and Litra (red wines) and Sensinverso (white wine).

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