World Geomorphological Landscapes

Bianca Carvalho Vieira
André Augusto Rodrigues Salgado
Leonardo José Cordeiro Santos *Editors*

Landscapes and Landforms of Brazil

Springer

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Series Editor 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 that not uncommonly can be traced back in time for tens of millions of years and include unique events. In addition, many landscapes owe their appearance and harmony not solely to the natural forces. For centuries, and even millennia, they have been shaped by humans who have 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 molded them in the past and that change them today. 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 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 the geomorphology of Brazil, a big country with a multitude of spectacular landscapes, from the very well known—such as the steep-sided domes of Rio de Janeiro, Iguazu Falls, or majestic rivers of the Amazonian Lowland—to many hidden gems scattered across the Brazilian Shield. For such a vast and varied territory to make a selection of case studies must have been an arduous task, so inevitably they present only a small fraction of what Brazil has to offer in terms of geomorphological sceneries to enjoy. To discover and learn more, go to Brazil! This would be an unforgettable geomorphological experience.

The World Geomorphological Landscapes series is produced under the scientific patronage of the International Association of Geomorphologists (IAG)—a society that brings together geomorphologists from all over the world. The IAG was established in 1989 and is an independent scientific association affiliated with the International Geographical Union (IGU) and the International Union of Geological Sciences (IUGS). 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 rigor, is the most appropriate means to fulfill these aims and to serve the geoscientific community. To this end, my great thanks go to the editors of this volume—Prof. Bianca Carvalho Vieira as the senior editor, and Profs. André Augusto Rodrigues Salgado and Leonardo José Cordeiro Santos as co-editors. They embarked on a massive and time-consuming task to select the sites to cover, to invite a large group of contributors and to guide them through the writing and reviewing process. I am sure they see this final result as rewarding. Brazil did not have a book about its geomorphological richness in English before, now this impressive natural legacy can be enjoyed by the global geomorphological community. I also express my gratitude to all chapter authors who have shared their passion and expert knowledge with us. *Muito obrigado*!

Piotr Migoń

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Part I

Brazil: Long-term Natural Evolution of Environment

1

Brazil: A Land of Beautiful and Undiscovered Landscapes

Bianca Carvalho Vieira, André Augusto Rodrigues Salgado,
and Leonardo José Cordeiro Santos

Abstract

At over 8.5 million square Km, Brazil is a country of continental dimensions. Brazil contains 27 states, including the Federal District, and is divided into five major regions: South, Southeast, Northeast, Central-West, and North. It is important to note that this country has diverse, unfamiliar landscapes. For example, the Central-West Region of Brazil was the least-known region of the world until the early 1940s and did not have towns or villages. Given the size of the Brazilian territory and the insufficiency of geomorphological and cartographic studies on an appropriate scale for analysis, as previously noted by the Brazilian Professor Aziz Ab'Saber, there are several landscapes that have never been studied and others that remain unknown to Brazilian geomorphology. For this volume, considering the aspects mentioned, specific criteria were used to choose 32 geomorphological landscapes, including the landscape's scenic beauty and the availability of results of more systematic research on its evolution, particularly its geological, climatic, and geomorphological aspects that could effectively explain its forms, processes, and dynamics.

Keywords

Continental dimensions • Several geomorphological landscapes • Undiscovery landscapes

At over 8.5 million km^2, Brazil is a country of continental dimensions. Brazil contains 27 states, including the Federal District, and is divided into five major regions: south, southeast, northeast, central-west, and north (Fig. 1.1).

The southern region, approximately 576,000 km^2, includes the states of Rio Grande do Sul, Santa Catarina, and Paraná (Fig. 1.1). This region has a subtropical climate and consists of a series of mountain ranges and plateaus primarily covered by tropical and subtropical forests (predominantly pines) and fields. The population is predominantly of European origin and mainly composed of descendants of Italian and German immigrants, among others, who immigrated in large numbers from the nineteenth to mid-twentieth century.

The southeast region (comprising the states of São Paulo, Minas Gerais, Rio de Janeiro, and Espírito Santo), approximately 924,000 km^2, is located predominantly in the humid tropical zone, and contains a series of plateaus and mountains with a portion of the most uneven relief in the Brazilian territory. The vegetation ranges from humid tropical forest to rupestrian fields on the tops of mountains, passing through areas of savanna (Cerrado) and scrublands (caatinga) in the more western and northern territories. The climate tends to be tropical, semi-humid, and even semiarid in the north. This region is the most populous and industrialized and has the largest economy in Brazil. The population derives from many backgrounds, including Portuguese immigrants, the

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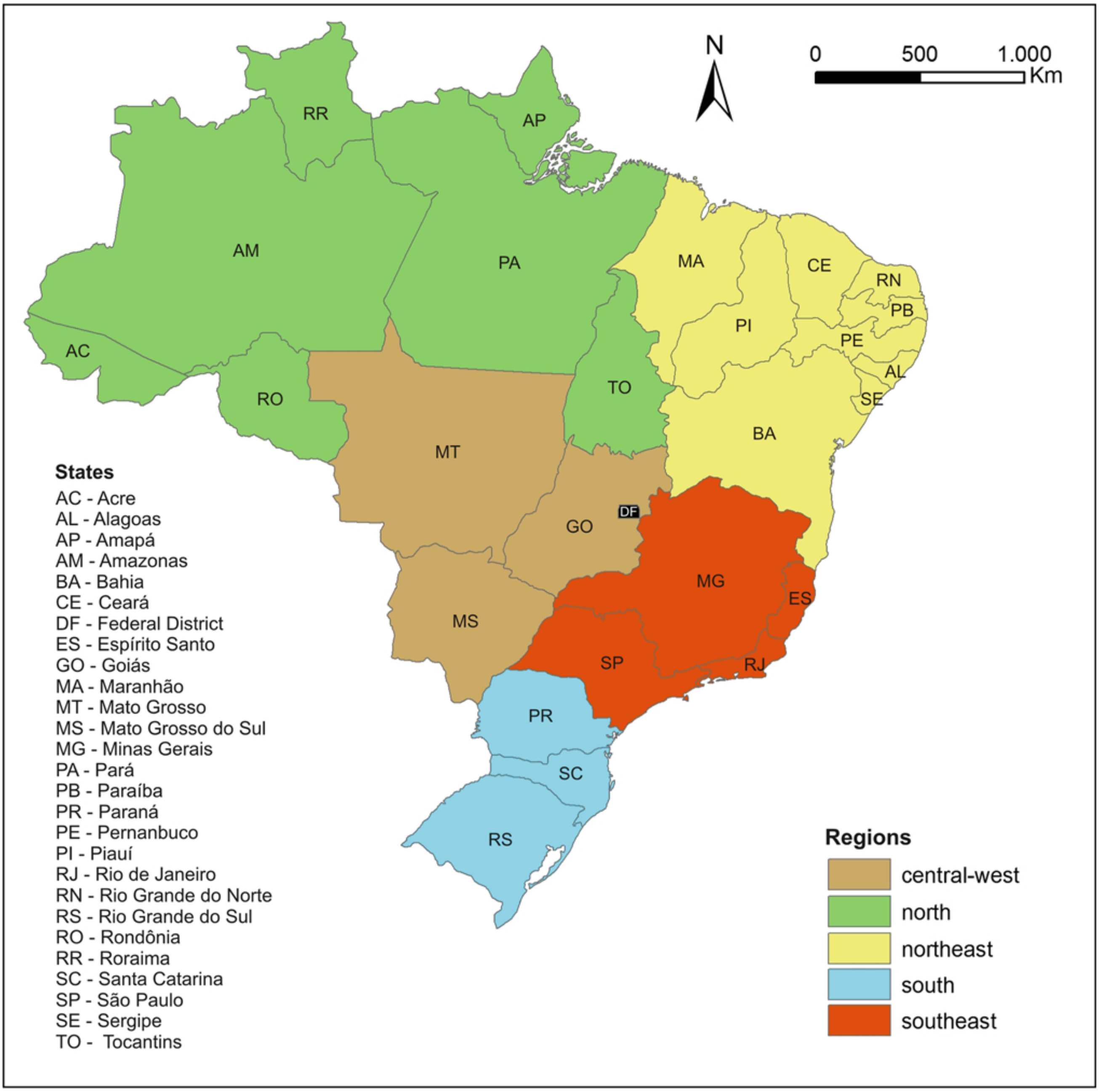

Fig. 1.1 Administrative division of Brazil. *Draw* by Breno Marent

descendants of miscegenation between the Portuguese and local Amerindians, African-descended individuals, the descendants of immigrants from other regions in Europe (mainly Italians, Germans, and Spaniards), Asian-descended individuals (particularly Japanese), and immigrants from other regions of Brazil, mainly the northeast region. The three largest cities of Brazil are located in the southeast region: São Paulo, Rio de Janeiro, and Belo Horizonte.

The northeast region, approximately 1.554 million km^2, comprises the states of Bahia, Sergipe, Alagoas, Pernambuco, Paraíba, Rio Grande do Norte, Ceará, Piauí, and Maranhão (Fig. 1.1). The coastline is typically humid tropical, whereas the inland is subjected to semiarid climatic conditions. Whereas there are many mountains and plateaus in the inland, the relief mainly consists of topographically lower plateaus and flattened or more even surfaces. On the coast and close to the northern region, the natural vegetation is marked by tropical forest. However, scrub predominates in the inner region because of the semiarid climate. Regarding its historical occupation, this region was the first to be colonized by the Portuguese in the sixteenth century and received many slaves trafficked from Africa. Thus, this region has strong traditional and cultural aspects that are tied to ancient interactions between the Portuguese, Amerindians, and Africans.

The central-west region is the second largest in the country, approximately 1.606 million km^2, and comprises the states of Goiás, Mato Grosso, Mato Grosso do Sul , and the Federal District (Fig. 1.1). This region has a predominantly semi-humid tropical climate. The central-west relief consists mainly of plateaus, tablelands, and gently rolling or flattened plains, where savanna vegetation mainly occurs. This region has the smallest population among the five regions, mainly because of its most recent occupation, which only developed after the construction and inauguration of Brasilia—the capital of Brazil—in 1960. Currently, despite receiving immigrants from all regions of Brazil, the central-west region has been most heavily colonized by farmers from the southern region.

The northern region, approximately 4 million km^2, comprises the states of Acre, Rondônia, Roraima, Amazonas, Amapá, Pará and Tocantins (Fig. 1.1). The northern region is the Amazon region of Brazil where, although exceptions occur, it has a super-humid tropical climate and a relief composed mainly of plains and lowered plateaus covered by tropical rain forest (the Amazon rain forest). This region has a larger population than the central-west region; however, because it includes a large area of the Brazilian territory (approximately 45 %), it is the least populated (the lowest population density). Indigenous people and their descendants are common in this region.

After presenting the general characteristics of Brazil, it is important to note that this country has diverse, unfamiliar landscapes. For example, the central-west region of Brazil was the least known region of the world until the early 1940s and did not have towns or villages. The Amerindians of this region, mainly the Xavante people, were considered fearsome. Waterways, such as the Araguaia and Tocantins (both among the 50 largest in the world), did not have their sources recognized. Major mountain ranges, plateaus, and other river systems also remained completely unmapped. Much of this territory had not been flown over, and information regarding the northern region, particularly the Amazon, was also unknown. Currently, this situation has changed with the incorporation of these areas into the Brazilian nation. However, the "Geography of the Brazilian territory" has been generally explored, many places remain unknown to Brazilians themselves, particularly in the north and central-west regions.

Given the size of the Brazilian territory and the insufficiency of geomorphological and cartographic studies on an appropriate scale for analysis, as previously noted by the Brazilian Professor Aziz Ab'Saber, there are several landscapes that have never been studied and others that remain unknown to Brazilian geomorphology. The characteristics of the Brazilian territory continue to influence the current disproportion of studies regarding the extent and depth of the treatment of information.

Thus, although Brazil has many significant beautiful landscapes in the north and central-west, these regions are not extensively covered in the second part of this book because of the absence of more systematic and scientific studies that may, more broadly, be informative regarding their evolution.

For this volume, considering the aspects mentioned, specific criteria were used to choose 32 geomorphological landscapes, including the landscape's scenic beauty and the availability of results of more systematic research on its evolution, particularly its geological, climatic, and geomorphological aspects that could effectively explain its forms, processes, and dynamics. The inevitable consequence of the use of these criteria is that most Brazilian landscapes presented in this book are concentrated in the south, southeast, and northeast regions. Moreover, considering the two geotectonic mega-compartments into which the Brazilian territory can be divided, the northern and central-west regions belong to a less active compartment with a more uniform and less diversified relief. In addition to having a greater altimetry and diversity of landscapes, the other regions have an older historical occupation and the highest population densities in Brazil.

Thus, the purpose of this book is not to present the different geomorphological processes responsible for the genesis and evolution of the Brazilian relief or to address environmental problems, which are characterized in Brazilian geography and geomorphology within the general systems theory framework. For this book, we attempted to select landscapes with considerable scenic values that illustrate an important portion of the geomorphological units previously mapped by several authors, thus enabling the correlation between the genesis of these units and the climatic and morphotectonic influences in their formation and colonization processes.

Therefore, "The Landscapes and Landforms of Brazil" contains two sections that explain the broader formation of the territory and its geomorphological complexity. The first section consists of three chapters to describe its geological evolution, particularly in the context of South America (*Geological Background: a Tectonic Panorama of Brazil*), its main geomorphological aspects (*Long-Term Geomorphological Evolution of the Brazilian Territory*), and some climactic characteristics from the past and present (*Climates of Brazil: Past and Present*).

The second section features 32 landscapes (Fig. 1.2) divided by region. To better understand the distribution of these forms of relief, this book was divided into 5 "large sets of landscapes."

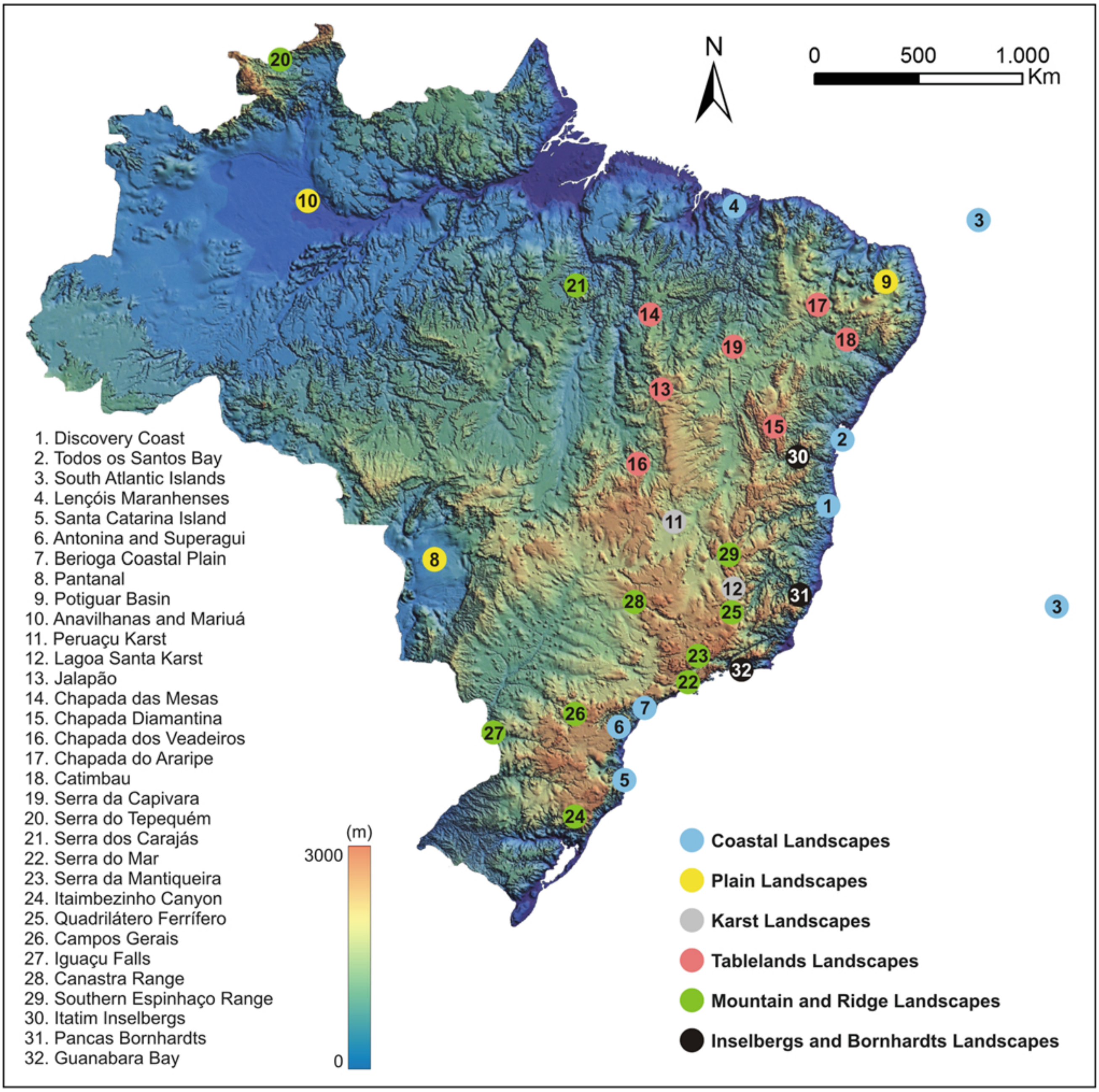

Fig. 1.2 The geomorphological landscapes presented in this book. *Draw* by Breno Marent and adapted from a DEM from JBL Françolin

The initial five chapters describe the main coastal plains and islands of Brazil that initially attracted and were described by colonists (Discovery Coast, Todos os Santos Bay, Fernando de Noronha and Trindade, Lençóis Maranhenses, Santa Catarina Island, and the Bays of Antonia and Superagui, Bertioga). The plains are then described (Pantanal, Potiguar Basin, Anavilhanas and Mariuá). The typical karst landscapes appear in the third section (Peruaçu and Lagoa Santa). The tabular forms and large plateaus are presented next and represent lush landscapes that occupy large areas throughout the Brazilian territory (Jalapão, Chapada das Mesas, Chapada Diamantina, Chapada dos Veadeiros, Araripe, Catimbau, and Serra da Capivara). The Brazilian mountains and plateaus are also discussed in this book and present a striking geomorphologic configuration from the geological structures and climatic aspects (Tepequém, Carajás, Serra do Mar, Serra da Mantiqueira, Itaimbezinho, Quadrilátero Ferrífero, Campos Gerais, Iguaçú

Falls, Canastra Range, and Serra do Espinhaço). Spectacular landscapes formed by inselbergs and bornhardts are presented at the end (Itatim, Pancas and Guanabara Bay).

Thus, although this book was never intended to present all of the Brazilian landscapes of geomorphological interest, we hope that the reader acquires a good understanding of these regions, which exemplify the diversity and beauty of the landscapes and shapes of Brazil. Furthermore, we believe that this book may contribute effectively to the research and teaching of Brazilian geomorphology. We, the editors, thank those who helped build Brazilian geomorphology because without them, it would be impossible to advance the hypotheses and theories launched at the beginning of its organization and, in some manner, formed the basis of our current geomorphological knowledge.

Geological Background: A Tectonic Panorama of Brazil

2

Fernando Flecha de Alkmim

Abstract

The landforms and landscapes discussed in this book developed in a variety of terrains, which together express the diversity of the geological background of the Brazilian territory. Located essentially in the old and relatively stable nucleus of the South American plate (known as the South American platform), Brazil comprises seven major categories of tectonic units, which are as follows: cratons, Brasiliano orogenic systems, Palaeozoic sag basins, equatorial margin basins, eastern margin basins, sub-Andean basins, and Tertiary rifts. The cratons together with the Brasiliano orogenic systems form the Precambrian basement of the continent. Exposures of these units comprise three distinct morphotectonic domains, namely the Guianas, central Brazil, and Atlantic shields. The four cratons delimited in Brazil represent stable lithospheric pieces that escaped the effects of the collisional processes responsible for the amalgamation of Gondwanaland, the large landmass from which South America and other southern continents derived. The Brasiliano orogenic systems form a network of collisional belts between the cratons, which were stitched together by the end of the Neoproterozoic Era. The Phanerozoic basins of Brazil record the long residence of South America in Gondwana and Pangaea, the breakup of the supercontinent during the Early Cretaceous, and subsequent processes. Large Palaeozoic sags cover a substantial portion of the Brazilian interior, whereas the eastern and equatorial margins host Cretaceous to Recent sedimentary successions. The tectonic units distinguished in the Brazilian territory have distinct expressions in the large-scale topographic relief. The lowlands are underlain by the cratons and covered by Palaeozoic sag basins. The highlands correspond to the Neoproterozoic orogenic systems, on which Phanerozoic structures such as arches, plateaus, and uplifts are superimposed.

Keywords

South American platform • Cratons • Brasiliano orogenic systems • Phanerozoic basins • Brazil

2.1 Introduction

From a geological Brasiliano orogenic systemsstandpoint, the geomorphological provinces focused in this book correspond to regional and local land surface expressions of rock assemblages and structures that characterize the various tectonic units exposed in the Brazilian territory. Together, these landscapes can be considered a manifestation of the Brazilian geodiversity.

Brazil is almost entirely located in the old and relatively stable nucleus of the South American plate known as the South American platform (Fig. 2.1). Defined as the portion of the continent that escaped the effects of the Andean orogenies (Almeida 1967; Almeida et al. 1981, 2000), the South American platform is underlain by Precambrian rocks and surrounded by the younger terrains of the continent,

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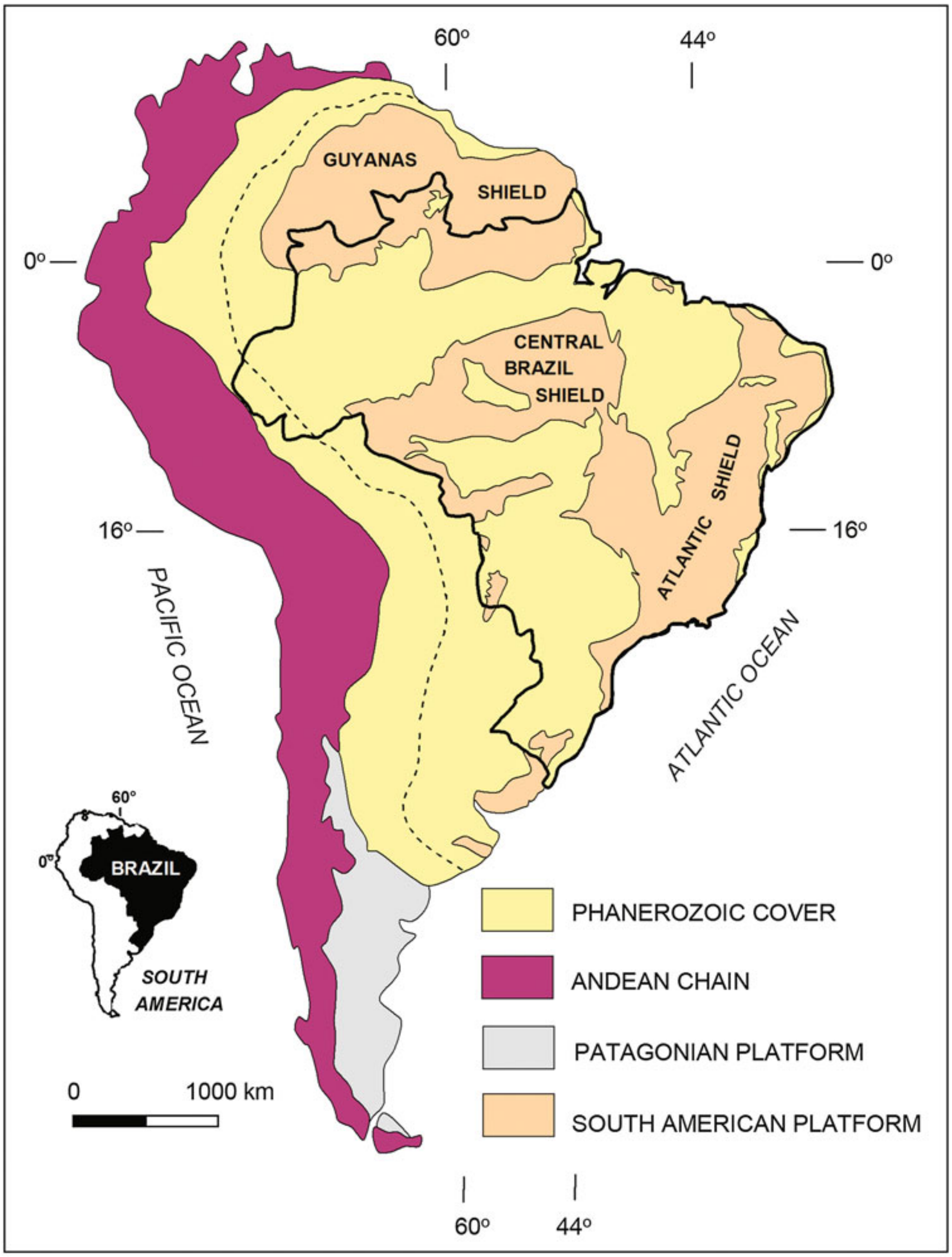

Fig. 2.1 Simplified tectonic map of South America, showing the South American platform and its shield areas (modified from Almeida et al. 1981)

represented by the Patagonian platform, the Andean chain, as well as the Pacific and Atlantic continental margin systems. Only a small portion of westernmost Brazil, the Acre basin (see next section), lies in the sub-Andean domain.

A substantial part of the South American platform is covered by Phanerozoic sedimentary successions. The areas of the platform, where the Precambrian basement is exposed, are collectively referred to as the Brazilian shield. Actually, the Brazilian shield comprises three distinct morphotectonic domains: the Guyanas, central Brazil (or Guaporé), and Atlantic shields (Fig. 2.1).

2.2 Tectonic Units of Brazil

In the Brazilian geological literature, each individual component of the South American platform and its Phanerozoic cover is traditionally portrayed as a structural province, defined as a geographically continuous domain, which differs from the adjacent terrains in terms of stratigraphy, tectonic evolution, metamorphic history, and age (Almeida et al. 1981; Bizzi et al. 2001). For simplicity, the building blocks of Brazilian geological framework are here discriminated on the basis of their tectonic function and age. Accordingly, seven categories of tectonic units can be recognized in the Brazilian territory: (i) cratons, (ii) Brasiliano orogenic systems, (iii) Palaeozoic sag basins, (iv) equatorial margin basins and associated intracontinental rifts, (v) eastern margin basins and associated intracontinental rifts, (vi) sub-Andean basins, and (vii) Tertiary rifts (Fig. 2.2).

Cratons and Brasiliano orogenic systems, corresponding to two distinct lithospheric types, are the fundamental components of the Precambrian nucleus of South America. The Precambrian core of the continent was amalgamated as various plates converged and collided to form the large Gondwanaland by the end of the Neoproterozoic and beginning of the Palaeozoic Era (Brito Neves et al. 1999; Cordani and Sato 1999; Campos Neto 2000; Almeida et al. 2000; Alkmim et al. 2001). The cratons of the South American platform, defined as old and stable lithospheric pieces that were not affected by the Neoproterozoic collisional processes, correspond to the internal parts of the plates that converged during the assembly of West Gondwana, i.e., South America and Africa. The so-called Brasiliano/Pan-African orogenic systems, forming a network of collisional belts between the cratons, represent the margins of those plates, as well as micro-continents and magmatic arcs also involved in the amalgamation of West Gondwana (Campos Neto 2000; Almeida et al. 2000; Alkmim et al. 2001) (Fig. 2.3).

At the very end of the Palaeozoic, around 250 Ma, Gondwana joined Laurasia to form Pangaea. Pangaea remained as a supercontinent for ca. 120 Ma, until the end of the Jurassic Period, when it started to break apart, giving rise to present-day continents and oceans. The Palaeozoic, continental margin, sub-Andean, and Tertiary basins make up the Phanerozoic cover complex of the South American platform and its margins. These basins record the residence of the Precambrian nucleus of the continent in Gondwana and Pangaea, the break up history of the supercontinent, and tectonic events occurring after individualization of the South American plate. As a consequence of the dispersal of Pangaea and generation of the South Atlantic in the Lower Cretaceous, some cratons and Brasiliano/Pan-African orogenic systems split in two. Their counterparts are now exposed in the eastern Brazilian and western African shields (Porada 1989; Trompette 1994) (Fig. 2.3).

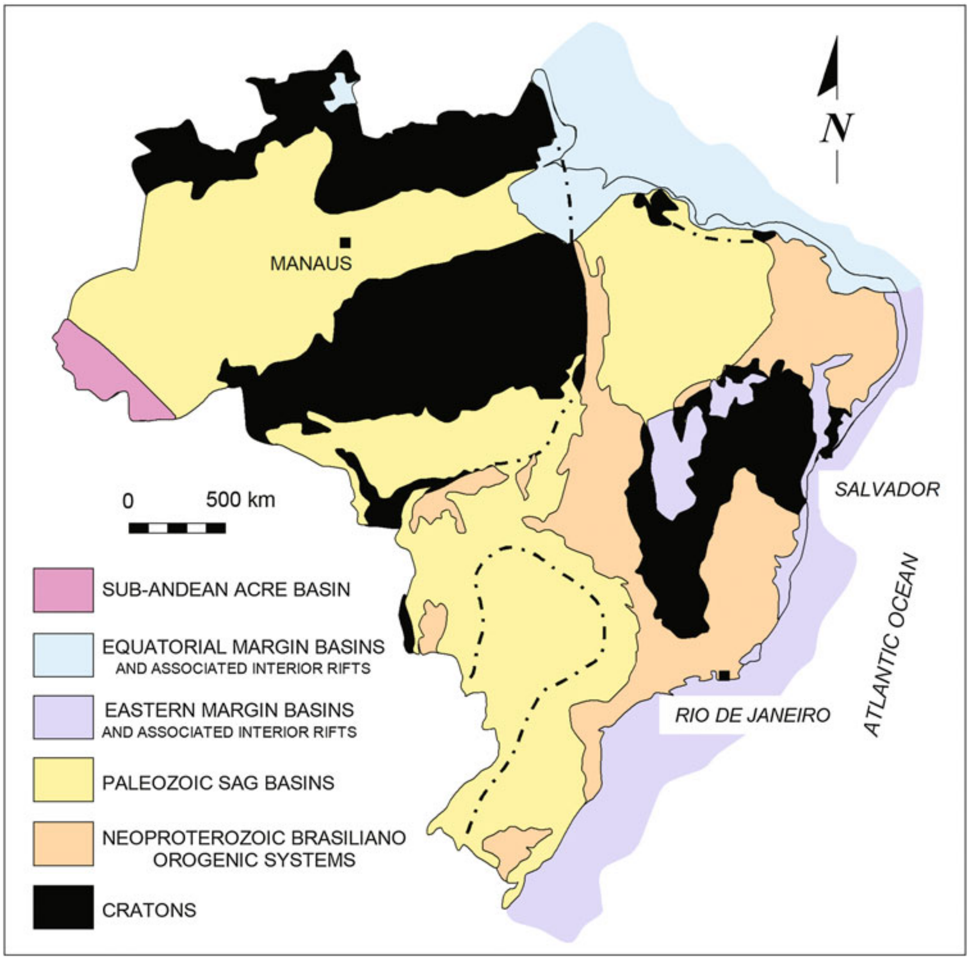

Fig. 2.2 Simplified tectonic map of Brazil, showing the distribution of the various categories of tectonic units

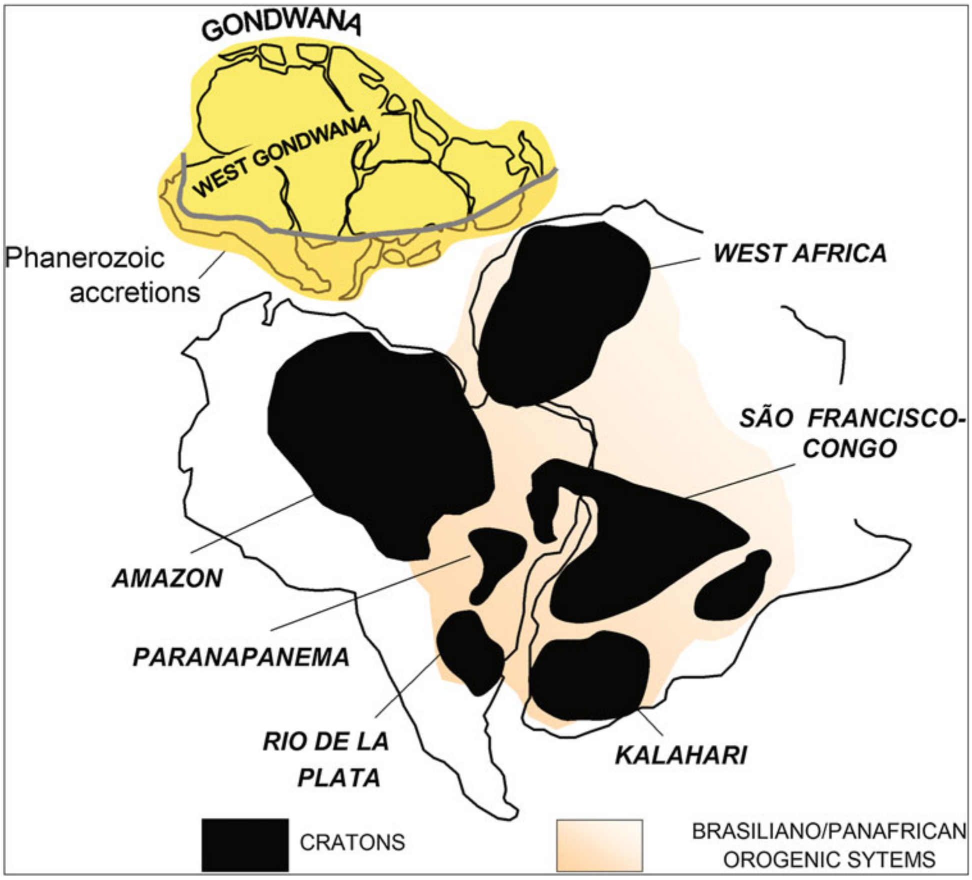

Fig. 2.3 Schematic map of West Gondwana, showing the cratons and Brasiliano/Pan-African orogenic systems (modified from Alkmim and Martins-Neto 2004)

2.2.1 Cratons

The South American platform contains four cratons (Almeida et al. 1981, 2000) (Fig. 2.4). The large Amazon[1] craton, extending far beyond the Brazilian borders, consists of an Archaean core—the so-called central Amazonian province—bounded by Palaeoproterozoic and Mesoproterozoic terranes, respectively, to the northeast and southwest (Tassinary et al. 2000; Santos et al. 2000; Santos 2003). The intracratonic Solimões and Amazon Basins cutting across the structural grain of the basement separate the Guyanas and central Brazil shield areas.

The São Francisco craton is the best exposed and one of the most intensively studied Precambrian terrains of South America. Located in eastern Brazil, it is made up of an Archaean and Palaeoproterozoic basement older than 1.8 Ga and a sedimentary cover that includes Proterozoic and Phanerozoic strata. Reconstructions of West Gondwana indicate that the São Francisco craton was connected to the Congo craton that underlies a vast segment of central West Africa (Almeida 1977; Alkmim 2004; Alkmim and Martins-Neto 2012) (Fig. 2.3).

The only exposure of the São Luis craton consists of a Palaeoproterozoic granite–greenstone terrain. Fringed to south by the Neoproterozoic Gurupi orogenic belt, the São Luis apparently represents a small fragment of the West African craton that remained in South America as the West Gondwana split apart (Trompette 1994; Brito Neves et al. 1999; Cordani et al. 1999; Campos Neto 2000; Almeida et al. 2000).

The existence of a cratonic mass beneath the large Paraná Basin in south Brazil (Fig. 2.4) has been inferred on the basis of geophysical studies. Previously portrayed as an extension of the Rio de la Plata craton partially exposed in Uruguay and northern Argentina, this piece of crust, called Paranapanema craton, is now interpreted a distinct crustal block (e.g., Almeida et al. 2000; Schobbenhaus and Brito Neves 2003).

2.2.2 Brasiliano Orogenic Systems

The Brasiliano Tocantins, Borborema, and Mantiqueira systems form a network of interfering orogens developed as the plates represented by the cratons of the platform were stitched together during the assembly of West Gondwana between 640 and 500 Ma, i.e., in the course of the Ediacaran and Cambrian periods of the Neoproterozoic and Palaeozoic eras, respectively (Brito Neves et al. 1999; Campos Neto 2000;

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[1] Originally referred to as the Amazonian craton.

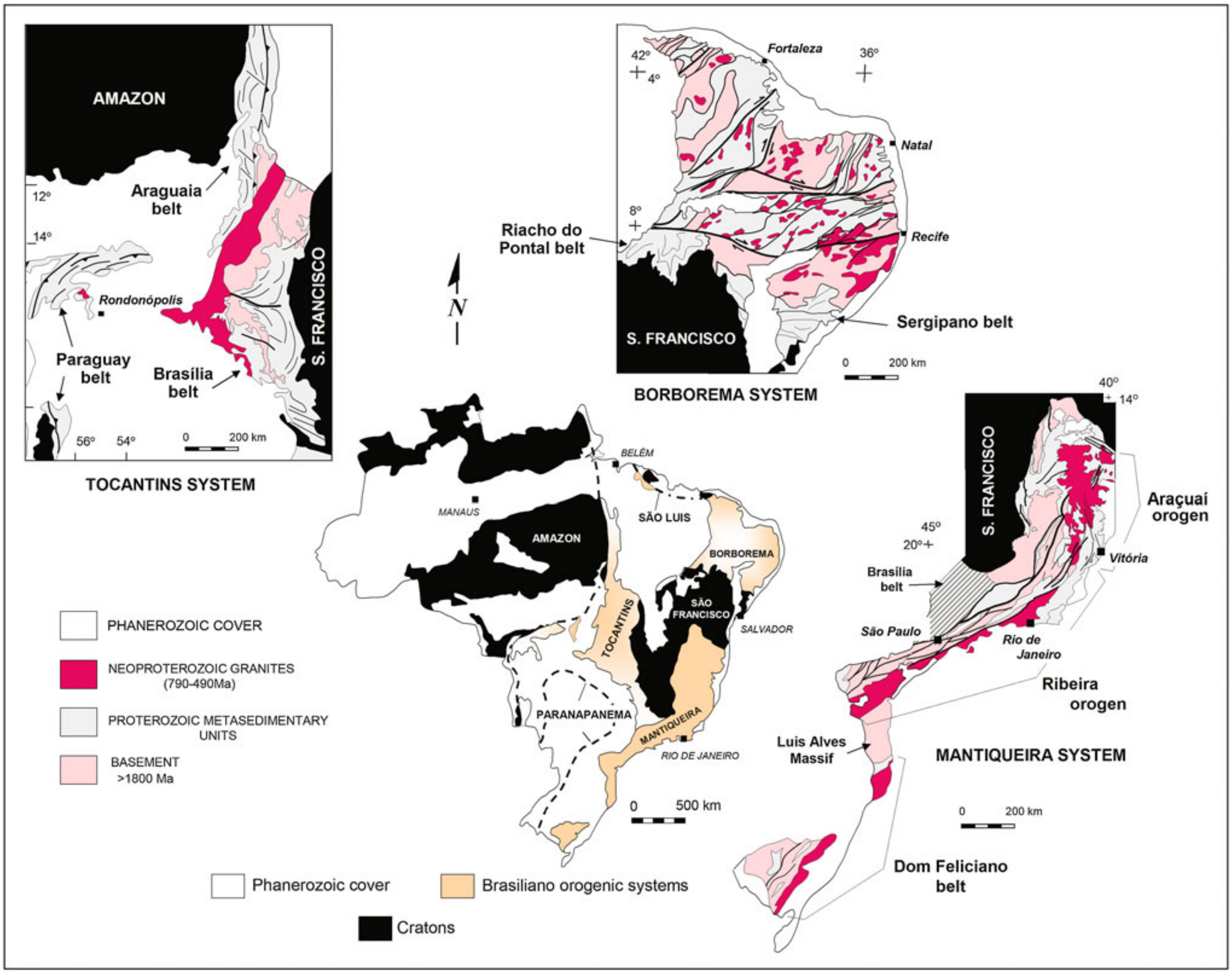

Fig. 2.4 Cratons and Brasiliano orogenic systems exposed in Brazil (detail maps based on Bizzi et al. 2001)

Almeida et al. 2000; Schobbenhaus and Brito Neves 2003) (Figs. 2.3 and 2.4). The Tocantins system in central Brazil encompasses the Araguaia and Paraguay belts developed along the margin of the Amazon craton, as well as the Brasília belt that fringes the São Francisco craton to west (Pimentel et al. 2000; Alvarenga et al. 2000; Dardenne et al. 2000) (Fig. 2.4). The diachronic collisions of the paleocontinents Paranapanema, São Francisco–Congo, and Amazonia, also involving a magmatic arc and a micro-continent (Pimentel et al. 2004; Valeriano et al. 2004), resulted in the consumption of the Goianides ocean (Brito Neves et al. 1999) and uplift of the Tocantins mountain system, The ca. 1,200-km-long and 150-km-wide Araguaia belt is made up of an Archaean and Palaeoproterozoic basement overlain by Neoproterozoic metasedimentary successions. N–S-trending faults and folds promoted tectonic transport of these units toward the Amazon craton (Alvarenga et al. 2000). Separated from the Araguaia belt by the Neoproterozoic Goiás magmatic arc and the Archaean Crixás-Goiás block, the Brasília belt corresponds to an up to 300-km-wide and 1,200-km-long orogenic zone, in which a Archaean/Palaeoproterozoic basement and Proterozoic metasedimentary successions younger than 1,800 Ma locally cut by granitic rocks are folded and thrust toward the São Francisco craton (Pimentel et al. 2004; Valeriano et al. 2004). As the youngest branch of the Tocantins system, the Paraguay belt describes a pronounced curve along the southeastern edge of the Amazon craton and involves a thick succession of Late Neoproterozoic sedimentary rocks (Alvarenga et al. 2000).

The Mantiqueira system straddles the southeastern coastal region of Brazil, forming a ca. 2,500-km long Neoproterozoic collisional domain composed of the Araçuaí orogen, the Ribeira orogen, and the Dom Feliciano belts, whose African counterparts are the West Congolian and the Kaoko belts (Fig. 2.4). Closure of the so-called Adamastor ocean that separated the paleocontinents Paranapanema and São

Francisco-Congo led to the generation of the Mantiqueira system (Brito Neves et al. 1999; Campos Neto 2000; Heilbron et al. 2004). The Araçuaí orogen corresponds to northern segment of the system. It consists of an external fold–thrust belt (also called Araçuaí belt) that curves along the eastern margin of the São Francisco craton, and an internal zone made up of high grade metamorphic and granitic rocks. In the external Araçuaí belt, the Archaean basement is covered by Proterozoic metasedimentary rocks which are intensively folded and thrust toward the São Francisco craton. The N–S-trending structures of the Araçuaí orogen bend toward NE and merge with the characteristic fabric elements of the Ribeira orogen around 21S latitude (Pedrosa-Soares and Wiedemann-Leonardos 2000; Pedrosa-Soares et al. 2001; Alkmim et al. 2006). The Ribeira orogen, partially dominated by a system of NE-trending dextral strike-slip shear zones, involves a Palaeoproterozoic basement, high grade Proterozoic metasedimentary units, the Neoproterozoic Rio Negro magmatic arc, and a considerable volume of granitic rocks (Trouw et al. 2000; Heilbron et al. 2004). The Luiz Alves gneiss massif separates the Ribeira orogen from the Dom Feliciano belt, which also consists of a Palaeoproterozoic basement, Meso- to Neoproterozoic sedimentary succession, and Neoproterozoic granitoids (Basei et al. 2000; Heilbron et al. 2004) (Fig.2.4).

Differently from all previously described Brasiliano orogenic zones, the Borborema in northeastern Brazil comprises a gigantic system of strike-slip shear zones, which apparently roots in the Tocantins system (Fig. 2.4). The fanlike array of dextral shear zones anastomoses around various basement massifs covered by Proterozoic metasedimentary units and intruded by a large volume of Neoproterozoic granites. The system also contains two fold–thrust belts, the Riacho do Pontal and Sergipano belts that bound the São Francisco craton to the north (Brito Neves et al. 2000)

2.2.3 Palaeozoic Sag Basins

Some regions of West Gondwana started to subside soon after its assembly, being converted into the initial depocenters of the large and long-lived Solimões, Amazonas, Parnaíba, Paraná, and Parecis intracontinental basins (Pedreira et al. 2003; Milani et al. 2007). The triggering mechanism of the initial subsidence of these basins between 470 and 450 Ma (Meso- to Neo-Ordovician) is still controversial, though evidence for precursor rifts has been documented in all of them (Tankard et al. 1998; Milani et al. 2007).

The Palaeozoic basins of Brazil share a series of common features. Their overall architectures are characterized by the uniform shallow dips of the infill strata toward the center and the presence of regional arches and highs. They all correspond to successor and polyhistoric depocenters, filled by major stratigraphic sequences bounded by regional unconformities of approximately the same age. Their fill units record important tectonic and climatic events affecting West Gondwana in the course of the Palaeozoic, such as major marine incursions during the Silurian, Devonian and Early Permian, the Silurian and Permo-Carboniferous glaciations (documented in the Solimões and Paraná Basins, respectively), as well as arid climatic conditions that predominated during Late Permian, Triassic, and end of the Jurassic. Besides this, the Amazonas and Paraná Basins also host thick Upper Jurassic and Eo-Cretaceous flood basalts and related intrusions, the magmatic event precursor of the West Gondwana breakup (Zalán 2004; Milani et al. 2007).

2.2.4 Equatorial, Eastern Margin, and Associated Intracontinental Rifts

The dispersal of West Gondwana in the Eo-Cretaceous, following the disaggregation of Pangaea, led to the opening of the Atlantic ocean and the generation of passive and transform margin basins along the borders of newly individualized South American and African continents.

The eastern continental margin of Brazil comprises a series of typical passive margin basins, whose development evolves from south to north with the formation of a complex system of interconnected rifts. The rift phase is recorded in these basins by a succession of Neocomian lacustrine sediments. The subsequent transitional phase is marked by the deposition of terrigenous sediments and carbonates during the Aptian, followed by the drift phase, which starts with the formation of a vast salt basin in the region that extends from the Santos to the Sergipe-Alagoas Basin and the equivalent area in the African margin (Fig. 2.5). The advanced stages of the drift phase are recorded by transgressive and regressive marine sequences of Neo-Cretaceous and Tertiary ages, respectively (Mohriak 2003; Zalán 2004; Milani et al. 2007).

The Brazilian equatorial margin evolved as a transform margin during the opening of the Atlantic. Consequently, significant differences in structural styles and nature of fill successions exist between the equatorial and eastern margin basins. Dextral strike-slip motions along E–W-trending fault zones punctuate the evolution of the equatorial margin basins from their onset in the Aptian to the full development stage in the Tertiary (Matos 2000; Mohriak 2003)

Considerable areas of the continental interior also experienced the effects of extensional tectonics that resulted in the generation of the Atlantic. Basement structures were reactivated, leading to the nucleation of intracontinental rifts such as the Tacutu, the Recôncavo-Jatobá-Tucano, and Potiguar onshore basins (Fig. 2.5).

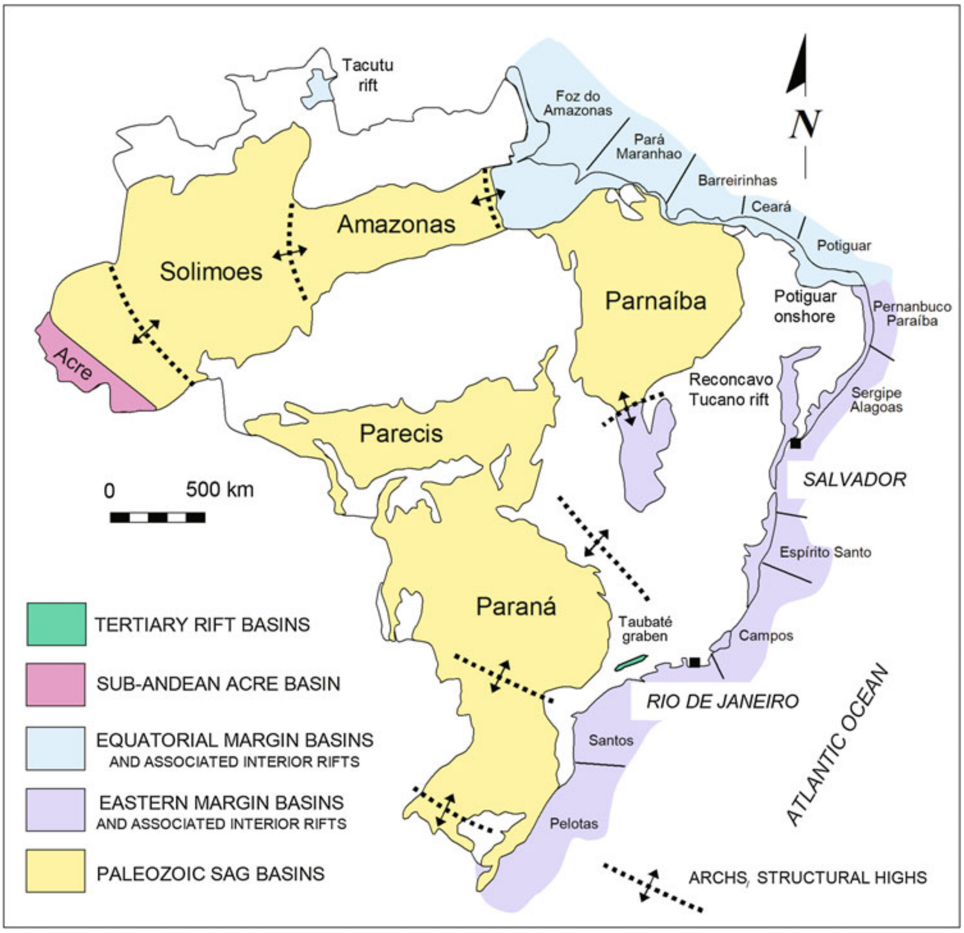

Fig. 2.5 Tectonic units of the South American platform cover complex, i.e., basins of the Brazilian territory (based on Milani et al. 2007)

2.2.5 The Sub-Andean Acre Basin

Located along the border to Peru, the Acre basin, like the adjacent Solimões sag, experienced a long development history that started by the end of the Silurian. By the end of the Eo-Cretaceous, the Acre basin was caught by the so-called Juruá orogenic front that caused its deformation along reverse faults and thrusts, as well as its conversion in an Andean foreland basin. During the Andean uplift pulses in the Tertiary, especially in the course of the Miocene-Pliocene Quechua phase, a thick package of terrigenous sediments accumulated in the basin (Pedreira et al. 2003; Cunha 2007).

2.2.6 Tertiary Rifts

A substantial area of southeastern Brazil was affected by extensional deformation between the end of the Eocene and beginning of the Miocene. Reactivation of eastern margin basin structures, reorganization of drainage systems, and nucleation series of rifts, such as the Taubaté and Resende basins (Zalán and de Oliveira 2005), are the main manifestations of this episode, whose causes are not yet clearly understood.

2.3 Tectonic Units and Their Topographic Expression

A comparison of the tectonic and topographic maps of Brazil reveals a good correspondence between the previously described tectonic units and large-scale topographic features (Alkmim and Martins-Neto 2004) (Fig. 2.6). The lowlands are underlain by the cratons and host the Palaeozoic sag basins as well as large river systems, such as the Amazon, Paraná, and São Francisco. The highlands, on the other hand, correspond to the Brasiliano orogenic systems, on which Phanerozoic structures such as arches, plateaus, and uplifts are superimposed. Among these, the most prominent features are the Alto Paranaíba arch, the Serra do Mar uplift, the Mantiqueira range, and the Borborema plateau.

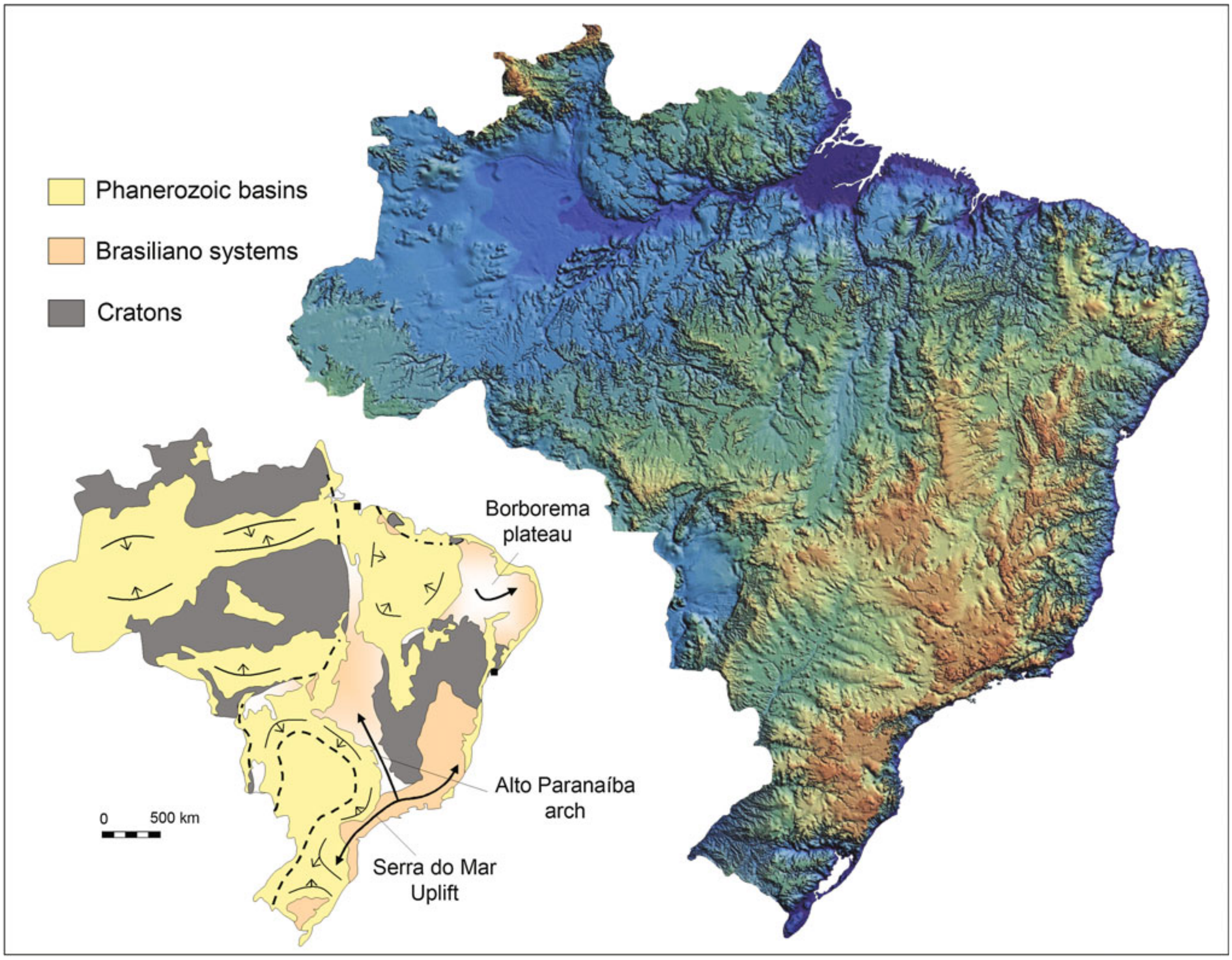

Fig. 2.6 Tectonic units and large-scale structures and their expression in the topographic relief of Brazil (modified from Alkmim and Martins-Neto 2004)

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3 Long-Term Geomorphological Evolution of the Brazilian Territory

André Augusto Rodrigues Salgado, Guilherme Tatison Bueno,
Alisson Duarte Diniz, and Breno Ribeiro Marent

Abstract

In Brazil, there is great diversity in the geomorphological evolution of landscapes as a result of the country's massive geographical size (over 8.5 million km^2). Diverse climates and palaeoclimates acting on different tectonic compartments, substrates, and reliefs have generated a rich diversity of natural landscapes. The Brazilian territory can be broadly divided into two tectonic mega-compartments: Amazonian Brazil and Atlantic Brazil (Extra-Amazonian Brazil). These two compartments are separated by a lineament known as the Transbrasiliano Lineament, which crosses the country in a southwest to northeast direction. Amazonian Brazil is characterised by lower elevations and a more uniform relief, whereas Atlantic Brazil contains higher elevations and exhibits greater topographic diversity and complexity.

Keywords

Long-term relief evolution • Amazonian Brazil • Atlantic Brazil • Transbrasiliano Lineament

3.1 Introduction

Brazil is a country of continental geographic dimensions. However, despite its large size, the entire country is contained within a single geotectonic unit known as the South American Platform (Almeida et al. 1981), which forms the central-eastern region of South America (Fig. 3.1). Because Brazil is located away from the plate margins, the country exhibits a certain degree of tectonic homogeneity. However, in tectonic and structural terms, Brazil cannot be considered to be a single and homogenous compartment. Additionally, whereas humid tropical climates predominate throughout Brazil, there is substantial climatic variation within the country's territory, a phenomenon that seems to have been important in the past (Oliveira et al. 2005). Therefore, any attempt to summarise Brazil's long-term geomorphological evolution must recognise that a single course of evolution does not adequately describe the Brazilian landscape. Given the enormous size of Brazil, there have been many distinct paths of geomorphological evolution because each region has experienced a different geotectonic history, climate, and palaeoclimate. However, based on the existence of two tectonic mega-compartments separated by an extensive structural lineament (the Transbrasiliano Lineament, which follows a trajectory of N45°E), the Brazilian territory can be subdivided into two regions distinguished by their reliefs (Fig. 3.1): (1) northern and western Brazil, also referred to as Amazonian Brazil and (2) southern and eastern Brazil, which was originally known as Extra-Amazonian Brazil

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Fig. 3.1 Major geotectonic units of South America and the Transbrasiliano Lineament. Adapted from Schobbenhaus and Campos (1984) and Saadi et al. (2005)

(Saadi et al. 2005) but will be referred to as Atlantic Brazil in this study.

As described by Saadi et al. (2005), the geomorphological region of "Amazonian Brazil" is the region of the country where the relief is more uniform and the landscape is dominated by lowlands that are mostly below 500 m in elevation (Fig. 3.2). This part of Brazil overlies a predominantly cratonic geotectonic compartment that was not deeply affected by the Brasiliano/Pan-Africano[1] Cycle. According to (Saadi et al. 2005), "Atlantic Brazil" is the region of Brazil where the relief is more varied, mountains and plateaus make most of the topography, and altitudes above 500 m are more common (Fig. 3.2). This region was more deeply affected by the Brasiliano/Pan-African Cycle and is tectonically more active than Amazonian Brazil.

Because of the differentiation between Amazonian Brazil and Atlantic Brazil described above, in which the former region has a more homogenous relief and the latter is more heterogeneous, gross relief and its origin are described separately for the two regions in this chapter. Because Atlantic Brazil has a greater diversity of landscapes, its geomorphological evolution was analysed based on the region's various geotectonic compartments. In contrast, the geomorphological evolution of Amazonian Brazil is presented as a uniform story that developed through time, without analysing the history of individual geotectonic compartments.

3.2 Long-Term Geomorphological Evolution of Atlantic Brazil

Although it is not the oldest event to have a geostructural impact on the regional landscape, the Brasiliano/Pan-African Cycle was a remarkable event and is fundamental to understand the subsequent structuring of this portion of the globe (Almeida et al. 1981). The cycle laid the foundation for the entire geotectonic evolution of Brazil because it was responsible for the formation of western Gondwana. Furthermore, it was during this cycle that an intrusion of magma into the crust occurred in the form of granite plutons that, once exhumed, gave rise to the famous "Sugar Loaves" (Fig. 3.3), one of the most striking and well-recognised landforms in Brazil. In addition, during the Brasiliano/Pan-African Cycle, the individualisation of most of the geotectonic units of Atlantic Brazil occurred, including the Paraná Basin, the São Francisco Craton and the ancient Tocantins, Borborema and Mantiqueira orogens. The latter are composed of the Araçuaí and Ribeira orogens (Fig. 3.4).

3.2.1 Paraná Basin

The Paraná Basin is one of the major sedimentary basins (in addition to the Amazonas, Solimões, Parecis and Parnaíba basins) of the South American platform (Fig. 3.4). The basin is approximately 1,600,000 km^2 in size, and its origin is related to the stabilisation of the South American platform after the Brasiliano event, approximately 400 Mya. The basin formed on depressed zones created by faulting. The zones sank through a process of lithosphere stretching, subsidence under accumulated sediments and other processes caused by lithosphere dynamics (Almeida and Carneiro 2004). According to the aforementioned authors, during the evolution of the basin, epeirogenic movements and marine invasions occurred, in addition to sediment deposition and related transgressive-regressive cycles from the Mid-Ordovician to Neo-Permian. Notably, the fragmentation of western Gondwana from the Jurassic to the Cretaceous intensely affected the Paraná Basin by causing tectonic uplift and basaltic magmatism with flows up to 2,000 m thick (Mizusaki and Thomaz Filho 2004). These structures were associated with weaknesses in several directions, predominantly in the north/west and north/east directions (Santos et al. 2006).

The current topography of the Paraná Basin is characterised by a set of highlands and mesas surrounded by

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[1] The Brasiliano/Pan-Africano Cycle occurred between 790 and 500 Mya. It affected the western portion of the Gondwana continent and was characterised by the generation of orogenic belts and the individualisation of cratonic areas.

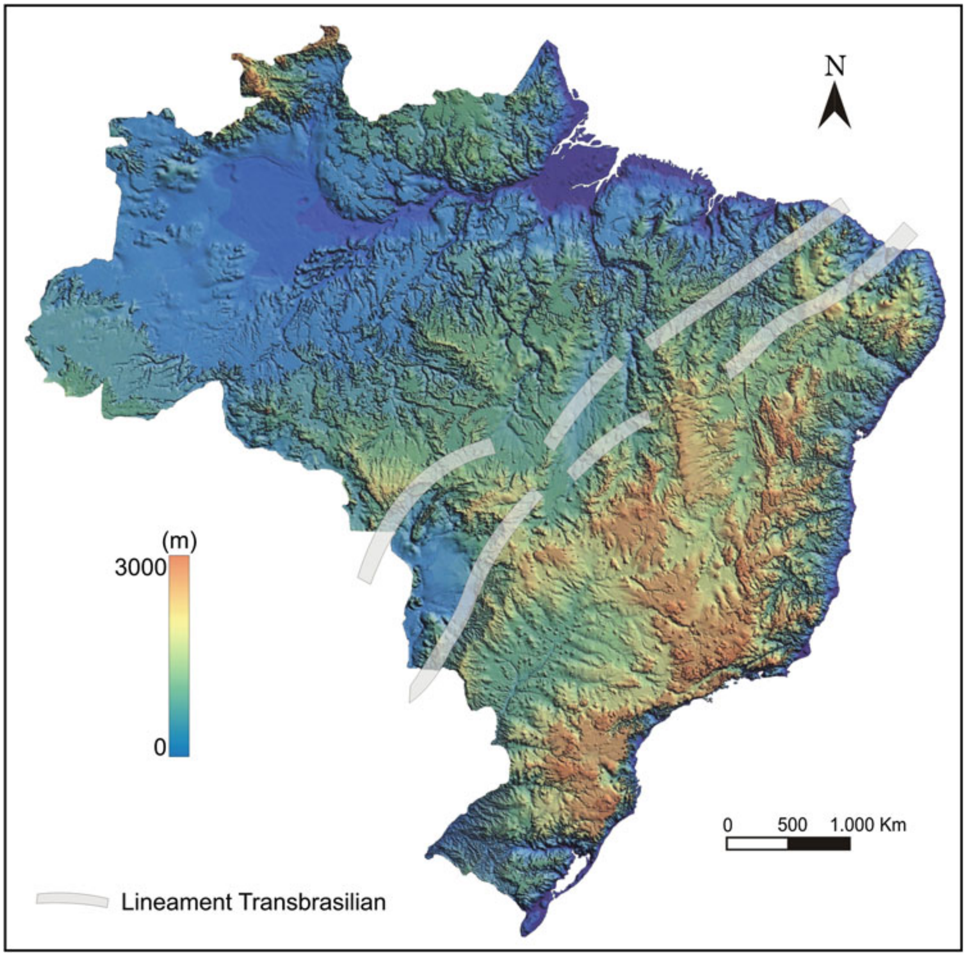

Fig. 3.2 Digital elevation model (DEM) of Brazil and the Transbrasiliano Lineament. Adapted from J.B.L.Françolin (not published) and from Saadi et al. (2005)

depressions whose contacts are marked by the escarpment faces of cuestas (Ross 1985). The upper elevations of the basin are supported by basaltic flows, primarily overlying the cuestas. These higher portions of the basin form horizontal, flattened terraces that are inclined towards depressions located within the highlands. The highest elevations of these landforms are approximately between 900 and 1,500 m above sea level, whereas the depressions are at approximately 600–900 m in elevation in the east and approximately 200 m in elevation in the south.

3.2.2 The São Francisco Craton

The São Francisco Craton (Fig. 3.4) is the western portion of a large craton that was broken in two with the Gondwana break and subsequent opening of the Atlantic Ocean (Trompette et al. 1992; Alkimin and Marshak 1998). The eastern portion of the craton remained in Africa and is known as the Congo Craton. The São Francisco Craton is further subdivided into two compartments (Alkimin and Marshak 1998): the southwestern portion and the northeastern portion, which in some studies is recognised as an independent cratonic area called the Salvador Craton (Trompette et al. 1992).

The main substrate of the São Francisco Craton is the Bambuí Group, which formed as an association of siliciclastic and biochemical lithofacies (Iglesias and Uhlein 2009) with a high occurrence of carbonate rocks. Most of the rocks within the São Francisco Craton exhibit little deformation, which is consistent with the relatively low level of tectonic activity that has occurred in the area since its individualisation as a cratonic area. The boundaries of the São Francisco Craton are currently scarped along a contact with the Araçuaí and Tocantins orogens and are almost entirely coincident with the boundaries of the São Francisco River hydrographic basin. Most of the karst relief in Brazil is concentrated on the western and eastern margins of the São Francisco Craton.

Because of its relatively high tectonic stability, the São Francisco Craton is known as one of the areas with the highest occurrence of planation surfaces in Brazil. King (1956) was the first researcher to identify these surfaces. Based primarily on topographic criteria, he identified the

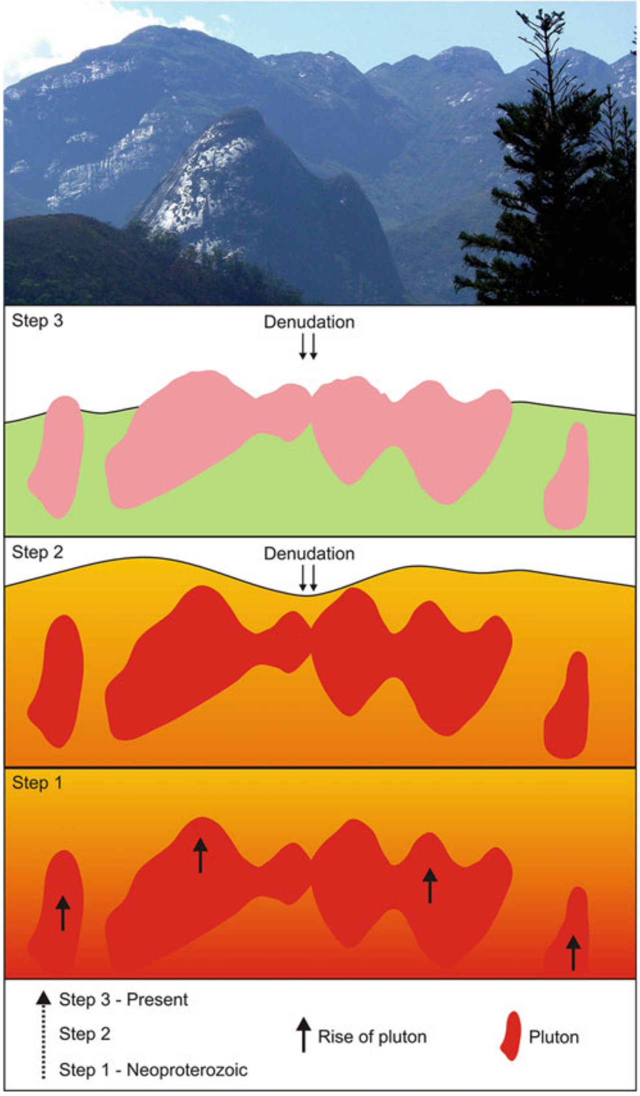

Fig. 3.3 Genesis of the sugar loaves at Serra do Mar in Petrópolis, Rio de Janeiro, southeastern Brazil (Photo by Ronald Salgado and Draw by Breno Marent)

existence of five different planation cycles on the edges and within the interior of the craton: Gondwana (Lower Cretaceous), post-Gondwana (Upper Cretaceous), South American (Palaeocene to Miocene), Velhas (Pliocene) and Paraguaçu (Pleistocene). More recent studies have questioned the existence of these surfaces (Varajão 1991; Valadão 1998), although there is a consensus regarding the existence of the South American Surface. According to Valadão (1998), this surface is not only spatially extensive but was also carved over a long period of time, continuing to develop from the Cretaceous through the Middle Miocene. (Valadão 1998) also suggested that epeirogenic uplift in the Miocene and Late Pliocene facilitated the formation of two other surfaces embedded in the South American Surface: (i) a surface dating from the Miocene through the Pliocene, known as South American Surface I and (ii) a surface dating from the Pleistocene, known as South American Surface II.

3.2.3 Mantiqueira/Araçuaí Orogen

The Mantiqueira Orogen can be described as a large system that contains two main orogens (Fig. 3.4): (i) Araçuaí to the north and (ii) Ribeira to the south. The Araçuaí Orogen formed during the Brasiliano/Pan-African Cycle approximately 600 Mya (Trompette et al. 1992; Alkimin and Marshak 1998) as a result of tectonic forces acting from east to west. This orogen consists of two compartments: (i) a western compartment that represents the collision front with the São Francisco Craton (Serra do Espinhaço) and (ii) an eastern compartment that represents the land closer to the coast, which mainly comprises crystalline basement outcrops.

The elevation in the western compartment, the Serra do Espinhaço, occasionally reaches more than 2,000 m above sea level. These high elevations are the result of uplift that occurred on the collision front of the old orogen and the high resistance of the substrate (which is primarily quartzite) to erosion and denudational processes over time (Barreto et al. 2013). The mountains currently present the morphology of a highly faulted and fractured quartzite plateau, with elevations primarily between 1,200 and 1,500 m. Several residual masses stand out throughout the plateau, occasionally reaching hundreds of meters in height (Fig. 3.5).

Lower elevation landforms that primarily developed over granite–gneiss are predominant in the eastern portion of the Araçuaí Orogen. Acting upon these rock types in the southeast portion of the orogen, the humid tropical climate combined with increased tectonic activity has created a “sea of hills” landscape. The primary characteristics of this type of landscape are the presence of hills of a “half orange” shape. However, particularly in areas closer to the Atlantic coast, greater tectonic activity in the shear zones combined with differential erosion has exposed granite plutons. The plutons, which are substantially more resistant than the surrounding rocks (Salgado et al. 2014), appear in the landscape in the form of sugar loaves (Fig. 3.3). In the northeastern region of the Atlantic compartment of the Araçuaí Range, the relatively low level of tectonic activity combined with a drier climate has resulted in a topography of large flat surfaces with staggered areas of higher elevation. Even within this levelled landscape, granite plutons have been exposed in the shear zones. In these regions, the plutons have formed sugar loaves. However, their height is less prominent (Fig. 3.6).

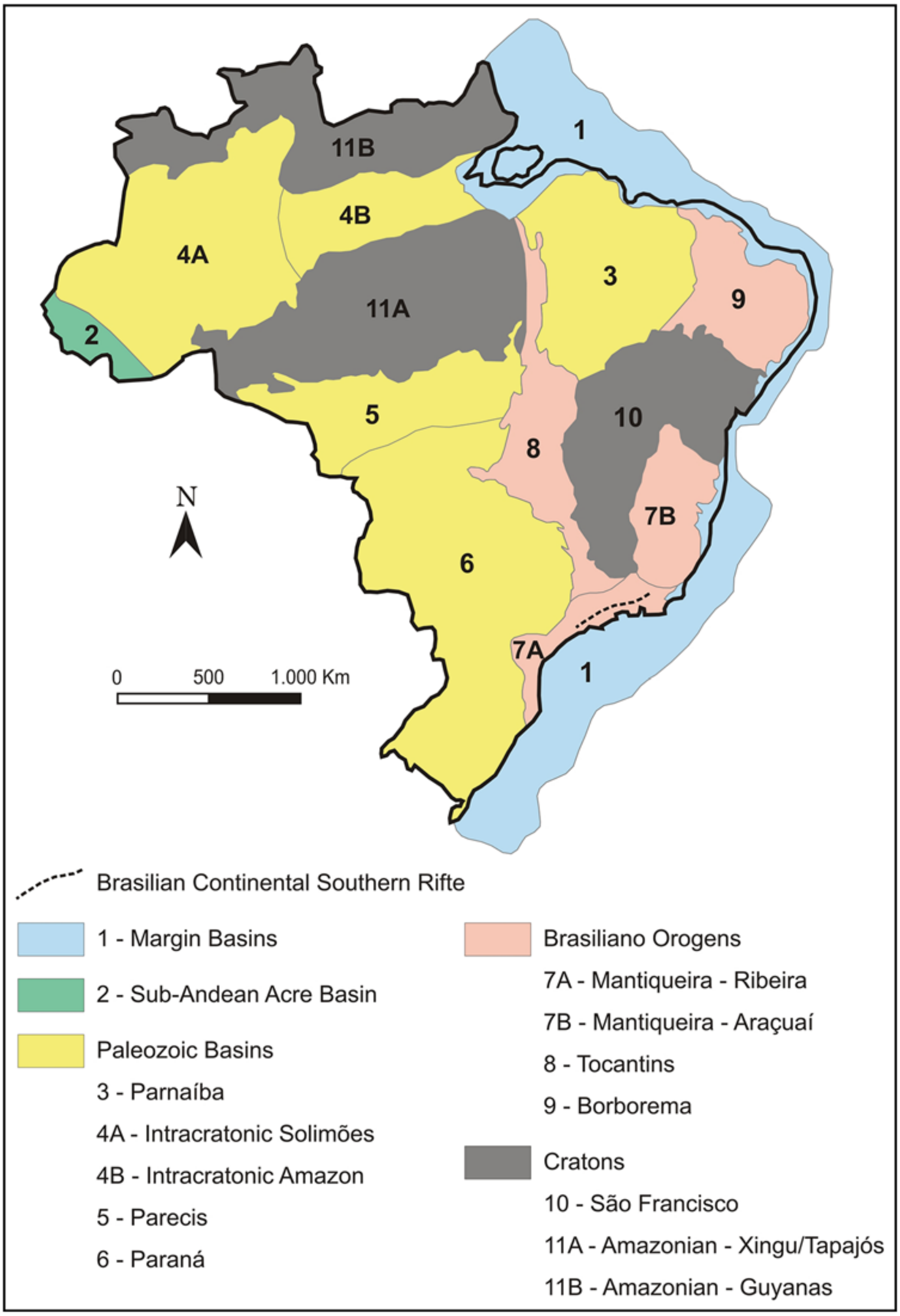

Fig. 3.4 Simplified map of the geotectonic mega-units of Brazil

3.2.4 Mantiqueira/Ribeira Orogen

To the south of the Mantiqueira system is the old Ribeira Orogen. This orogen is mainly composed of a system of blocks separated by transcurrent faults oriented to the northeast. The orogen generally exhibits a "sea of hills" relief. However, the opening of the South Atlantic Ocean and the subsequent uplifting of the Serra do Mar have made the landscape highly complex.

The Serra do Mar is a typical divergent continental margin scarp (Summerfield 1991), approximately 1,000 km long and located along the southern and southeastern coast of Brazil (Almeida and Carneiro 1998). The elevation of the scarp ranges from approximately 800 to 2,000 m at its

Fig. 3.5 Typical landscape in the Serra do Espinhaço, State of Minas Gerais, southeastern Brazil: **a** quartzite outcropping on the surface (foreground) and scarps (regional dip from west to east) generated by the folded relief (background); **b** wavy relief typical of the eastern edge of the São Francisco Craton (foreground) and the highly faulted and fractured quartzite scarp (background), which is the front of the ancient orogen

highest point. The events that resulted in the uplift of the scarp began during the Jurassic with the beginning of the separation of Africa and South America and the subsequent emergence of the Atlantic Ocean (Hackspacher et al. 2004; Hiruma et al. 2010). This event was polycyclic, predominantly distensional and with movements of a transcurrent, compressional or long-term mixed nature (Conceição et al. 1988). In addition, the plates experienced rotational movement around an axis, which caused crustal stretching of the areas farther from the centre of rotation. These forces were felt with greater intensity in the southern–southeastern region than in the northeastern region of Brazil because the northeastern area was located at a greater distance from the rotation axis of the plates (Macedo 1989).

The Mesozoic separation was a South Atlantic event that generated distensional forces, developing normal faults in blocks (Macedo 1989) and reactivating old tectonic structures of the basement consolidated since the Brasiliano/Pan-African Cycle (Almeida and Carneiro 1998). The previously mentioned opening of the South Atlantic, which lasted from the Jurassic to the Late Cretaceous, included the following stages: thermal uplift; generation of fissures leading to the emergence of basaltic flows; thinning of the crust with the emergence of depressed areas, which formed the Santos basin; and thermal subsidence in the Santos basin, which caused tilting of the platform and the formation of a broad topographic feature (uplifting of the Proto-Serra do Mar) parallel to the coast (Macedo 1989).

A tectonic event that began in the Palaeocene caused flexures and faults in this Proto-Serra do Mar, which resulted in the uplift of the western block and the abatement of the eastern block along the Santos Fault (Almeida and Carneiro 1998). Subsequently, as a result of intense erosion, the margin of the uplifted western block retreated approximately 40 km westward to its current position. In addition, the intense erosion exhumed the granite plutons in the Serra do

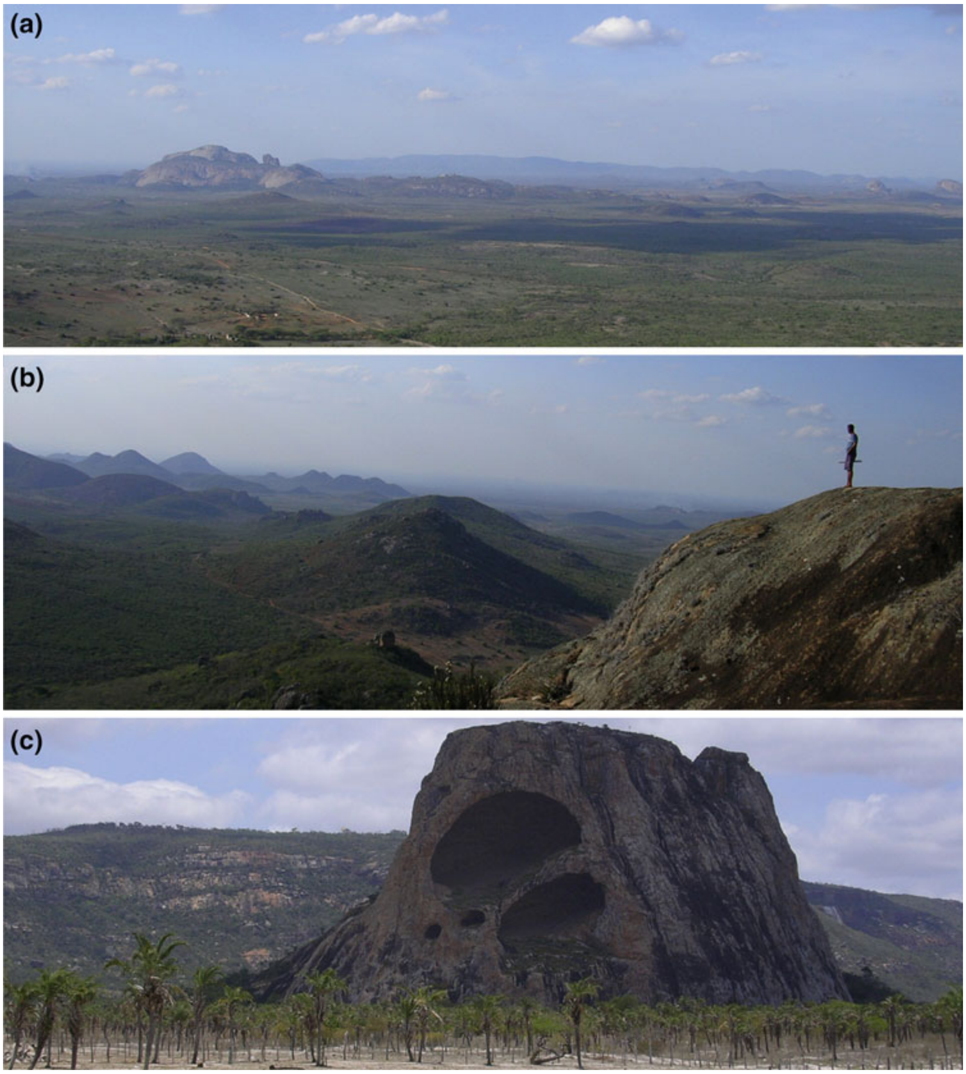

Fig. 3.6 Planed surface with sugar loaves in the form of inselbergs in the semi-arid region of the state of Bahia, eastern Brazil: **a** panoramic view of the flattened surface with inselbergs in the background; **b** cluster of inselbergs; **c** granite inselberg in detail, exhibiting the presence of cavities in its surface, which are common in inselbergs in the region

Mar. Because the granite is more resistant to weathering than the gneiss–migmatites that surround it (Salgado et al. 2014), the granite stands out in the landscape in the form of "sugar loaves" (Fig. 3.3). This gave the region its characteristic appearance of a steep mountain range, which follows the Brazilian southern and southeastern coast.

3.2.5 Tertiary Rifts: Continental Rift of Southeastern Brazil

Small Tertiary rifts occur associated with the Ribeira Orogen in the southeastern region of Brazil between the cities of Rio de Janeiro and São Paulo. In geomorphological terms, these rifts are grouped into a single unit called the Continental Rift of Southeastern Brazil (Fig. 3.4).

The genesis of the rifts appears to be related to the final stages of the evolution of the Serra do Mar. In summary, extensional deformation and the uplift and abatement of crustal blocks related to the tectonic evolution of the Serra do Mar appear to have formed the Continental Rift of Southeastern Brazil (Riccomini et al. 2004). That is, the genesis of the Tertiary rifts is linked to the gravitational collapse of blocks within a faulted mega-plateau, which created rifts parallel to the coast. During this period, isostatic adjustment most likely uplifted the blocks by hundreds of metres causing them not to collapse (Zalán and Oliveira 2005). According to Riccomini et al. (2004), these uplifts are associated with Neoproterozoic shear zones that were reactivated as normal faults with a preferential northeast direction and generated the basins that comprise the Continental Rift of Southeastern Brazil. In addition, this process supposedly contributed to the uplift of the Serra da Mantiqueira.

The relief formed by the rifts is a direct result of the geotectonic history described above and the predominance of a humid climate. Thus, although there are areas with a less dissected relief in the region, the relatively high humidity favoured the genesis of "sea of hills" areas within the

Continental Rift of Southeastern Brazil. Furthermore, it should be noted that both the rift's southeastern shoulder (Serra do Mar) and its northwestern shoulder (Serra da Mantiqueira) are highly prominent in the landscape and separated from the interior of the rift by extensive scarps that are typically over 1,000 m high.

3.2.6 Borborema Orogen

The Borborema Orogen (Fig. 3.4) consists of a complex core of folded crystalline rocks and is characterised by the Brasiliano transcurrent faults and shear zones, which have a preferential east/west and northeast/southwest direction. Although the Borborema Orogen was affected by the opening of the Atlantic Ocean, the evolution of relief in this orogen was less affected than in the Mantiqueira Orogen. However, the Cretaceous uplift caused by the continental separation of South America and Africa clearly affected the evolution of the relief of this region (Peulvast and Sales 2004), which is characterised by smooth plateaus and broad flattened surfaces.

A semi-arid climate currently predominates in this region, and the planed surfaces are separated from one another by steps in the relief, with the oldest surfaces being topographically higher than the younger ones. Based on primarily topographic criteria, Bigarella and Andrade (1964) recognised four surfaces in the region that corresponded with those identified by (King 1956) in the São Francisco Craton. The oldest surface was related to Gondwana, and the other surfaces corresponded sequentially to the surfaces identified by (King 1956), such as the South American, Velhas and Paraguaçu surfaces. However, in the region of Chapada do Araripe in the State of Ceará, (Peulvast and Sales 2004) identified only two main levels of planed surfaces: high surfaces between 700 and 1,000 m above sea level and low surfaces, usually below 300 m in elevation and connected to coastal surfaces.

Morphologically, these surfaces show typical characteristics of erosional surfaces in arid and semi-arid regions, such as the presence of inselbergs (usually granitic), playas and pediments (Byran 1922; King 1953). However, the surfaces are not always completely flattened and are often slightly dissected or tilted (Peulvast and Sales 2004).

3.2.7 Atlantic Marginal Basins

In Atlantic Brazil, the Atlantic marginal basins deserve further description. Their origins are related to the formation of the passive margin of South America after the opening of the South Atlantic. For the most part, the marginal basins are submerged. However, at some points along Brazil's Atlantic coast, primarily along the coast of the northeastern region, there is a narrow emerged stretch (Fig. 3.4).

In the emerged areas, the basins are morphologically characterised by the occurrence of coastal coastaltablelands formed on the Barreiras Group. This group of sedimentary origin is attributed to the Miocene to Pliocene–Pleistocene period and occurs along nearly the entire coast of Brazil, from the state of Amapá in the northern part of the Amazon to the state of Rio de Janeiro in the central-southern region of the country. Although sandy materials predominate, the Barreiras Group is composed of a range of materials of varying particle sizes that range from coarse gravels to clayey facies. Traditionally, the origin of these sediments has been attributed to erosion of crystalline rocks of the continent inland (Furrier et al. 2006), and their deposition was thought to have occurred in a setting typical of tropical semi-arid climatic regions, such as alluvial fans or braided river systems. However, the origins of this group are now more controversial, and some studies demonstrate that the group originated in transitional and shallow marine environments (Arai 2006; Rossetti 2006). Nevertheless, tectonics have undeniably acted on the Barreiras Group (Furrier et al. 2006; Lima et al. 2006; Nogueira et al. 2006), contributing to the uplift of the tablelands and the increasing elevation moving from the coast to inland as a result of the crustal arch.

3.2.8 Tocantins Orogen: Transition Between the "Amazonian Brazil" and the "Extra-Amazonian Brazil"

The Tocantins Orogen lies only partially in Atlantic Brazil because it is crossed by the Transbrasiliano Lineament and is located on the southeastern margin of the Amazonian Craton and the western margin of the São Francisco Craton (Fig. 3.4). The portion located along the São Francisco Craton within Atlantic Brazil is primarily composed of the Brasília Belt. In lithologic terms, this region consists of a series of Proterozoic metasedimentary covers and areas of crystalline basement outcrops (particularly at the contact with the São Francisco Craton) and the occurrence of carbonate rocks from the Bambuí Group. The presence of the carbonate rocks makes this region one of the most important karst provinces of Brazil.

It is believed that during the formation of the Tocantins Orogen during the Brasiliano, the orogen reached dimensions similar to the modern Himalayas. However, after the initial formation, erosional and denudational processes prevailed. Thus, the current relief is characterised by a series of slightly dissected plateaus and tablelands. However, in several areas along the contact between this orogen and the

São Francisco Craton, particularly where the rocks are more susceptible to erosion, the highest surfaces of the Brasília belt are being eroded by the headwaters of the rivers that drain into the interior of the São Francisco Craton.

3.3 Long-Term Geomorphological Evolution of Amazonian Brazil

The extensive cover of rainforest and the relatively small occurrence of exposed and well-dissected shields give Amazonian Brazil the appearance of a homogeneous landscape lacking geomorphic diversity. The Amazonian landscape contrasts with the more varied relief of Extra-Amazonian Brazil, clearly evidencing the distinct geomorphological histories of the two compartments of Brazil. The relief in Amazonian Brazil is predominantly characterised by gentle topography with elevations below 500 m. Vast floodplains arranged in wide alluvial gutters are embedded in an even larger area of low Tertiary plateaus ("tabuleiros") that constitute the Amazonian landscape. The plains and the low plateaus are associated with crystalline terrain downgraded by Neogene pediplanation and slightly cuestiform hills that correspond to exposed Palaeozoic deposits (Ab'Saber 2004). This entire area of lowlands is surrounded by the inland concavity of the Andean and sub-Andean regions and by the Brazilian and Guyana Highlands.

It is not necessary to resort to the distant past to understand the geomorphological evolution of Amazonian Brazil because the geomorphological history of the region is primarily Cenozoic. However, the Amazonian Craton should be described (Almeida et al. 1976) because its ancient structure is an important developmental aspect of relief in this region. The Amazonian Craton is the fundamental basement of the large area located west and north of the wide Transamazônico Lineament (Schobbenhaus et al. 1975) that separates Atlantic Brazil and Amazonian Brazil, according to (Saadi et al. 2005) (Fig. 3.1). This craton is divided into two main structural provinces: the southern Guyana Shield to the north and Xingu or Tapajós to the south (Pires 1999). The two provinces generally exhibit folded and metamorphosed rocks and granitoids, and the most common lithologies are gneisses, migmatites, amphibolites, granites and gabbros (Schobbenhaus and Campos 1984).

Beginning in the Ordovician, distensional movements generated graben structures, which created depressed zones within the South American Platform. These areas began to receive sediments, initially marine and later continental, giving rise to large intracratonic sedimentary basins (Schobbenhaus and Campos 1984; Pires 1999). Four of the five main basins in Brazil (the exception is the Paraná basin) are west or north of the Transbrasiliano Lineament, including the Amazon, Parnaíba, Alto Tapajós and Parecis-Alto Xingu basins. The sediments deposited in these basins, which are relatively similar among the basins, were predominantly quartz sandstones, siltstones and shales, limestones and conglomerates (Schobbenhaus and Campos 1984). Sedimentation continued until the end of the Jurassic, when the South Atlantean event began. This event included basic magmatism (basaltic flows or diabase dikes), the formation of grabens and epeirogenetic movements of the South American platform.

An extensive post-Cretaceous uplift was responsible for elevating the central highlands, which lifted the crystalline shield and the Palaeo-Mesozoic sediments of the Parecis–Alto Xingu intracratonic basin to hundreds of metres in altitude. These high surfaces formed the relief of the highlands of central Brazil and established, on the continental scale, the divisions between the Amazon, Paraná and São Francisco hydrographic basins (Ab'Saber 1964). The Pantanal Mato-Grossense region, which was affected by post-Cretaceous uplift, functioned as an important watershed divide and supplied sediment to the high Paraná basin and the Parecis-Alto Xingu basin. This macroinversion of topographic positions did not occur through epeirogenic arching alone but through the association of epeirogenic arching with vertical movements and eventual faulting. The asymmetry of these uplifts ensured the tectonic individuality of the two large shields that border the Amazon Basin: the Guyana Shield and the Brazilian Shield (Ab'Saber 2004) (Fig. 3.4).

From the Late Cretaceous, a portion of the Amazon region remained relatively depressed, and sedimentation prevailed in its interior. Costa et al. (1996) identified the Eocene–Oligocene as a period of tectonic stability in the Amazon, which was marked by the development of well-developed lateritic profiles and bauxite duricrusts (Aleva 1979), particularly in the Amazon (Alter do Chão Formation), Marajó (part of the post-Rift sequence) and Parnaíba (Ipixuna Formation) basins. The Tertiary sedimentation was linked by Costa et al. (1996) to the final manifestations of the South Atlantean event (Schobbenhaus and Campos 1984) and the "Wealdenian Reactivation" (Almeida 1967), which was extensional in character.

The Tertiary period, particularly the Neogene, was marked by interspersed phases of erosion and sedimentation. These processes created the conditions for the formation of a broad detrital basin with an axis dipping to the east and the establishment of the Great Amazon River (Ab'Saber 2004). The Andean orogeny, which began in the Cretaceous but had greater intensity from the Oligocene to the end of the Miocene, did not directly affect the Brazilian landscape.

However, it was reflected in the epeirogenic movements of the platform, the establishment of new sediment source areas and the reorganisation of the drainage network. An intense orogeny pulse between 25 and 15 Mya (compressional tectonic episode Quechua I) induced the deposition of the sediments of the Solimões Formation (Noble et al. 1990; Campbell et al. 2006; Hoorn et al. 2010), which is one of the world's largest continental deposits (Sampaio and Northfleet 1973). These deposits are distributed throughout the western Brazilian Amazon.

At that time, the drainage network of the central part of the Brazilian Amazon was oriented to the west towards a system of lakes (Hoorn et al. 2010). After the depositional event, a stable phase allowed the formation of a broad flattened surface at the pan-Amazonian scale (Campbell et al. 2006) that truncated the various exposed lithologies. Calcite bands and nodules in outcrops of this palaeosurface indicate that the palaeoclimate was drier than the current climate (Gross et al. 2011). The flattened surface corresponds to the general level of the top of the low Amazonian plateau, which is located a few tens of metres above river level and dominates the landscape of central Amazonia. Two types of residual relief stand out from the flattened surface: "Sugar Loaves" pontoons (Fig. 3.7) that are hundreds of metres high and located in the areas of intrusive granitoids of the Guyana Shield in addition to lower elevation hills and mesas (Fig. 3.8), occasionally with ferruginous duricrusts that are relicts of old flattened surfaces. Thus, many "sugar loaves" and isolated mountainous lineaments occur in this extensive forested region, such as the Serra do Curicuriari (Fig. 3.7) in the upper Rio Negro, which reaches approximately 1,000 m in altitude; Serra do Uranari (260 m high); and the "pedra de Cucuí", which is over 400 m high.

Between 9.5 and 9 Mya, a new orogenic pulse (Quechua II) uplifted the cordillera (Campbell et al. 2006) and again favoured the intensification of erosion. Continental sediments in fluvial–lacustrine and deltaic environments (Içá Formation) were deposited on the flattened surface of the low plateau in the central-western Amazon (CPRM 2006). The high elevations of the Andean chain blocked

Fig. 3.7 Pontoons (Sugar Loaves) of intrusive granitoids in Serra do Curicuriari, located in the municipality of São Gabriel da Cachoeira, Amazonas

Fig. 3.8 Mesa residual relief standing out in the area of low plateaus, which is typical of the upper Rio Negro basin, state of Amazonas

atmospheric circulation from the east, which contributed to the establishment of humid climatic conditions, particularly in the western part of the basin. The opening of the drainage of the central part of the basin to the east (the Atlantic) occurred approximately 2.5 Mya, and the river network of the modern Amazon was reorganised. The deposition in fluvial–lacustrine and deltaic environments of Içá formation ended during the Pliocene, and erosion began to predominate over sedimentation (Campbell et al. 2006; Latrubesse et al. 2010). A network of small streams (locally known as igarapés) began to dissect the edge of the surface of the low plateaus, from the main drainage axes towards the interfluves, which generated a relief of hills with flat or convex tops.

In the central part of the interfluves of the low plateaus, hydromorphic zones developed because of poor drainage and high rainfall. Geochemical losses in these areas formed depressed, wide and shallow zones associated with Gleysols and Spodosols (Nascimento et al. 2004; Fritsch et al. 2006). Shorter, more open vegetation cover was established on these substrates. In the extreme northwestern region of the Brazilian Amazon, where rainfall exceeds 3,000 mm/year, these depressions occupy virtually the entire surface of the low plateaus, which causes geochemical lowering and planation of the surface (Dubroeucq and Volkoff 1998).

With the exception of the sediments of Andean origin, most of the sediments deposited in the Amazonian Brazil basins may have been derived from the lowering of the Guyana and Brazilian shields. The flattening of the crystalline terrain can be explained by the combined action of regional subsidence and inter-tropical pediplanation. For example, the Pantanal basin, with altitudes between 90 and 200 m, is a large area of sedimentation and flooding, whose source area is the Brazilian highlands, which surround the basin. This basin was formed by subsidence as a result of distensional forces in the Chaco foreland basin, a reflection of the last compressional forces of the Andean orogeny (Ussami et al. 1999). A sedimentary system governed by the Paraguay River developed in the depressed zone, with which several depositional features (fans, alluvial plains and lakes) are associated.

Many regions of Amazonian Brazil are marked by the deposition of sediments influenced by changes in sea level during the Quaternary, particularly during the late Pleistocene and the Holocene. The large geomorphological structures that resulted from this process can easily be observed and form landscapes of rare beauty. The Anavilhanas and Mariuá archipelagos are the result of this depositional process. According to Latrubesse and Franzinelli (2005), the tectonically controlled valleys and the rise of base levels produced hydrogeomorphological conditions along the Rio Negro that are responsible for the creation of these stunning river archipelagos.

3.4 Conclusion

Brazil has a great diversity of geomorphological landscapes. This diversity originated during the Brasiliano/Pan-African Cycle (of Neoproterozoic age), because during this cycle, the structure of the geocompartments that comprise modern-day Brazil was determined. The compartments include sedimentary basins, ancient orogens and cratons that were subjected to varied tectonic and climatic conditions through geological time. However, despite this diversity, at a large scale, the Brazilian relief can be subdivided into two mega-compartments: (1) Atlantic Brazil, which is primarily structured by old orogens, has a more diversified relief and altitudes that are often greater than 500 m above sea level and (2) Amazonian Brazil, which is primarily cratonic with a less diversified relief and altitudes that are generally lower than 500 m.

Atlantic Brazil, or Extra-Amazonian Brazil, has a diversity of landscapes that are structured by different geotectonic compartments, including the Paraná Basin, the São Francisco Craton, the Mantiqueira/Araçuaí, Mantiqueira/Ribeira, Borborema and Tocantins orogens, the Tertiary rifts and the Atlantic Marginal Basins. In Amazonian Brazil, the formation of wide floodplains and low plateaus produced a landscape with gentle topography. Associated with these plains and low plateaus are crystalline terrains lowered through Neogene pediplanation and slightly cuestiform hills that correspond to the exposed areas of Palaeozoic terrains. Two types of residual relief stand out from the flattened surface: pontoons (Sugar Loaves) with altitudes of hundreds of metres in areas of intrusive granitoids of the Guyana Shield and hills and mesas of lower altitude, occasionally with ferruginous duricrusts that are relicts of ancient planation surfaces.

Coastal tablelands, karst reliefs, flattened surfaces with inselbergs, “seas of hills”, “sugar loaves”, mountains, tablelands, wide floodplains, low plateaus and mesas and cuesta reliefs indicate the diversity of the Brazilian landscape, which is divided into two geotectonic mega-compartments. Thus, the Amazonian and Atlantic Brazil reveal a complex geological–geomorphological history of a continental-sized country and are therefore highly important for understanding the evolution of the natural landscape of South America.

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Climates of Brazil: Past and Present

4

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Abstract

This chapter describes the climactic patterns that prevailed in the Brazilian territory, particularly in the Quaternary, some observations made by travelers and naturalists, particularly during the colonial historic period, the first systematic studies of climactic geomorphology in Brazil, and, finally, the types of current, regional climates. It is noteworthy that the studies based on geological and climatic events have developed various methods to observe and understand the distinct and beautiful Brazilian landscapes. However, for decades, studies have not used climatic and geomorphological data to effectively contribute to the understanding of the origin and evolution of Brazilian landscapes. This situation may certainly be associated with Brazil's territorial extension, the great geomorphological complexity and absence of data and information climatic and geomorphological data.

Keywords

Past climates • Brazilian climactic domains • Brazilian Quaternary

4.1 The Quaternary in Brazil

Knowledge of the Quaternary in Brazil has evolved significantly, particularly since the 1970s, with the significant advancement of paleovegetational studies and palynological analyses to understand the climactic fluctuations that occurred during the last glaciation. Reflecting this growth, the First Symposium on the Quaternary in Brazil (Primeiro Simpósio do Quaternário no Brasil) was conducted in 1971, and the Technical-Scientific Committee of the Brazilian Society of Quaternary Geology was also created. In 1984, the Brazilian Association for Quaternary Studies (Associação Brasileira de Estudos do Quaternário—ABEQUA) was founded, which later united with the International Union for Quaternary Research (INQUA).

Despite the remaining gaps in the knowledge of paleoenvironments in Brazil, it is known that during the last glacial cycle, an intensification of cold fronts and advancement of polar air shaped a large portion of the landscapes in the current Brazilian territory. According to Oliveira et al. (2005), the current climatobotanical frameworks continue to adjust to these changes.

Throughout the Quaternary glaciations, the Brazilian climates, even those with tropical characteristics, were colder than at present. Between 115,000 and 70,000 BP during the beginning of the last Quaternary glaciation (Würm), the Brazilian territory experienced a period of maximum cold and aridity that had strong repercussions on the vegetation.

Climatic fluctuations were frequent between 70,000 and 22,000 BP with alternating drier and wetter periods. The final cool and arid period began approximately 22,000 years ago and lasted until approximately 14,000 BP, when the

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rainfall and temperatures increased again, thus favoring the return of forests (Thompson et al. 1995). At the end of the last glaciation, Brazil had a smaller forest area than at present, restricted to the western Amazon and patches of temperate forests in the central-south. A wide savanna belt covered the entire central area, and the east of Northeast Region had semiarid climate vegetation (Suguio 1999).

Approximately 10,000 BP, with an increase in temperature and humid climatic conditions, forest formations increased in abundance in the Amazon and central-south (Ledru 1992), and the Atlantic Forest of southeast Brazil was restricted to scattered patches in subhumid areas (Behling 1995). The conditions in the meridional plateau were also drier than at present, the most humid climates were restricted to the area occupied by savannas, and a drier, grassy steppe dominated the central region of Brazil (Fig. 4.1).

The slow retreat of ice sheets was accompanied by warming of the entire planet, and the glacial climates of the meridional sector of the Southern Hemisphere were mitigated but dry. Approximately 8,000–7,000 BP rain returned, which was more torrential, humidifying and making the continental climates milder. The intertropical climate zones were characterized by dryness and the presence of strong winds. Winters were considerably more severe, while summers were much warmer than the present ones.

The warmest interglacial period appears to have occurred between 5,600 and 2,500 BP. This phase is known as the *climatic optimum*, when the Earth was on average 2–3 °C warmer than at present. In Brazil, a drier climate caused the extinction of continental ice, except for high mountain areas. The coldest period of the interglacial occurred during the Iron Age (between 2,500 and 2,000 BP). Southern Brazil experienced the return of severe climate conditions. The second climatic optimum occurred between 200 and 1000 AD, when the most favorable weather conditions (mainly by moisture) caused an increase in forested area (Fig. 4.1). After a short warm period, the temperatures decreased again, and the weather became drier in the so-called Little Ice Age.

4.2 Climates in the Past 500 Years

Little was known about the weather and climate of Brazil before the arrival of Portuguese settlers, as the early inhabitants left no records because they had not yet developed a writing system. Thus, the initial descriptions of past climates

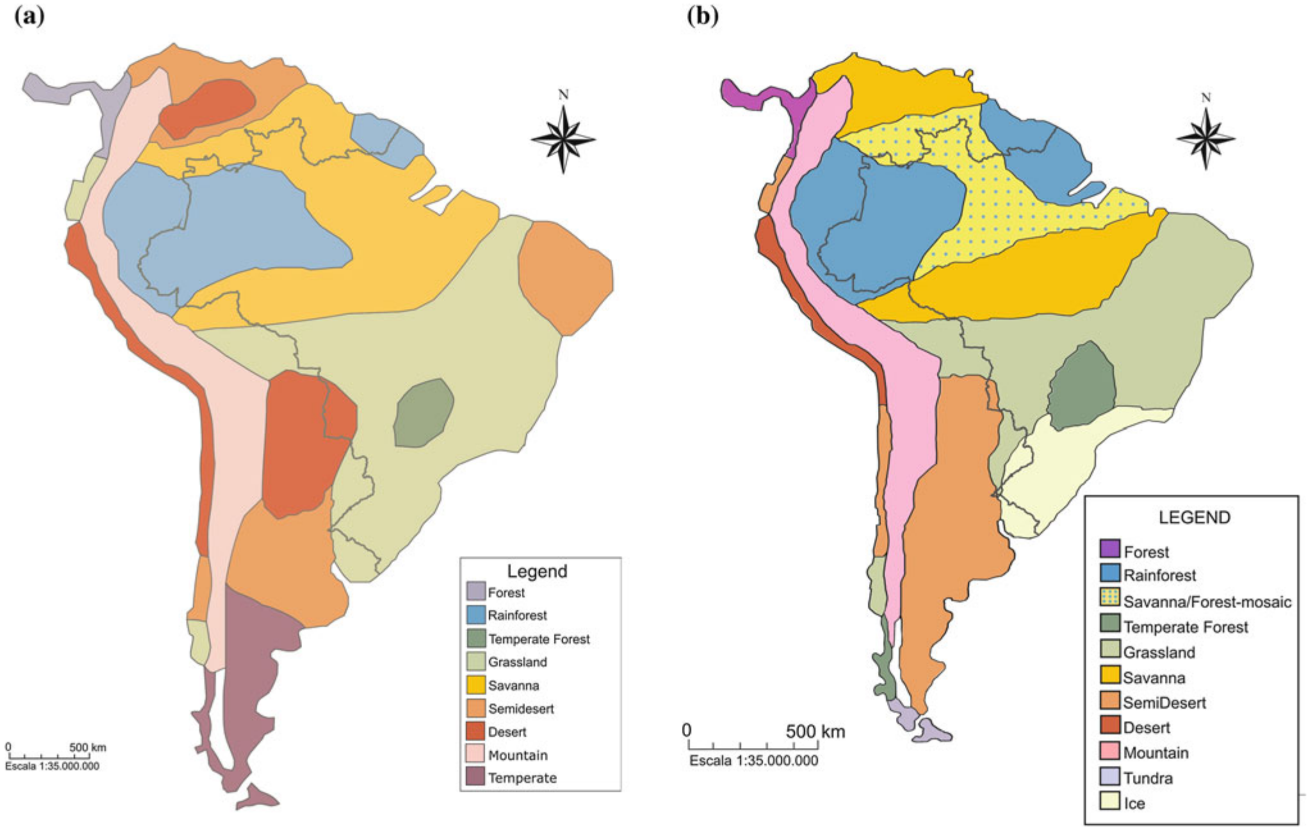

Fig. 4.1 Vegetation complexes in South America at 14,000 and 10,000 BP. Compiled by Jonathan Adams, Environmental Sciences Division, Oak Ridge National Laboratory, TN, USA. **a** South America before the onset of interglacial climates 14,000–13,000 y.a. 14C y.a. **b** South America at the end of last glacial period 10,000 14C y.a.

were only possible from observations of European naturalists and travelers, who had traveled through Brazilian lands between the sixteenth and nineteenth centuries. Such descriptions are important for Brazilian climatology because even with significant advances in paleoclimate studies over the past decades, Brazil has suffered for many years from the absence of climate and paleoclimate data that could have helped clarify relief forms. Thus, even non-scientific observations from the last 500 years have become important to understand climatic variations in the Brazilian territory.

Evidence of cooling in the seventeenth and eighteenth centuries is observed in the reports of travelers and naturalists who traveled over Brazilian land. Georg Marcgrave (a German in the service of the Netherlands–India Company), who lived in Brazil for 6 years (1637–1642), obtained a daily time series between 1640 and 1642 in Recife, Pernambuco, and recorded the conditions of weather, winds, and rains. Marcgrave's contemporary, Johannes de Laet, described another unusual event for that equatorial latitude (approximately 8° south): the penetration of an Atlantic polar anticyclone in winter of that same year. The temperatures dropped so much, particularly in the mountainous region of Pernambuco, that unprecedented cold and a dense fog, which was unusual for this region of Brazil, hit the region unexpectedly. According to Ferraz (1980), this weather conditions appear plausible, and the author stated that "From the point of view of climatology around the globe, this exceptional season fits well in the first period of the so-called Little Ice Age, from 1550 to 1650, in which the general advance of glaciers in the Alps, Scandinavia and Iceland was recorded, and, according to authorities on the subject, also resonated equally in the Southern Hemisphere."

Among Marcgrave's records, wind direction, days with thunder and lightning, and, more specifically, the number of days with precipitation deserve special attention. Because there were no rain gauges to measure rainfall, Marcgrave recorded the days when rainfall occurred and commented on episodes of more intense rainfall. Marcgrave states that in most cases, there were short, fast rains with low intensity (Table 4.1).

Other observations from Marcgrave (1942) referred to the pioneering bioclimatological considerations on the Pernambucan landscape, in which he sought some possible causes and stated that "the unfortunate heat of summer obliges the inhabitants not to cultivate the land. The hills themselves, for those months because of the heat of the sun, are fruitless and dry inside, so that not only every herb but also trees die from time to time and the grass burned once, mainly because the rapid wind furthers the fire in a large area. Thus, they flourish superbly during the rainy season, and die in dry months" (p. 32).

One century later, the first measurements and records of meteorological observations emerge for Brazil. Between 1754 and 1756 in the town of Barcelos in the State of Amazonas, Priest Sermatoni described weather changes based more on feelings than experimentation. In the 1780s, the Portuguese astronomer Sánches Dorta recorded air temperatures in Rio de Janeiro (1781–1788) and São Paulo (1788 and 1789), which were published in the Memoirs of the Academy of Sciences of Lisbon (Memórias da Academia de Ciências de Lisboa) (Sant'anna Neto 2004). All of the data presented demonstrate lower temperatures and less abundant rainfall compared to the climatological normals, thus reinforcing the occurrence of a colder and drier period between the sixteenth and nineteenth centuries.

The German naturalists von Martius and von Spix conducted several measurements of temperature, pressure, and characteristics of tropical rainfall during the first quarter of the nineteenth century. However, the itinerant character of the investigations did not provide longer measurements that covered the entire annual cycle of climate variability. However, the French naturalist and botanist Auguste Saint-Hilaire toured the lands of central-south Brazil for several years between 1816 and 1822 and, in an extremely detailed fashion, observed and noted the fauna, flora, and weather conditions for each area visited. Saint-Hilaire provided descriptions and ventured brilliant explanations for the Brazilian natural framework, which was the result of his undeniable scientific training.

In Saint-Hilaire's reports on weather and climate, he described the extreme episodes related to rainfall (intensity, hail, and snow), temperature (heat waves and frosts) and gales, and storms in considerable detail. On his journey from the province of São Paulo to Rio Grande do Sul State between 1820 and 1821, Saint-Hilaire said that the winter was severe from July to September, and the temperatures

Table 4.1 The number of days with rain

Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1640	12	14	21	22	24	19	26	22	12	11	10	10	203
1641	6	15	13	21	24	18	19	15	8	7	7	13	166
1642	16	9	16	21	19	22	14	16	13	7	7	4	164
1640/2	11	13	17	21	22	20	20	18	11	8	8	9	178
1961/90	13	18	17	18	20	24	25	24	24	17	10	10	220

A comparison with data recorded by Marcgrave (1640/1642) and INMET (1992) for Recife/PE were below 0 °C for several days. Frosts occurred almost every night, and the volume of ice was such that the people gathered to make ice cream (Saint-Hilaire 1974). Saint-Hilaire suggested that the climate of São Paulo best suits "our kind" (referring to Europeans) because the winters were "mild" in addition to being humid (Saint-Hilaire 1976). The author also described the vegetation around the city of São Paulo and commented on the formation of pines, which were distinguished by symmetrical, high tops. Saint-Hilaire mentioned the permanence of wetlands on the Tietê Plain for two to three months, which brought tremendous benefits to farmers at that time, in addition to making the landscape "beautiful."

Saint-Hilaire's commentary on the highest peaks of the mountain region between São Paulo and Rio de Janeiro is notable because he states that one could observe a white cloak of snow in the winter months. The volume of snow was so large that it could replace imports of ice that were transported from Portugal.

According to Araki (2012), the Portuguese Augusto Emílio Zaluar mentions the occurrence of snow in his passage through the Vila de Queluz (now the Paraíba Valley) in September 1859: "this enormous portion of the large Espinhaço mountain range called Mantiqueira, offers a superb perspective from this point, especially for those who examine the western side of the village; from here, some of the highest peaks are observed, such as Itatiaia, which has often been seen covered in snow such as the summit of the Alps."

According to Araki (2012), references to severe cold conditions are recurrent in all sources consulted on weather and climate for the nineteenth century. Until the first half of the nineteenth century, the few periods with meteorological records of the Brazilian territory were from private enterprises, particularly foreigners. Because of the new demands of this young country, which achieved independence from Portugal in 1822, the Imperial Observatory was created in Rio de Janeiro in 1827 to better understand weather and climate and systematize the production of information on the climate of Brazil. Thus, a long process of systematic collection and analysis of meteorological and climatic elements began.

4.3 Geomorphology and Climate: First Systematic Studies

Geomorphological studies in Brazil, which aim to understand the landscapes modeled in past climates, have significantly advanced in recent years. The results of such studies are presented, even if briefly, in the chapters of the second section of this book. Thus, only some of the initial impressions, reports, and scientific observations on the relationship between past climate (particularly the Quaternary) and the different Brazilian landscapes are referred to below.

It is noteworthy that the evolution of Brazilian geomorphology was marked by profound discussions and theoretical formulations regarding the origin of the numerous territorial landscapes. Thus, it would be impossible to discuss all scientific influences that have contributed over the years. Studies based on geological or climatic facts determined the various methods of observing, clarifying, and understanding such distinct and immense Brazilian landscapes, such as Lamego (1950) "Análise tectônica e morfológica do sistema Mantiqueira do Brasil" ("Tectonic and morphological analysis of the Mantiqueira system of Brazil"), Ruellan (1944) "A evolução geomorfológica da Baía da Guanabara e das regiões Circunvizinhas" ("The geomorphological evolution of Guanabara Bay and the surrounding regions"), Azevedo (1949) "O Planalto brasileiro e o problema da classificação de suas formas de relevo" ("The Brazilian Plateau and the problem of classifying its relief forms"), Leuzinger (1948) "Controvérsias Geomorfológicas" ("Geomorphological Controversies"), and King (1956) "A Geomorfologia Oriental do Brasil" ("The Eastern Geomorphology of Brazil").

Geomorphological studies based on climatology were mainly developed from physical geography under the strong influence of the French school from the 1940s to 1960s by studies conducted by Emmanuel de Martonne and Jean Tricart (Suguio 2000).

In the 1930s, Emmanuel de Martonne was Secretary-General of the International Geographical Union (IGU) and conducted several field studies in Brazil, particularly on the morphological problems of Tropical Atlantic Brazil (1943). One of the major contributions of de Martonne (1943) was uncovering a poorly known terrain to elucidate the complexity of morphostructural and morphoclimatic processes on the Atlantic coast of Brazil and the role that the author attributed to the preponderance of rainfall variations to the relief morphology. For de Martonne, the central aspects were the relationships of the relief with the structure and originality of the tropical pattern.

The discoveries of Jean Tricart marked the climate geomorphology studies in Brazil. However, it is important to note that Charles Darwin, in 1841, had mentioned the influence of sea-level fluctuations during the Holocene and the formation of "beach rocks" (*remarkable bar of sandstone*) from the coast of Pernambuco (Suguio 2000). In more recent decades, the works of Ab'Saber (1958) "Conhecimentos sobre as flutuações climáticas ao Quaternário no Brasil" ("Knowledge of the climatic fluctuations in the

Quaternary in Brazil") and Bigarella (1964) "Variações climáticas no Quaternário e suas implicações no revestimento florístico do Paraná" ("Climatic variations in the Quaternary and its implications on the floristic coat of Paraná") are also noteworthy.

Cailleux and Tricart (1957), in their study "*Zones phytogéographiques et morphoclimatiques au Quaternaire au Brésil*" (Phytogeographic and morphoclimatic zones during the Quaternary in Brazil), describe the first paleoclimatic observations in South America based mainly on biogeographic boundaries and geological formations from the Quaternary. In this work, the authors evaluated the possible influence of climate oscillations during the Quaternary in the Brazilian territory. For example, for the Northeast, the authors stated that "the Quaternary geological formations of NE indicate, of course, a relative climatic stability," writing for instance that "In current drier areas, such as around Patos (Paraíba), we did not find accumulated sand due to wind, which would prove the existence of distinctly more arid climates." However, particularly in the states of Rio de Janeiro, Sao Paulo, and Belo Horizonte, their observations showed significant climatic changes, e.g., "(…) around Rio de Janeiro, in the middle valley of Paraíba and the region of the Southern coast of São Paulo, in a current zone of hydrophilic forest, detrital Quaternary glacis appear, dissected in terraces."

Damuth and Fairbridge elaborated the first integrated paleoclimatic interpretation for South America in 1970 (Fig. 4.2) and outlined the likely situations of cold currents during glacial and interglacial periods (Ab'Saber 1977). However, an evaluation on the influence of climate change on Brazilian landscapes began after the research of Bigarella and Ab'Saber (1964), particularly focusing on the cyclicity of relief using geomorphological, sedimentological, and ecological evidence from observations of *geomorphic features* (e.g., pediments and river terraces), *correlative deposits* (e.g., deposits of terraces, piedmont deposits, and paleosols), and *ferruginous crusts* (e.g., local fields of cacti and refuges for flora and fauna).

In southern Brazil, Bigarella et al. (1961) described at least three different levels of detrital and rocky pediments based on sedimentological studies, whose origin was not related to the current humid climate but to more severe past semiarid conditions. Such studies, particularly on the Santa Catarina Mountains, showed the performance of Quaternary semiarid morphoclimatic processes linked to periods of low sea levels and corresponding with glacial periods. According to Bigarella (1964), "the gentle climate fluctuations that were effective in humid phases were responsible for conspicuous erosion and largely for the sculpting of today's topographic landscape. In a forested area subject to a constant humid

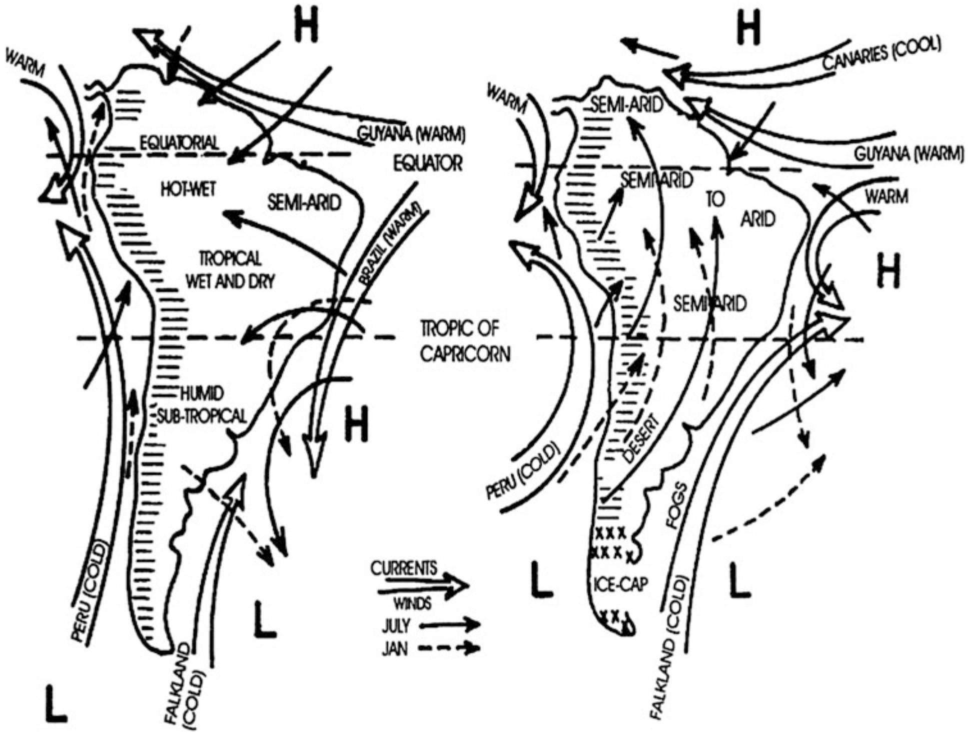

Fig. 4.2 Climatic mechanisms and paleoclimatic differences between the current interglacial period (*left*) and possible glacial situation during the Pleistocene (*right*). Elaborated by Damuth and Fairbridge (1970) cited in Ab'Saber (1977)

climate, small erosion would have been possible in a short time, as were the Pleistocene humid intervals."

In his work "Espaços ocupados pela expansão dos climas secos na América do Sul, por ocasião dos períodos glaciais quaternários" ("Spaces occupied by the expansion of dry climates in South America due to Quaternary glacial periods"), Ab'Saber (1977) defined the natural areas of South American landscapes from 12,000 to 18,000 AP and referred to the last Pleistocene glacial stage by identifying paleospaces occupied by dry climates.

Ab'Saber shows, for example, a trend of Araucaria vegetation moving to lower latitudes toward the high altitudes of the Serra do Mar and Serra da Mantiqueira. This movement also shows that the expansion of scrub penetrated numerous interior compartments of the current Brazilian intertropical plateaus in areas currently containing forests or savannas. Savannas and savanna forests penetrated the eastern and central Amazon. According to the author, "in the space of the Amazonian lowlands, only refuges remain in the old 'islands of moisture' of some more exposed slopes of rounded small mountain ranges and hills, and perhaps in the southwest arch of the Andean slopes, and northern facade of the Guianas." With the return of wet conditions, there was the domain of rainforest/ombrophile forest formation over savanna and savanna over scrub, although savanna enclaves are observed in the Amazon (refuges), Araucaria in the Serra do Mar and Serra da Mantiqueira, scrub in middle São Francisco, middle Araguaia and the Mato Grosso Pantanal, and other species related to semiarid environments of the glacial stages (Ab'Saber 1977).

4.4 Types of Current Regional Climates

On a macro-regional scale, one can consider two large climate controls responsible for climate's action in shaping the relief: the intensity of trade winds (the Amazon and Brazil Tropical Atlantic) and invasions of polar anticyclones (southern Brazil). Variations in ocean water temperatures and cycles of Earth movements cause profound changes in temperature and rainfall conditions in the Brazilian territory (Sant'Anna Neto and Nery 2005).

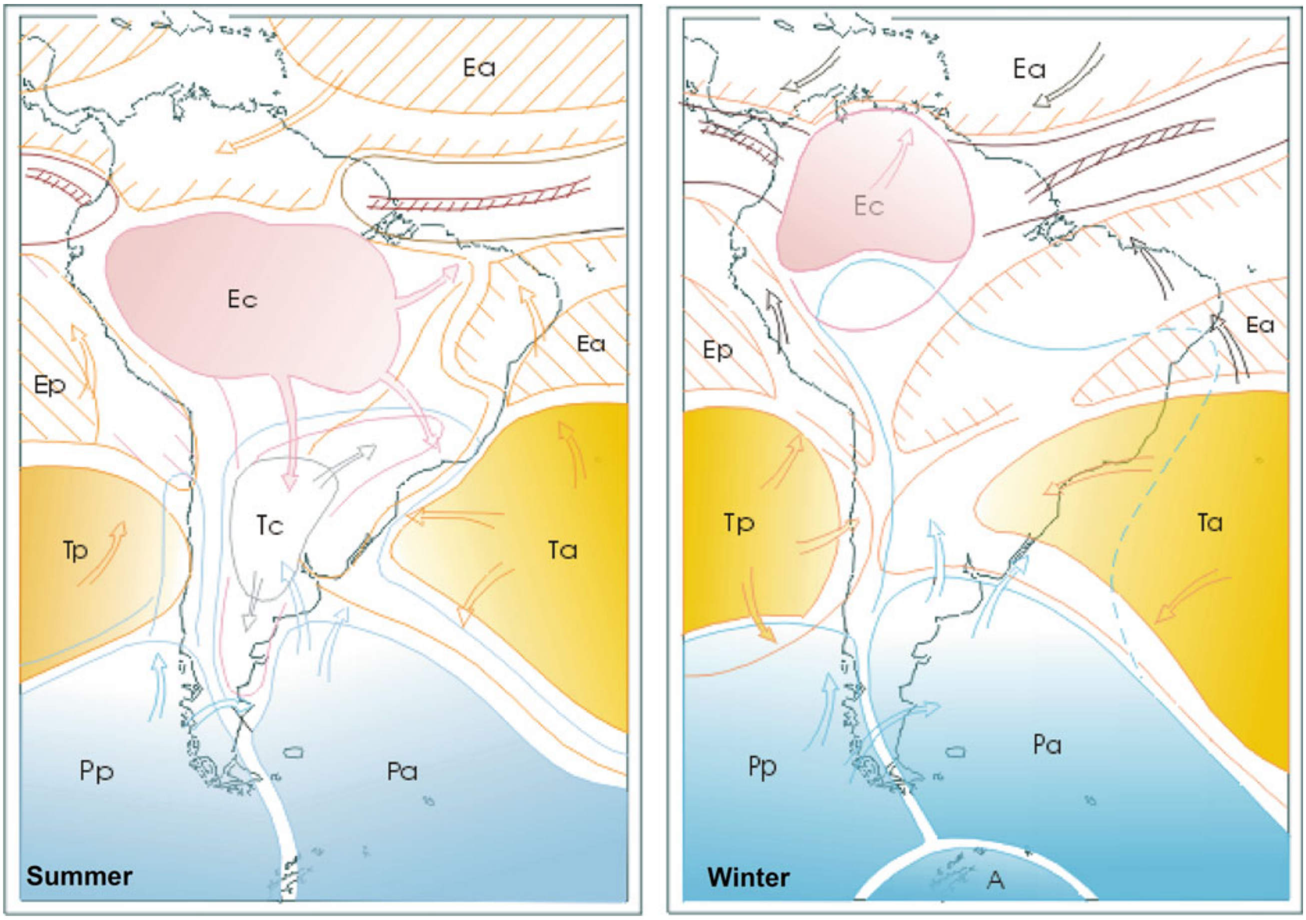

Fig. 4.3 The source areas and trajectories of atmospheric systems in the *summer* (**a**) and *winter* (**b**). *Source* Monteiro 1973 (ed. by Boin 2000)

Because of the geographical position of the Brazilian territory, a diverse range of regional climates is distributed spatially in a manner that characterizes different temperature and rainfall regimes, which are predominantly tropical. The climates of Brazil regionally are multiplies into varieties depending on the coastal shape, altitude, and relief outline. From the perspective of dynamic climatology, the atmosphere above the territory is controlled by both equatorial and tropical systems and polar masses. Five air masses and three large perturbed systems operate more frequently and configure regional climates.

The source areas and trajectories of the main acting atmospheric systems change between summer and winter and modify rainfall more intensely than thermal conditions because of the tropical nature of the area (Fig. 4.3). In summer, continental masses (equatorial—Ec and tropical—Tc) advance over the Northeast, Central-West, and South regions. Polar systems are restricted to the South and produce more rain than cold during this time of year. In winter, the continental masses yield to the ocean masses, which generate days with stable weather stable days. Polar systems cause a drop in temperature in the Central-South and tropical regions and produce rain in the Northeast (Fig. 4.3).

The geographical characteristics of the territory, associated with the genesis and dynamics of the active weather systems, result in abundant rainfall regimes except for the semiarid Northeast. Much of Brazil receives an annual rainfall exceeding 1,200 mm. However, in some cases, such as the central region of Brazil, these rains are heavily concentrated over 3 or 4 months, and because of high temperatures, significant water deficits occur during autumn and winter.

The thermal regime is predominantly tropical with high annual average temperatures (between 20 and 25 °C) and significant seasonal variations in the Central-South Region. Summers are warm across the Brazilian territory, but the highest temperatures in the Northern and Northeastern regions occur in spring (September to November, up to 40 °C) because of a decrease in rainfall. In winter (June to August), the South (because of latitude) and Southeast (because of altitude) regions have relatively low temperatures, when there are incursions of polar systems (8–14 °C winter average, with lowest under 0 °C).

In the Amazon, a hot and rainy humid equatorial climate occurs. In the southernmost region of the country, there is a mesothermal climate, which is often called subtropical humid. In other regions of Brazil, tropical climates prevail,

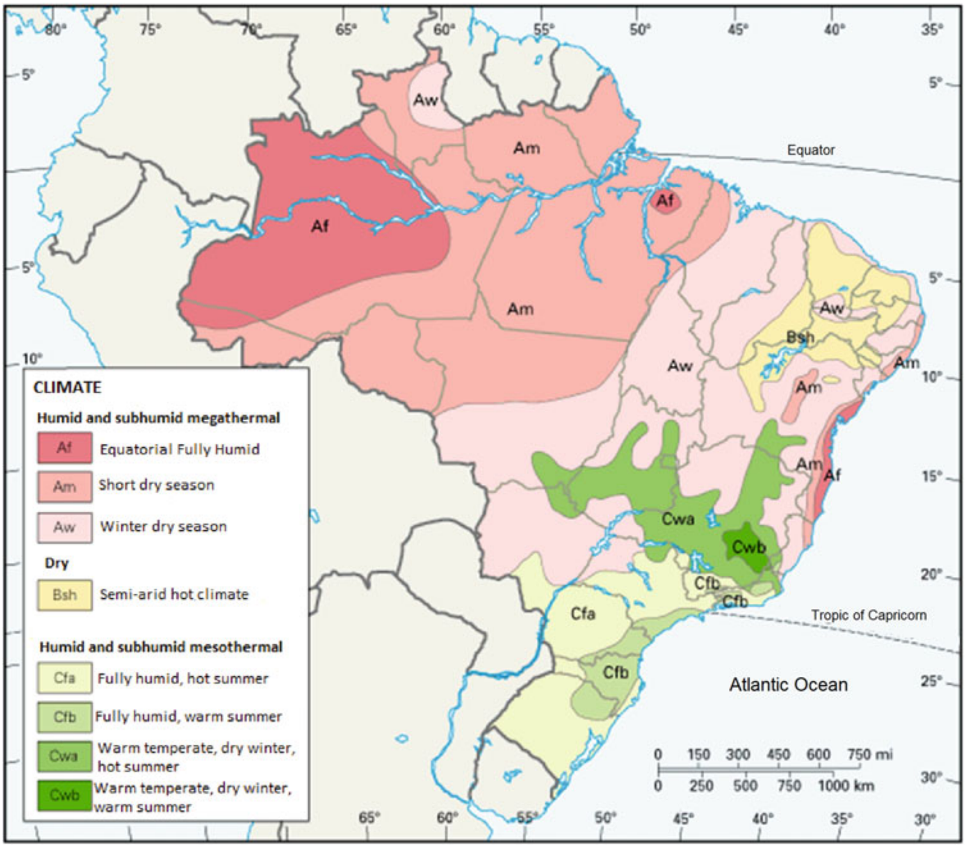

Fig. 4.4 The occurrence of climate types in the Brazilian territory according to Köppen (adapted from Köppen and Geiger 1928)

which are drier in the Northeast Region (semiarid climate), monsoon type in the Central Region (the Central-West Region), tropical of highlands plateau in the Southeast Region, and humid tropical in the eastern coastal zone (Nimer 1989; Conti and Furlan 1996).

Considering the extent of the territory, it is natural to observe a variety of climatic types ranging from hot and dry/humid to cold and humid. In addition to the latitudinal (north to south) and altimetry variations, the effect of maritime/continentality is associated with this diversity of factors. Moreover, the role of the Atlantic polar mass (aPm), which is prevalent in autumn/winter months, is noteworthy and its advances through the Central-South Region of Brazil promotes significant reductions in air temperature.

Köppen proposes an approach that synthesizes climate types, in which—for the territory of Brazil—three climatic types are described: A (subhumid, humid megathermal), B (dry), and C (humid and subhumid mesothermic). Climate type A and its subtypes (Af, Am, and Aw) are manifested over the North Region and partial Central-West, and Northeast regions of Brazil. Climate type B (Bsh) occurs in the semiarid scrub area of the Northeast Region, and type C (Cfa, Cfb, Cwa, and Cwb) occurs particularly in the Southeast and South regions. Figure 4.4 shows the climatic types according to Köppen (adapted from Köppen and Geiger 1928) and considers that the natural vegetation would represent the expression of the region's climate. The modifications and criticism of the system are always related to the thermal/water limitations of certain types of climates for different regions (Rolim et al. 2007).

4.5 Final Considerations

In the early twentieth century, with the establishment of universities and research institutions, a significant network of meteorological posts and stations was formed, which covered most of the Brazilian territory and provided more accurate information for the development of climatological studies. Thus, studies of climate variability and changes in Brazil require greater density of observation stations, so that major weather problems of the past can be elucidated and projections for the future can be attempted.

In the context of global climate change, it can be stated with a certain likelihood of success that the regional climates of Brazil are becoming warmer and rainfall is more concentrated. From the perspective of landscape dynamics, which in recent decades has experienced strong anthropogenic influences, climate change leads to increased fragility and reduced environmental balance and results in an increase in catastrophic events, mainly related to rainfall (floods, erosion, inundations, and landslides).

The rapid deforestation and removal of native vegetation caused by the expansion of agribusiness for soy and sugarcane, the increase in extensive pastures, and the large population increase have systematically pressured Brazilian biomes and landscapes, thus stripping and exposing them to bad weather and allowing catastrophic extreme events to occur with greater frequency and intensity.

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Part II

Extraordinary Landscapes of Brazil

Discovery Coast: The Brazilian Landscape First Sighted by Europeans

5

Carlos César Uchôa de Lima and José Maria Landim Dominguez

Abstract

The Discovery Coast was the first landscape sighted by Portuguese explorers when they arrived in Brazil in 1500. This region's geomorphology is marked by the predominance of coastal tablelands, sustained by Miocene sediments of the Barreiras Formation, which were primarily deposited in tidal plains, tidal channels, and braided river systems. These tablelands are cut by wide, flat-bottomed river valleys and form sea cliffs when they reach the coastline. This last feature was presented in detail in the letter to the king of Portugal that communicated the discovery of Brazil and first described the physical aspects of the Brazilian territory. To the west of the tablelands, there is a mountainous relief sustained by a Precambrian basement, marked by an intricate system of fractures and dominated by siliceous metamorphic rocks. Other geomorphological domain of the Discovery Coast includes the Quaternary plains, which develop locally, beach rocks, and coral reefs. The predominance of flat relief in the tablelands, which is associated with weakness zones and represented by joints and faults related to Quaternary tectonics, promoted a morphogenesis in which tectonic forces tilted structural blocks. This morphogenesis changed the direction of the currents and the drainage pattern that develops along the Discovery Coast.

Keywords

Coastal tablelands • Barreiras formation • Sea cliffs • Quaternary plains • Quaternary tectonics

5.1 Introduction

The Discovery Coast (Fig. 5.1) has unique relevance for Brazil because it is included in the first geomorphological description of the South American continent made by the Portuguese sailors who arrived there in 1500 under the command of Pedro Álvares Cabral. The region has a hot climate with no dry season, an annual rainfall of approximately 2,000 mm Projeto Costa do Descobrimento 2000 (Discovery Coast Project 2000) and a mean annual temperature above 20 °C, which reaches a maximum above 30 °C in summer. Rainfall is concentrated between April and June and is influenced by cold fronts from the south.

Coastal tablelands predominate in the coastal zone (Fig. 5.2). These tablelands are sustained by Miocene sediments (Barreiras Formation), cut by U-shaped river valleys with flat bottoms and steep walls, and separated by horizontal interfluves. The tablelands reach the coastline, forming red and white sea cliffs, which are characteristic of the region. The Quaternary plain is discontinuous and narrow as a result of decreased sediment input to the region. Coral reefs occur along the entire section as do beach rocks.

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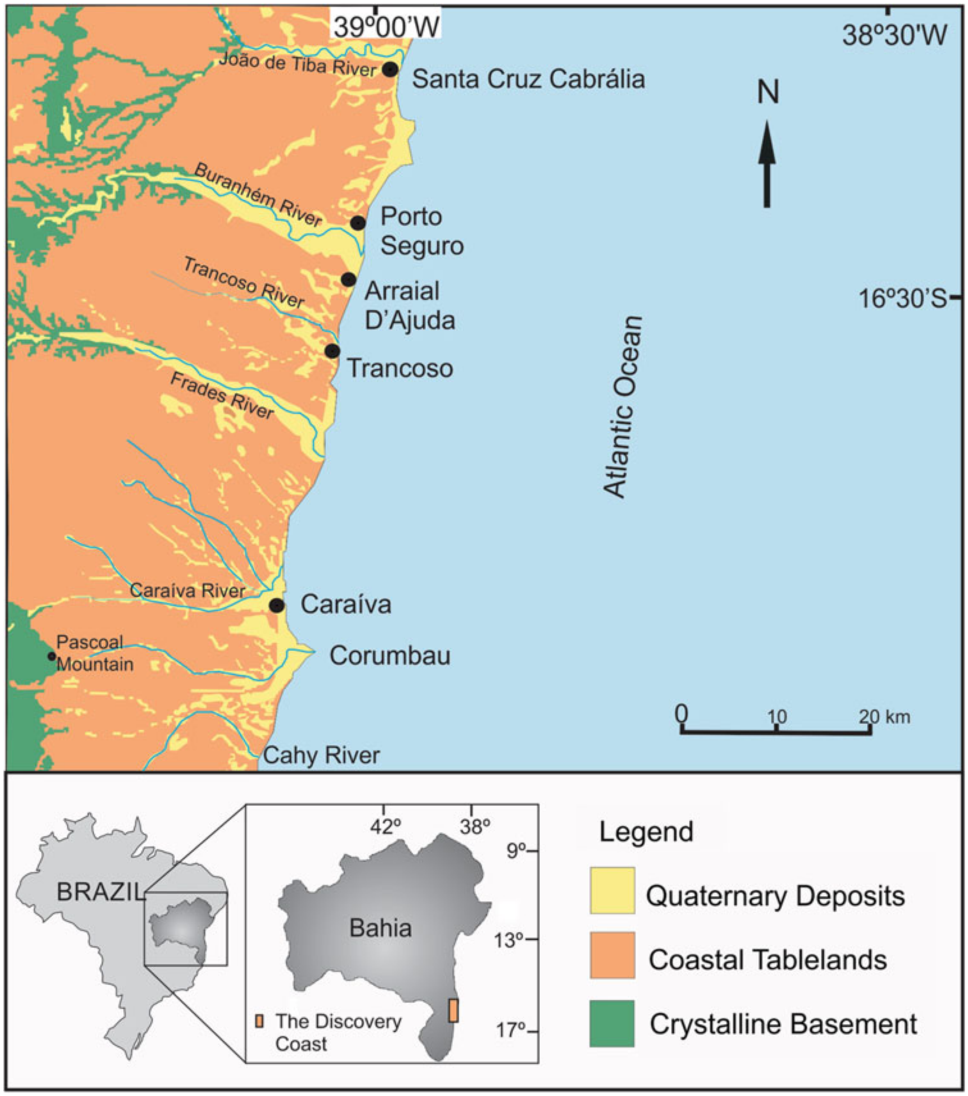

Fig. 5.1 The Discovery Coast. The map shows geomorphological domains with predominant coastal tablelands. The mountainous relief is sustained by crystalline bedrock in the west. Sediments of the Quaternary plains appear along the coastline. The Discovery Coast is located on the southern coast of Bahia State, Brazil

In the more internal coastal zone, a hilly and mountainous relief appears with peaks that are occasionally sharp. The hills and mountains are sustained by the high-grade metamorphic rocks of the crystalline basement (Fig. 5.2). One of these hills is known as Monte Pascoal (586 m a.s.l.) and was the first feature sighted by the Portuguese. These morphological attributes, which are associated with the historical and cultural value of this landscape, attract thousands of tourists to the region annually.

5.2 Historical Aspects of the Discovery Coast

The region known as the Discovery Coast, which is located on the southern coast of Bahia State, Brazil, was the first landscape sighted by the Portuguese explorers when they arrived in Brazil. The letter prepared by the onboard scribe, Pero Vaz de Caminha, and sent to the king of Portugal, reported the discovery of a new land, among other things, and faithfully described the region's geomorphology: "And so we continued our way through this sea until Tuesday the eighth day of the Easter, which were twenty-one days of April, said island being distant 660 leagues, according to what the pilots said, we came across some signs of land, which consisted of very many long seaweeds, that the navigators call 'botelho', and others that they named 'rabo-de-asno'. And next Wednesday morning, we came across the birds that they named 'fura-buxos'….On this day, in the evening, we made sight of land! First of a large mountain, very tall and round; and of other lower hills to the south of it; and low land, with large groves: the captain named the tall mountain Monte Pascoal, and the land, the Terra da Vera Cruz."

The coastal tablelands are described in substantial detail in another section of the letter: "This land, sir, from the southernmost point to the northernmost point, which we

Fig. 5.2 **a** Overview of the Discovery Coast with the coastal tablelands (foreground). The tablelands are cut by river valleys and exhibit cliffs along the coastline. In the background, the mountainous relief sustained by the lithologies of the crystalline basement can be observed; **b** The development of cliffs over several kilometers long marks areas where the coastal tablelands meet the coastline. The cliffs consist of Barreiras formation sediments that date from the Miocene

have seen since the port, is such that it will be as so twenty or twenty-five leagues of coast. Throughout the sea, in some parts, there are major red or white barriers; and the land on the top is low and full of large groves. From end to end, it's all beach-palm, very low and very beautiful."

After this historic letter, only in 1902 did American geologist John Casper Branner describe the geological–geomorphological coastal tablelands. Branner used the term "barriers," which occurs in the letter by Pero Vaz de Caminha, to designate the Barreiras Formation. This formation sustains the relief of these tablelands (quoted in Mendes et al. 1987).

The historical value of the Discovery Coast, which is associated with the presence of remnants of the Atlantic Rainforest, was decisive for the Brazilian government in creating the Monte Pascoal National Park in 1961. In addition, two other national parks were created: Discovery National Park and Pau Brasil National Park. These parks, in addition to a state park, integrate the conservation units present along the Discovery Coast.

5.3 Geological–Geomorphological Units of the Discovery Coast

5.3.1 Mountainous Relief—Crystalline Basement

The hills and sierras that form the crystalline basement on the Discovery Coast (Fig. 5.2) integrate the Eastern Pegmatite

Province of Brazil (Neves et al. 1986). The origin of these rocks is associated with the reworking of Archean rocks during the Transamazonian (920 Ma) and Brasiliano (570–540 Ma) tectonic cycles. The main lithologies that constitute the basement along the Discovery Coast are gneisses, granitoids, schists, calcosilicate rocks, and quartzites.

Morphologically, the crystalline basement consists of hills and sierras with a maximum altitude of approximately 600 m and topographical unevenness that can reach more than 200 m. The relief that makes up the high residuals of the basement is significantly dissected, with a drainage density that ranges from fine to medium. This intense dissection is related to the humid climate and its influence on rocks that possess an intricate system of fractures in the NE–SW and NW–SE directions, exerting strong structural control on the landscape.

In certain locations, structural features are revealed by straight river waterways or abrupt changes in valley orientation, although the drainage pattern is predominantly dendritic to sub-dendritic (Fig. 5.3). Where the coastal tablelands meet the residual elevations of the basement, sharp edges or ridgelines are formed, as exemplified by Monte Pascoal (Fig. 5.3b).

5.3.2 Coastal Tablelands—Barreiras Formation

The Barreiras Formation has practically continuous extension along the Brazilian coast, from Rio de Janeiro State to Amapá State (Suguio and Nogueira 1999). The age of these sediments has been attributed to the Miocene (Arai 2006; Rossetti et al. 2013), although many authors have found ages that range from the Miocene to the Pleistocene (Mabesoone et al. 1972; Bigarella 1975; Suguio et al. 1986). Regarding the source of the sediments that constitute the Barreiras Formation, Bigarella (1975) states that the lithology observed depends on the nature of the source area located near the sedimentation zone.

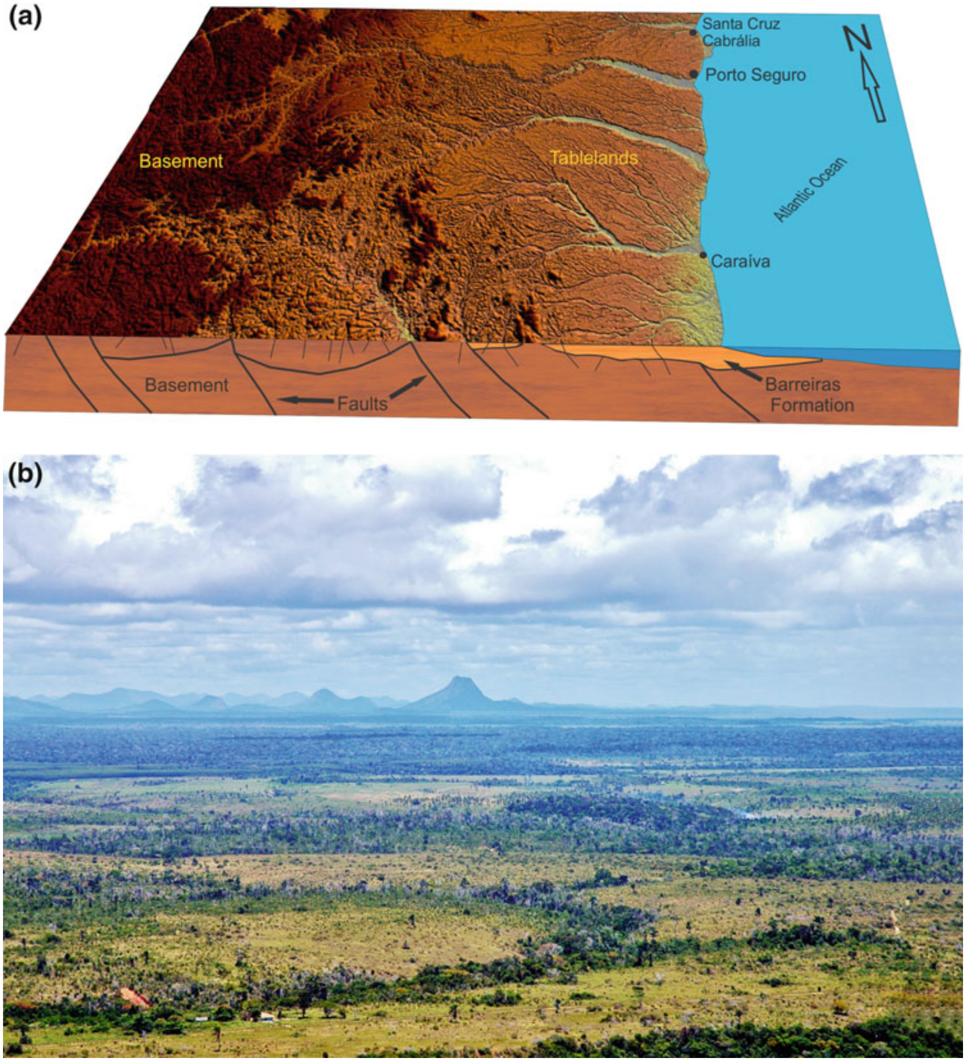

Fig. 5.3 **a** Schematic outline of the Discovery Coast showing coastal tablelands and high points of the basement. Note that the drainage appears with a dendritic to sub-dendritic pattern and occasionally accompanies the lineament; **b** Monte Pascoal, a rise in the crystalline basement that has substantial historical value because it was the first feature sighted by Portuguese explorers in the Brazilian territory

For the Discovery Coast, Lima (2002) documented the presence of black tourmaline and garnet in arcosic sandstones with angular and poorly sorted grains. These mineralogical characteristics indicate little chemical change and short transport before deposition. The presence of garnet, which is an unstable mineral, reinforces the idea of little reworking and the direct origin from the basement.

Lima et al. (2006) documented the facies diversity within the Barreiras Formation and found predominantly sandy and muddy sediments, with conglomeratic facies occurring locally. The sediments are texturally immature, dominated by sub-angular and more rarely sub-rounded grains. Mineralogically, there was an increase in the mineral maturity of the sediment from the bottom to the top.

Classically, the Barreiras Formation has been considered to be of continental origin (Mabesoone et al. 1972; Bigarella 1975; Lima 2002; Lima et al. 2006). However, several studies have identified sediments of marine origin in the coastal Pará (Arai 2006) and Maranhão States (Rossetti 2006). For the sediments of the Barreiras Formation on the Discovery Coast, Lima (2002) identified several channelized features that may coalesce, giving rise to thick sandstone packets that are 4 m or thicker. Several of these channeled bodies exhibit evidence of lateral migration, which corroborates the interpretation that the sediments were deposited in a braided fluvial plain (Lima et al. 2006).

More recently, Rossetti and Dominguez (2012) conducted a study on the Barreiras Formation throughout the coastal area of Bahia State and found diagnostic sedimentary structures of tidal processes and various ichnological associations representing coastal/transitional environments, similar to those documented for Brazil's northern region. These authors organized the sedimentary deposits of the Barreiras Formation in ten facies associations, which are predominantly marine-transitional. Among the most common lithofacies associations are mouth bars and tidal channels, which are associated with a deltaic structure. In addition, according to Rossetti and Dominguez (2012), the Barreiras Formation was deposited in onlap on older rocks of the Precambrian and Mesozoic, which occurred in association with a high sea level during the middle and lower Miocene.

The coastal tablelandstablelands on the Discovery Coast vary in width between 20 and 100 km and exhibit flat terrain with a slight gradient toward the sea. When the tablelands reach the coastline, they form active cliffs that are several kilometers long and reach up to 40 m high (Fig. 5.2b). In certain sections, inactive cliffs covered with vegetation mark the boundary between the tablelands and the Quaternary plain, or occur where the beaches are wider (Fig. 5.4). Wide, flat-bottom valleys, flanked by steep walls and associated with major rivers flowing into the region, cut the flat surface of the tablelands.

Fig. 5.4 Partially vegetated cliffs appear in areas in which the beaches are wider, which indicates little erosive action at these sites

The lithological homogeneity and flat surface favor the development of a dendritic drainage pattern on the tablelands. However, their slight slope toward the sea and, in several cases, to the northeast and southeast ultimately causes the local appearance of a sub-parallel pattern. In addition, several sections of rivers are embedded in fault zones, and some of these waterways abruptly change their orientation, which suggests a structural control on the regional drainage pattern (Lima et al. 2006).

The morphodynamics of coastal tablelands is linked to drainage density that ranges from medium to high and promotes uniform dissection of the relief, with shallow valleys that deepen toward the coast and are bordered by slightly curved convex slopes. In locations at which the sedimentary packet is thin or where the basement crops out, the dissection becomes, controlled by rocky substrate and fractures present in these rocks. Heavy rainfall has a significant influence on the morphodynamic processes, with the superficial runoff creating rills and gullies in the slopes of interfluves (Mendes et al. 1987).

5.3.3 The Quaternary Plain

Because of the decreased input of fluvial sediments to the coastal zone, a well-developed Quaternary plain is only present in the localities of Corumbau and the section between Porto Seguro and Cabrália (Fig. 5.5, see Fig. 5.1 for location), where protection provided by reef structures positioned beyond the coast favored accumulation of beach sediments in a process similar to that resulting in the formation of tombolos and salients. In these two Quaternary plains, there are beach deposits that have accumulated in association with the high sea levels of the Marine Isotope Stage 5e (123,000 years BP) and Marine Isotope Stage 1 (current). Other features of the Quaternary age and characteristic of the coastal zone are beach rocks and coral reefs.

The beach rocks represent ancient deposits of the surf zone cemented by calcium carbonate, later exhumed by coastline erosion. The cementing is typically superficial and extends up to 3–4 m thick. The ages reported for these sandstones are always less than the 7,000 cal years BP

Fig. 5.5 Aspects of the Quaternary plain on the Discovery Coast near the municipality of Santa Cruz Cabrália, Brazil. This small Quaternary plain was formed at the rear of a set of reef structures, also shown in the *photograph*

(Martin et al. 1999). The predominant sedimentary structures are cross-bedding stratifications, which formed under the action of longitudinal currents in the surf zone. Many occurrences of beach rocks on the Discovery Coast are associated with the mouths of large valleys that cut the coastal tablelands (Fig. 5.6) and are the testimony to the falling relative sea level during the Holocene.

The numerous reef structures on the Discovery Coast are found away from the coastline and form reef banks that occasionally reach several kilometers wide (Fig. 5.7). Their sides above the seafloor range from approximately 10 to over 20 m. Although located away from the coast, these reefs significantly interfere with the coastal dynamics by causing salients and tombolos. The flat top of these reefs has generally been attributed to a falling relative sea level of approximately 3–4 m, which has affected Brazil's eastern coast over the past 5,000 years.

5.4 Morphotectonics and Evolution of the Relief

Several morphotectonic features present on the Discovery Coast have been emphasized since 1980s. For example, Tricart and Silva (1968) drew attention to the gentle tilting of the coastal tablelands to the southeast, which would continue throughout the continental shelf. Additionally, various alignments of valleys and depressed areas are targeted according to the orientations of Precambrian basement faults, which may represent a recent reactivation of these weakness lines. Moreover, according to Tricart and Silva (1968), several evidences in coastal deposits suggest tectonic movements. Among these movements is the right-angle form of the tributaries of the Trancoso River (see Fig. 5.1 for location), which also suggests reactivation of Precambrian lineaments.

Fig. 5.6 Mouth of the Buranhém River in the city of Porto Seguro, Brazil. It is partially blocked by beach rocks, such as the one shown in the *photograph*. These rocks represent ancient beach deposits cemented by calcium carbonate and later exhumed by the erosive retreat of the coastline

Fig. 5.7 Recife de Fora near the city of Porto Seguro, Brazil. This is a typical example of a reef whose top was flattened due to reworking by waves

For the section between Porto Seguro and Santa Cruz Cabrália, Mendes et al. (1987) and Bittencourt et al. (1999) suggested a clear tilting of the coastal tablelands to the NE, which is evidenced by the alignment of the drainage pattern in the block located north of the Buranhém river valley, where the river borders a fault plane (Fig. 5.8).

Lima et al. (2006) noted the existence of three high blocks separated by structural lows, which correspond to the valleys of the region's main rivers, between the cities of Cabrália and Caraíva (Fig. 5.8a). The drainage patterns observed on the surface of these blocks suggest their differential tilting. The homogeneity of the sediments that support the coastal tablelands in the region theoretically favors the development of a dendritic drainage pattern.

In block 1, located between the structural lows represented by the João de Tiba (Fig. 5.8b) and Buranhém river valleys (Fig. 5.8c), the longest river courses tend to be parallel and flow NE (N70°), and most of the tributaries display this pattern. For block 2, which is bordered to the north by the Buranhém River and to the south by the Frades River (Fig. 5.8d), the river courses are directed E–SE (N106°). Certain drainage anomalies observed in this block are related to fractures, indicating structural control in certain sections of the rivers. In block 3, which is bordered to the north by the Frades River and to the south by the Caraíva River, the average direction of drainage is N129°, with the primary courses flowing into the Caraíva River, indicating that the block tilts to the SE (Fig. 5.8). One of the longest tributaries of the Caraíva River has a straight NW–SE course, which suggests that the river is controlled by a fault zone.

These observations suggest post-sedimentation tectonic reactivation with sufficient intensity to promote the tilting of blocks, thus modifying the drainage pattern. Lima and Vilas Boas (2004) suggested that the regional drainage pattern, originally dendritic, was reshaped by the tilting of blocks during the Quaternary.

Faults were observed by Lima (2002) and Lima et al. (2006) to affect the Barreiras Formation sediments and associated Quaternary deposits, indicating tectonic reactivation during the Quaternary. This reactivation helped shape the relief currently observed. In addition to the faults, these authors found conjugated systems of neotectonic joints in the directions NE–SW and NW–SE. Statistical analyses of

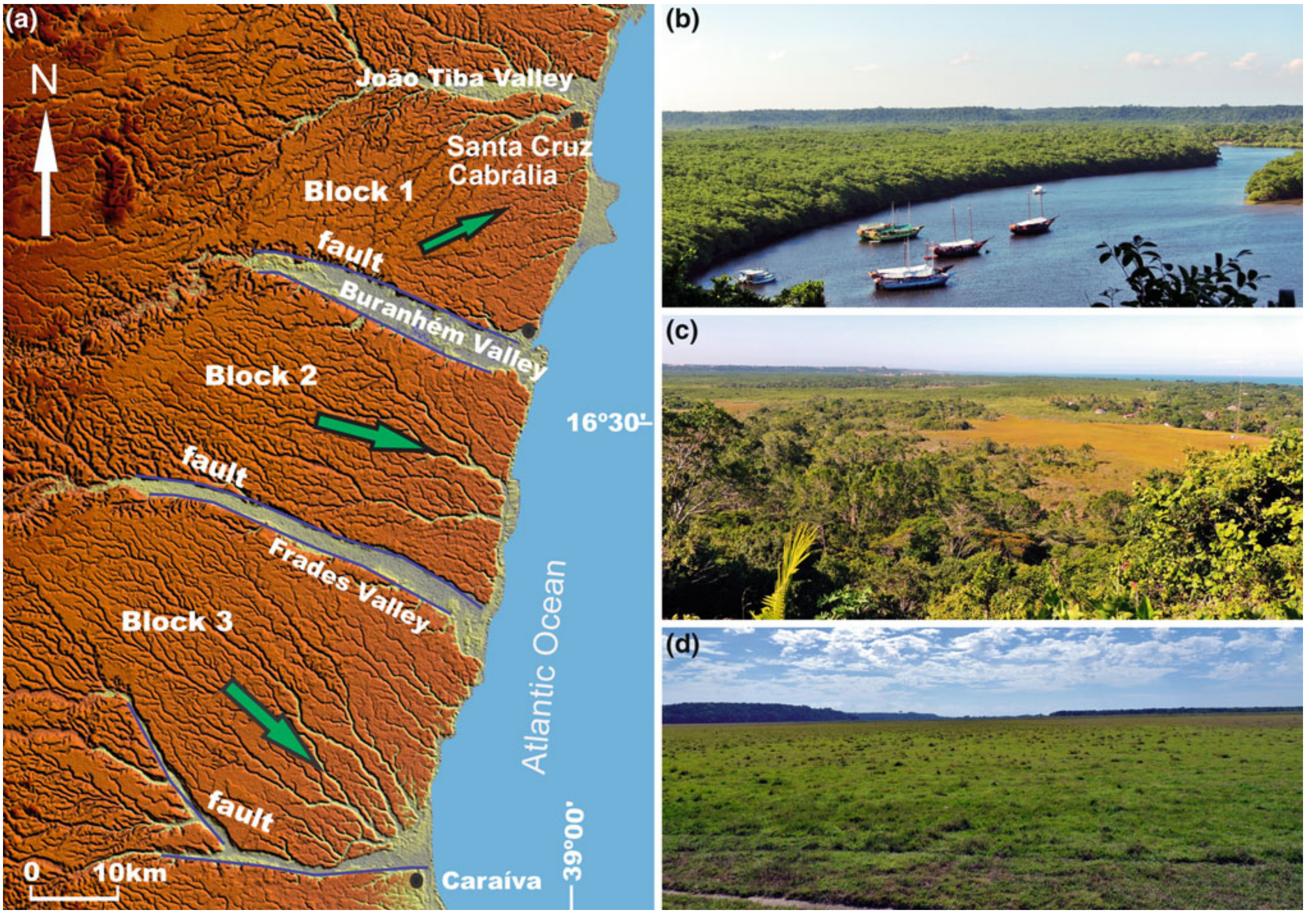

Fig. 5.8 **a** Structural blocks bordered by faults between the municipalities of Santa Cruz and Cabrália Caraíva, Brazil. Hypsometric map showing the three structural blocks. *Arrows* indicate the general direction of drainage for these three blocks (modified from Lima 2002; Lima and Vilas Boas 2004; Lima et al. 2006); **b** João de Tiba river valley; **c** Buranhém river valley; **d** Frades river valley

the joints by Lima et al. (2006) revealed that the maximum compression, which is currently experienced by the sediment that sustains the tablelands, has a NW direction, forming a 25° angle with the coastal zone's overall orientation.

5.5 Conclusions

The geomorphology of the Discovery Coast is represented by three domains. The first consists of a hilly to mountainous relief, which is substantially dissected, marked by sharp edges or ridgelines, and sustained by a crystalline basement. However, the most representative geomorphological domain consists of the coastal tablelands. These tablelands are flat, horizontal, or exhibit a gentle slope toward the coast and are cut by broad river valleys with flat bottoms and steep walls. Along the coastline, Quaternary plains have developed in certain locations, which are represented by beach deposits that have accumulated as a result of the high sea levels that occurred during the Quaternary. The development of the relief along the Discovery Coast was significantly influenced by Quaternary tectonics, which was responsible for the origin of faults and joints. These faults and joints are the result of paleotensions in the NW–SE direction. Several of these faults promoted the tilting of structural blocks, which induced changes in river flow direction and altered the drainage pattern that developed on the structural blocks of the coastal tablelands.

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6

The Todos os Santos Bay—An Ephemeral High-Stand Feature Incised into an Aborted Cretaceous Rift

José Maria Landim Dominguez

Abstract

This chapter discusses the Todos os Santos Bay (Baía de Todos os Santos—BTS), one of the Brazil's largest embayments. Salvador, which is one of the largest metropolises in the country and was Brazil's first capital, is located on its shores. The bay is a feature of erosional character, with sub-bays, several islands, hard bottoms, and abrasion terraces. The reduced supply of fluvial sediments into the BTS is not yet sufficient to fill the bay. These characteristics, associated with almost oceanic salinity and temperature conditions of its waters, are responsible for the relatively preserved scenic beauty of the bay, which is a major tourist destination in the country.

Keywords

Bays • Sea level • Erosion • Aulacogen

6.1 Introduction

Todos os Santos Bay, located on the east coast of Brazil, is the second largest bay in the country and occupies an area of 1,223 km^2 during high tide (Lessa et al. 2009) (Fig. 6.1). The bay was discovered during a Portuguese expedition in 1501 and is depicted in the famous Cantino Planisphere dated 1502. Salvador, the seventh largest Brazilian metropolis, is located at the entrance of the bay, with a population of approximately 3.5 million inhabitants. Salvador was the first capital of Brazil, and for many years after its founding (March, 29, 1549), it was the largest city in the Americas and an important center of the sugar industry and slave trade. This legacy remains today in its Afro-Brazilian culture and large black population. The historic center of Salvador, also known as "Pelourinho," was designated in 1985 a World Heritage Site by UNESCO.

The freshwater discharging into the BTS mainly originates from three rivers: the Paraguaçu, Jaguaripe, and Subaé. The first river is the most important, being responsible for approximately 92 % of the discharge (Lima and Lessa 2002). The main driving forces in the BTS circulation are the tides, which have a height of 1.87 m in syzygy and 0.98 m in quadrature in the oceanic area. The tidal wave undergoes amplification of up to 70 cm in syzygy between the entrance of the bay and its northern portion (Lessa et al. 2009). The currents are generally weak in most of the bay (<30 cm/s), with the greatest speeds observed in the channels and straits (40–50 cm/s) (Xavier 2002). BTS is set on sedimentary rocks of the Recôncavo sedimentary basin of Jurassic–Cretaceous age. In 1939, oil was discovered in this sedimentary basin in Lobato, on the outskirts of Salvador. This chapter discusses the geology, geomorphology, and evolution of Todos os Santos Bay.

6.2 Geology

Todos os Santos Bay is set on the Recôncavo sedimentary basin, a part of an aulacogen or aborted rift formed during the separation of South America and Africa (Fig. 6.2). The beginning of the Recôncavo basin formation occurred approximately 145 Ma (lower Cretaceous) (Silva et al. 2007). The basin-filling period ended at the end of the

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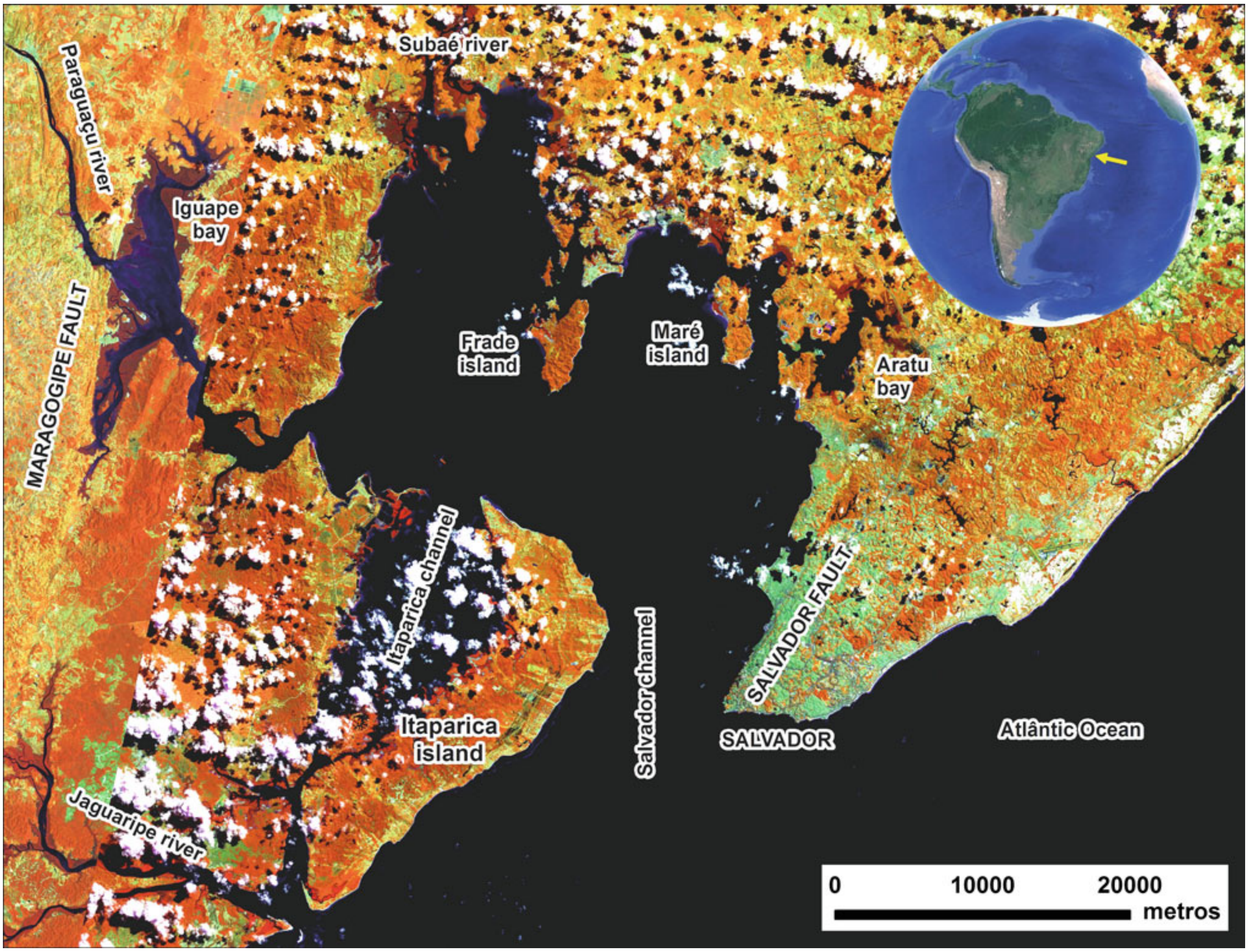

Fig. 6.1 Todos os Santos bay

Aptian (115 Ma). Since then, the region has undergone uplift, which may have reached almost 2,000 m (Daniel et al. 1989; Davison 1987; Magnavita et al. 1994). The Recôncavo rift developed on aeolian–fluvial sediments dating from the Late Jurassic (Brotas Group); for this reason, these sediments are considered as part of an evolution phase of the basin called pre-rift. The Recôncavo rift exhibits the geometry of a half-graben, with the greatest subsidence recorded along the Salvador fault, which is its eastern boundary and is also where the basin depocenter is located, with sediment accumulation up to 8 km in thickness. The Recôncavo basin is separated from the Atlantic margin basins by a crystalline basement high called the Salvador high. The western edge of the basin exhibits a flexural character with negligible subsidence and is marked by the Maragogipe fault (Fig. 6.2). The sedimentation through the syn-rift phase of the basin evolution occurred in a deep lake, similar to the lakes currently existing in eastern Africa; these lakes were most likely a few hundred meters deep with anoxic bottom waters, where fine-grained sediments, rich in organic matter, accumulated (Santo Amaro Group). The lake was eventually silted by fluvial systems (São Sebastião Group), where associated deltas and gravity flows were deposited (Ilhas Group), with conglomerate wedges accumulating along the Salvador fault (Salvador Formation) (Magnavita et al. 2005; Cupertino and Bueno 2005). The final silting of the basin occurred approximately 125 Ma and was followed by uplifting over approximately 10 million years, when the sediments from the Marizal Formation were deposited (Magnavita et al. 1994, 2005). The latter are considered as belonging to the post-rift phase of the basin. Since approximately 90–100 million years ago, erosion processes have dominated the region. Therefore, the Recôncavo basin did not undergo marine flooding during its main development phases. The region might have experienced a marine transgression only during the Early–Middle Miocene. There are sediments from the Barreiras Formation, of transitional marine origin from approximately this period (Rossetti and Dominguez 2012; Rossetti et al. 2013) that discontinuously cover the Jurassic–Cretaceous sediments of

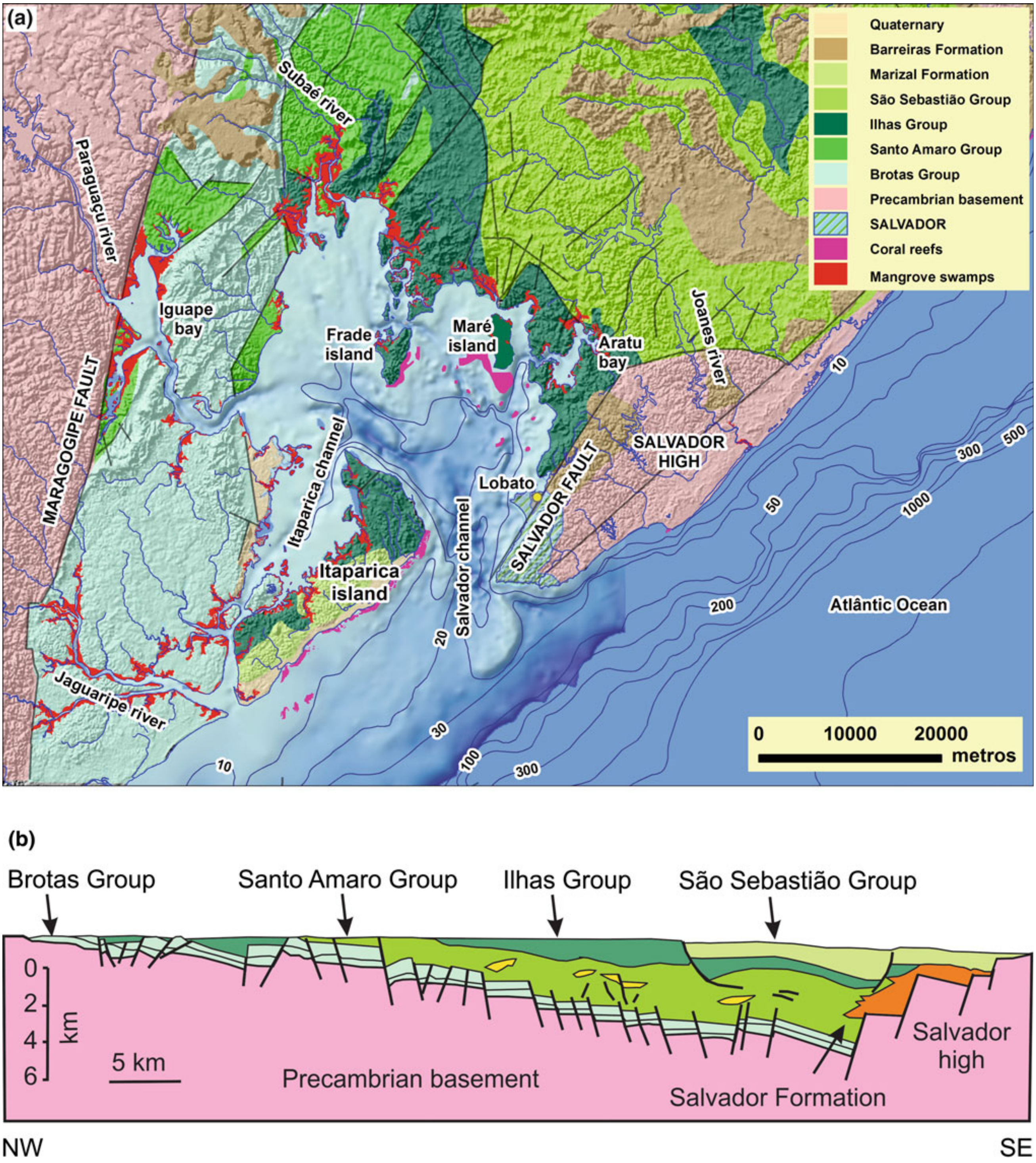

Fig. 6.2 **a** Geology of Todos os Santos bay (modified from Magnavita et al. 2005). **b** Geological cross section of the Recôncavo sedimentary basin (modified from Magnavita et al. 2005). Bathymetry and the distribution of mangrove swamps and known coral reefs are also shown

the Recôncavo basin and the adjacent basement (Fig. 6.2). There are also records of a deposit of fossiliferous marine shale (Sabiá Formation), of Miocene age, described from just one outcrop (Petri 1972).

Major lithology types outcropping along the BTS shoreline are as follows: (i) crystalline basement rocks along the Salvador and Maragogipe faults, which delimit the basin to the east and to the west; (ii) Jurassic sandstones from the pre-rift phase, restricted to the western shore of the bay; and (iii) shales, siltstones, and sandstones of the Santo Amaro and Ilhas Groups from the syn-rift evolution phase of the Recôncavo basin (Fig. 6.2).

Interestingly, the Recôncavo basin is the only region in Brazil where sediments from the syn-rift phase of the continental margin evolution are exposed, mainly on the cliffs surrounding the BTS. In the other regions of the Brazilian continental margin, these sediments are buried by piles of marine sediments, several kilometers thick, deposited during the various evolution stages of the South Atlantic. The organic sediments that constitute the source rocks of almost all the oil present in the Brazilian continental margin were accumulated in the deep lakes of the syn-rift phase. Thick

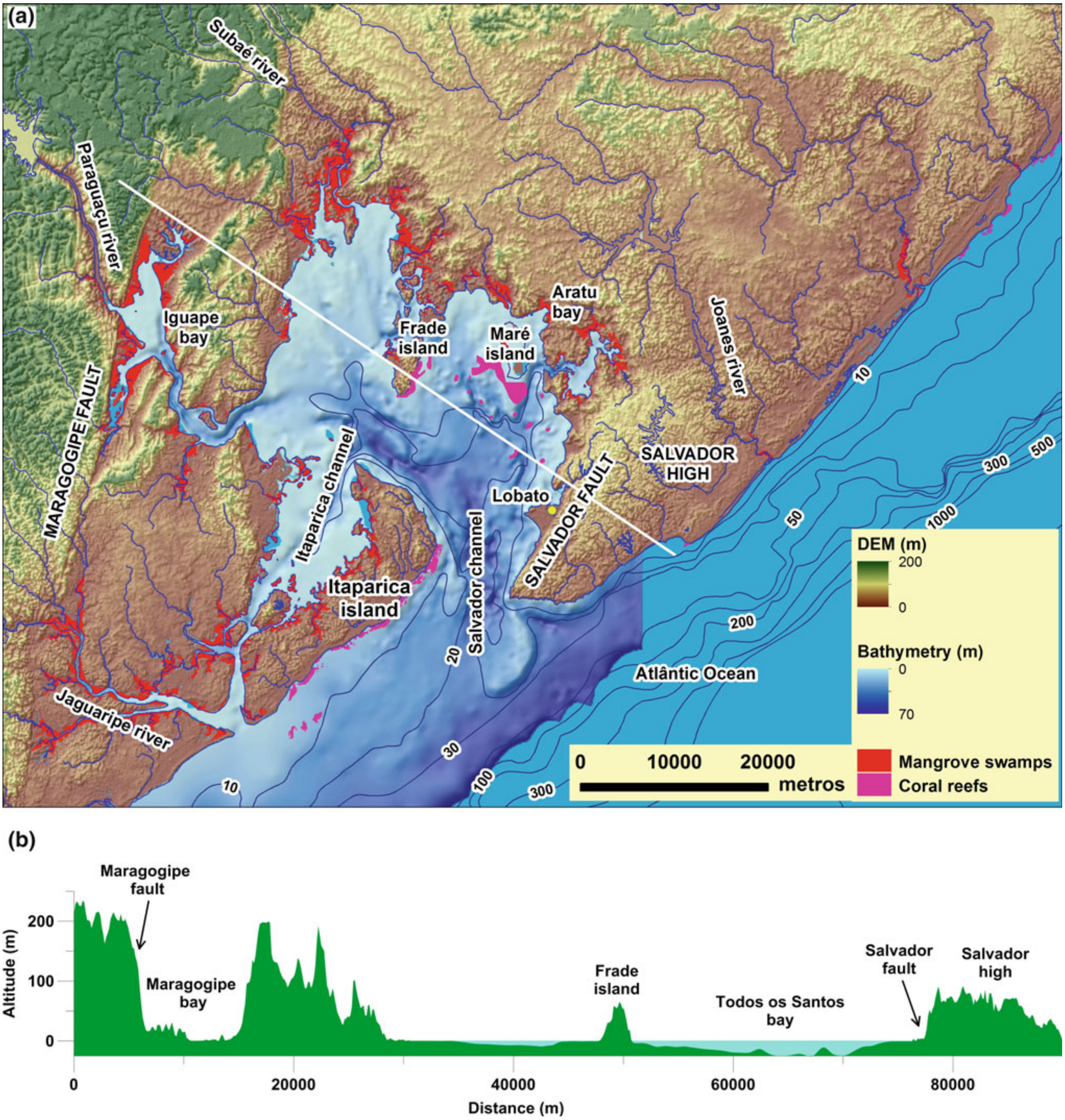

Fig. 6.3 **a** Digital elevation model (SRTM) of the lower portion of the Recôncavo basin and the Todos os Santos bay (Brazilian Navy Admiralty). **b** Topographic profile running NW-SE. See Fig. 6.3a for location

layers of salt, deposited during the initial phase of the formation of the South Atlantic, cover the sediments of the synrift phase mainly on sedimentary basins of eastern and southern Brazil. These deposits have been more recently called "pre-salt" and host the largest oil reserves in Brazil.

6.3 Geomorphology

Todos os Santos Bay exhibits a trapezoidal geometry in ground plan, inherited from the structural framework of the Recôncavo Basin (Figs. 6.2 and 6.3). BTS occupies a topographically lowered area that was directly carved in the Jurassic–Cretaceous sediments that fill the Recôncavo Basin. In the east and west shores of the bay, where the Recôncavo sedimentary basin contacts with the Precambrian basement, there is a pronounced elevation change of a few tens of meters, coinciding with the Salvador and Maragogipe faults (Figs. 6.3, 6.4, and 6.5).

Todos os Santos Bay contains two other smaller subbays, known as Aratu and Iguape bays. These bays communicate with BTS through narrow and relatively deep channels (20–35 m) that extend through the bay floor with a well-defined geometry to which smaller tributaries are added, originating from other BTS areas, such as the Subaé River and the Itaparica Channel. These channels were part of the drainage basin of the Paraguaçu River during the periods of low sea level, when this river flowed into the edge of the continental shelf. Although a substantial sediment deposition (up to 30 m) occurred in the northern half of the bay, the general configuration of this paleo-drainage has most likely been maintained through the action of tidal currents. The paleo-relief buried by the Holocene sedimentation is clearly visible in high-resolution seismic records. The interfluves of this paleo-relief led to the formation of the hard bottoms and abrasion terraces, which sometimes outcrop at low tide (Fig. 6.6). The largest expressions of these interfluves are the islands that are mainly located in the northern half of the bay, such as the Frade and Maré islands. Waves, locally generated by the dominant east winds or those that enter the bay from its bar, created the abrasion terraces carved in the Jurassic–Cretaceous rocks. These terraces border the islands, and the coastline stretches mainly to the east (Fig. 6.7). Some of the smaller islands have virtually disappeared

Fig. 6.4 The Salvador fault marks the eastern boundary of the Recôncavo basin. Because of the abrupt altitudinal change, Salvador city has been divided into a low and a high city

Fig. 6.5 The Maragogipe fault marks the western boundary of the Recôncavo basin. To the *left* of the photo are the Iguape bay and Maragogipe city

because of wave erosion processes, creating the hard bottoms mentioned above. In the particular case of Itaparica Island, abrasion terraces served as substrates for the growth of coral reefs (Araújo 1984; Leão et al. 2003) (Fig. 6.8). The large number of abrasion terraces and cliffs bordering BTS is a direct consequence of the reduced sediment delivery into the bay. This reduced sediment delivery is the reason why sandy beaches are relatively scarce features within the BTS (Fig. 6.7).

Between the western and eastern BTS boundaries, there is a drop in altitude of approximately 130 m (Fig. 6.3). However, with the exception of the Paraguaçu River, the major rivers immediately to the north of BTS flow into the Atlantic Ocean and follow approximately straight courses in the NW–SE direction. This fact led Tricart and Silva (1968) to suggest a recent age for the BTS, as there was no sufficient time to catch the neighboring drainage. In fact, digital elevation models of the terrain indicate the occurrence of incipient drainage capture processes in the small water courses that flow on the northern shore of the bay. It is possible that the Paraguaçu River also flowed into the Atlantic Ocean and that its original course in the lower reach, which also had a NW-SE direction, was diverted toward NE-SW (now represented by the Salvador Channel) when it met the crystalline rocks of the Salvador high through the carving process of the BTS during the Neogene.

6.4 Geomorphological Evolution

Since 90–100 million years ago, erosion processes prevailed in the Recôncavo basin region, not only because of the basin uplift but also due to eustatic lowering of the sea level since the Cretaceous. This prolonged subaerial exposure was interrupted by the rise in the sea level during the Early–Middle Miocene, when the sediments of transitional marine origin of the Barreiras Formation were deposited. The Todos os Santos Bay age should therefore be more recent than the Early–Middle Miocene.

Since the end of the Middle Miocene, the eustatic sea level has progressively decreased due to the resumption of ice accumulation in Antarctica and the beginning of the development of the large ice sheets in the Northern

Fig. 6.6 Example of an abrasion terraces outcropping in the northern portion of BTS during low tide. Sedimentary rock bedding is well visible

Fig. 6.7 Example of an abrasion terrace carved into Cretaceous rocks (eastern portion of the Frade Island)

Fig. 6.8 Coral reef growing on *top* of abrasion terraces carved into Cretaceous rocks (eastern portion of Itaparica Island)

Hemisphere. Consequently, in the last million years, the sea level has maintained an average position of approximately −62 m (Blum and Hattier-Womack 2009). This sharp decline of the base level triggered intense erosion that affected the coastal zone and was associated with the humid climate that prevails in the region. This drop in base level also favored differential erosion between the crystalline basement rocks and the sedimentary rocks of the Recôncavo basin, mainly affecting the finer grained rocks, which prevail in the stretch where the BTS is set (Dominguez and Bittencourt 2009). This prolonged subaerial exposure, associated with the differential erosion, topographically downgraded the relief in the sedimentary terrains of the Recôncavo basin relative to the neighboring crystalline basement. During the rare Quaternary high-stand episodes, similar to the present one, this low-lying region was flooded by the sea. As such, a bay was present only during these periods. Some authors, however, argue for a neotectonic origin of BTS based on the morphological expression of the boundary faults of the Recôncavo basin and rare seismic events of mild intensity that occurred in the region, mainly in the early twentieth century (Carvalho 2000; Lessa et al. 2000).

With the end of the Holocene transgression, the filling of the BTS began, and the accumulation of fine sediments prevailed in its northern half. Bioclastic sands were deposited, associated with the hard bottoms and abrasion terraces that occur in and around the bay. At the entrance of the BTS, an accumulation of the well-sorted siliciclastic sands of marine origin transported by the tidal currents is observed.

6.5 Conclusions

Todos os Santos Bay is the result of a combination of events dating from the separation of South America and Africa to the cooling of the planet during the Neogene. The lowering of the sea level since the Middle Miocene, which was accentuated during the late Quaternary, was vital to the development of the BTS. This drop in sea level favored the differential erosion between the Jurassic–Cretaceous sedimentary rocks of the Recôncavo basin and the crystalline rocks of the neighboring Precambrian basement, topographically lowering the landscape in the sedimentary rock areas. During the short periods of high sea level in the Quaternary, these lower regions were flooded, and a bay was present, similar to the one existing nowadays. In this sense, the BTS is an ephemeral feature, with an existence restricted to the short-duration Quaternary interglacial periods.

Because of the size and protected nature of the Todos os Santos Bay, the site was chosen by Portuguese settlers to establish the first capital of colonial Brazil, Salvador. The city rapidly became an important center for sugar and slave trade. This legacy remains today in its rich Afro-Brazilian culture and cuisine and large black population.

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7

Brazil in the South Atlantic: The Fernando de Noronha and Trindade Archipelagos

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Abstract

The Brazilian oceanic islands are privileged places for studying unique landforms, evolved under an active tectonic setting, and humid to semi-arid climates of marine influence. The main landform aspects of the two main islands (Fernando de Noronha and Trindade) are presented, showing the importance of volcanic activity at hot spots, with older events in Noronha, resulting in extensive weathering and erosion of the less resistant rocks (tuffs, scoria), compared with prominent phonolite massive stocks, forming exhumed pinnacles and domes of structural resistance. In contrast, Late Quaternary volcanism at Trindade resulted in the preservation of younger volcanic features, such as caldera remains, volcanic platforms and slopes, lava and scoria fields, and dark-sand beaches formed by high contents of primary mineral such as magnetite. Storm beaches composed of large clasts (cobbles) are also found in both islands. Trindade and Noronha islands show polyphasic aeolian features at some coastal sectors, with sand dunes of bioclastic carbonates, with greater extension in Noronha compared with Trindade. Uplifted marine terraces are found in both islands, associated with former high sea levels. In contrast, the presence of submerged terraces at Noronha and Trindade is related to a combination of glacio-eustatic variations (low sea levels) and epeirogenic uplift. In Noronha (Rata Island), we can find a rare case of oceanic karst landscape developed on calcareous sandstone, with abundant lapiez and dissolution features. Also, ornithogenic soils are widespread, with great importance for paleoecological studies of former bird colonies in these isolated islands. The most prominent landforms are structural and tectonically controlled, and the erosion degree in Noronha advanced much farther than in Trindade, exhuming pre-existent volcanic necks and similar structures, forming a complex and impressive landform scenery. Trindade reveals unique, endemic landscapes formed by pure stands of arboreal ferns (*Cyathea* sp.), where deep organic soils developed. Fluvial erosion is very limited, but there is evidence of a former greater importance of run-off in Noronha and Trindade.

Keywords

Oceanic islands • Volcanism • Island geomorphology • South Atlantic

7.1 Introduction

In Brazil, given the great extent of its coastline facing the south Atlantic (over 7,000 km) and adjacent oceanic area, we found several archipelagos. Widely known for its beautiful landscapes, such as the beaches of the Fernando de Noronha archipelago, these islands are very interesting environments for geomorphological studies. This chapter

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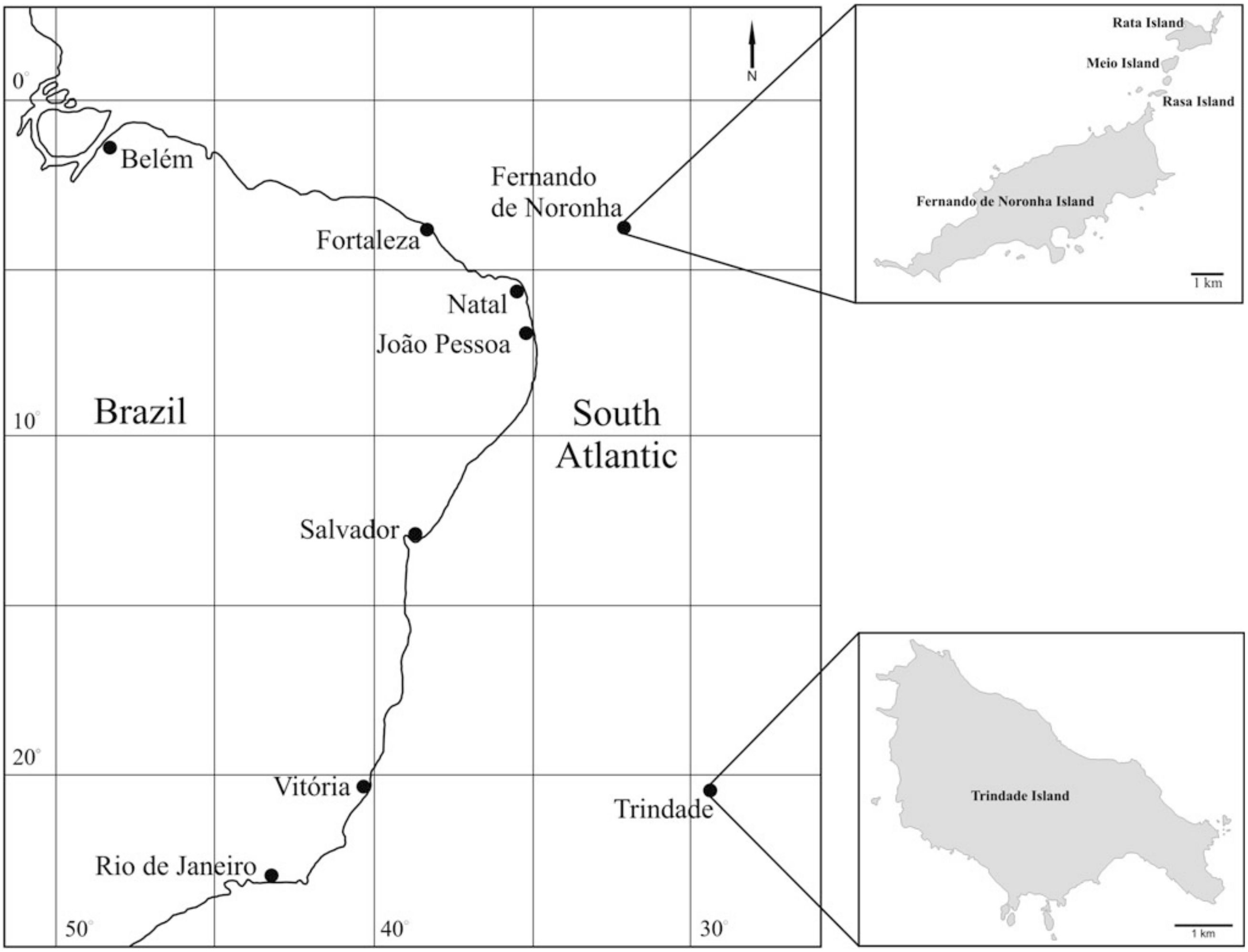

Fig. 7.1 Location in South Atlantic of Fernando de Noronha and Trindade Archipelagos

presents the general landform aspects of the two largest and most important oceanic archipelagos of Brazil: Fernando de Noronha and Trindade (Fig. 7.1).

7.2 Fernando de Noronha Archipelago

7.2.1 General Aspects

Noronha represents the most diverse volcanic landscape in Brazil. The islands of the Fernando de Noronha archipelago are located some 360 km NE of Natal City, Brazil (Fig. 7.1a) and ca. 2,600 km from the coast of Liberia in Africa. The area of the main island is 16.9 km^2, and with the other 20 islets, the total area of the archipelago is 18.4 km^2. Fernando de Noronha rises from a base 4,000 m deep and 60 km in diameter.

The archipelago has volcanic origin, formed of a substratum of pyroclastics intruded by a variety of alkaline eruptives, which in turn are overlain by two principal types of basaltic flows. The oldest rocks, Remedios Formation (Almeida 1955), represent a volcanic event in the Middle Miocene (Cordani 1970) and constitute a complex of tuffs and volcanic breccias intruded by phonolitic and trachytic bodies, many dykes and irregularly shaped masses of alkaline ultrabasic rocks. Ankaratritic flows and nephelinite dykes are associated with a younger group of pyroclastics (Quixaba Formation), characterising a new phase of volcanic activity between 6.6 and 1.81 Ma (Cordani 1970). Overlying these are the thick nepheline-basanite flows, belonging to the São José Formation. Drastic erosion of the Remedios Formation occurred before the Quixaba volcanic phase, which almost completely destroyed the external appearance of the Remedios, and one consequence was that presumably only the intrusive rocks remained. Sediments of aeolian and marine origin are restricted to coastal areas and marine terraces, which cover some 7.5 % of the archipelago area.

The soils of the Noronha are quite fertile but suffer from severe drought. In former times, the archipelago supported dense vegetation of both trees and bush, of species similar to those growing on the "Agreste" region of north-east Brazil. The destruction of the forests and bushes dates back to the earliest permanent occupation, in the eighteenth century, when wood was needed for various uses. The setting aside of pasture areas for goats, sheep and cattle aided further in the reduction of the natural vegetation cover. However, despite the widespread destruction in old times, the island presents a green and clothed aspect, especially during the wet season, with grasses, brushwood and trees abundant everywhere, even on the summits—except at the Morro do Pico, too steep to support plant life.

Fernando de Noronha was the first part discovered of what we call the Brazilian territory, under the name Sao Joao in a map of Juan de la Costa in 1500. However, it is generally accepted that Gonçalo Coelho was the real discoverer in the year 1503, at which time it was named Ilha da Quaresma. From 1738 to 1942, Fernando de Noronha was a prison, but after the latter date, it became part of the Federal Territory of Brazil, directly under the Ministry of War. At this time, Word War II was in progress, and for defensive reasons, the Brazilians placed the archipelago under military control. Today, the population and activities of the archipelago are almost entirely related to tourism.

Fernando de Noronha experiences a tropical climate with a well-marked wet season, in which oceanic influences are paramount; the temperature amplitude is small and there is uniform trend in the relative humidity. The climate is healthy, tending to be somewhat semi-arid, with long dry season.

The average annual temperature is 25.4 °C, with a range of only 1.5 °C. Maximum temperature experienced is 31 °C, minimum 18 °C, with a large daily variation during November in the dry season. March is the warmest month, 29 °C on average, while August is the coolest, 23 °C on average. The average annual rainfall is 1,318 mm, with a distinct wetter period from February to July. April is the wettest month, receiving 273 mm in 21 days on average, with the three wettest months providing some 60 % of the annual rain. August to January is the dry period, with only 8 mm falling on average in October, and only 31 mm on average during November–December. The temperature and rainfall characteristics would class the region as an Awi type of climate, according to Köppen classification (Almeida 2000).

Constant and dominant trade winds blow throughout the year, mostly from the ESE. In general, the climate of the archipelago is the same as that along the eastern seaboards of Rio Grande do Norte in continental Brazil, the rainfall being somewhat greater and the dry season not quite so marked on the mainland. During the long dry period, strong insolation takes most water from the soil and causes the regolith to have a cracked, desiccated aspect.

7.2.2 Geomorphology and Related Features

Landforms in Noronha are strongly controlled by the structural geology of the volcanic sequence. In the main island (Fernando de Noronha will relate to the largest island, unless otherwise stated), higher peaks tend to be distributed at the periphery, with Pico, Atalaia, Fraces, Madeira, Boa Vista, Dois Abraços, Bandeira and Santo Antonio, all over 105 m, lying within some 700 m of the shore, the island having a maximum breadth of 3.5 km. The highest point is Morro do Pico at 321 m, near the village of Remédios (Fig. 7.2). Now, here is the relief as pronounced or as spectacular as in Trindade (Sect. 7.2 of this chapter). In the central area, there is quite an extensive flat area, the Quixaba (Central) plain, with a mean elevation of 45 m, surrounded by peaks on all sides except the west (Fig. 7.2). This semi-arid plain descends down along a pediment surface to a lower coastal plain west of Sueste Bay, continuing westwards along the southern coast to the Viração plain.

Peaks are basically ankaratritic and phonolitic alkaline bodies rising prominently above the surrounding terrain, hence displaying a structural resistance to erosion. Morro do Pico (Fig. 7.3), which Branner (1889) called the most striking landmark to be found anywhere in the entire South Atlantic, is a phonolitic monolith (plug), rising 200 m in perpendicular bare walls above steep lower slopes covered in vegetation. At its base, a deep kaolinitic saprolite indicates paleoweathering of these rocks under a much wetter climate than the present.

Apart from individual peaks, the landforms are somewhat subdued and rolling, although the lower hillslopes can be quite steep. The overall incompetency of the drainage network to carve out marked valleys is a notable feature of the islands. Neither have the ephemeral streams eroded deep-incised valleys, nor are streams of any significant length.

Lying north of the main island are a series of islets, forming 'stepping-stones', leading to the largest and farthest removed, Rata Island (Fig. 7.4). Rasa and Cuzcus Islands are connected to S. Antonio Point, the northernmost point of the main island, by tombolos, one of which is covered at high tide, and formed by calcareous sandstone (calcarenites). Among these northern islets, Sela Gineta is the highest, 128 m, also having steep slopes. In general, the offshore islets present a somewhat domal, structural profile due to its basaltic to sedimentary nature (with a prominent sand dunes cover). Only Frade shows steep, rugged outlines due to its volcanic origin.

The southern coast is much more indented, being also a structural feature, oriented in relation to the dominant winds. The upper slopes are usually composed of phonolitic masses, with embayments in tuffs. Everywhere, marine erosion is powerful, with swells from SE having the strongest erosional effects and coastal evolution is most advanced. In the

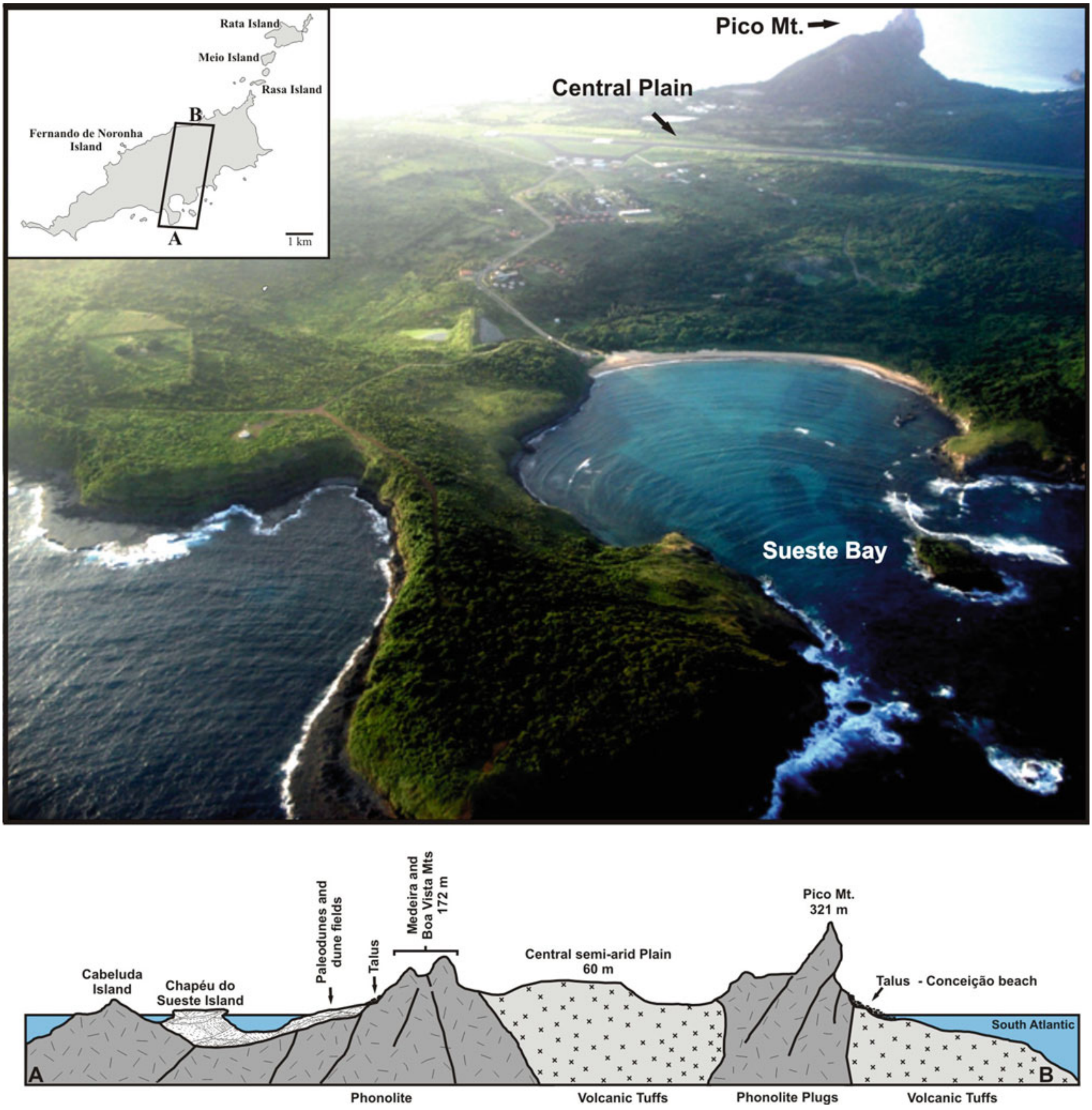

Fig. 7.2 Fernando de Noronha main landforms, viewed from a geomorphological and geological transect between Morro do Pico and Sueste Bay, illustrating the paleodunes complex of the southern coast superimposed on weathered phonolite slopes of Medeira and Boa Vista Hills. The Chapéu do Sueste Island is a relic of a former larger Late Quaternary dune field system, at lower sea level regime, now eroded by strong southern winds and ascending sea levels

northern coast, waves are less destructive and the coastline in general is straight, with longer beaches. Along the southern and eastern coasts, calcareous reefs formed by Lithothamnium algae are best developed.

In general, the coasts are steep, rugged, with precipitous slopes descending down to the sea level. Sheltered bays are rare (Caieira Bay, Santo Antonio harbour). Although marine erosion is powerful, inland denudation is slow in the interior.

The insular platform with less than 50 m deep waters surrounding the archipelago extends over 3 km N off Quixada beach, and 3.5 km SE of Caracas Pt. These appear to represent the maximum breadths of the platform, exposed

Fig. 7.3 View of Pico Mt., Fernando de Noronha Archipelago, South Atlantic

during the last glacial maximum. On the other hand, depths of 738 m occur 2.5 km S of the Sapata Peninsula and here the platform appears to be narrowest, eastwards as far as Pt. Capim Açu.

Marine terraces occur here and there, suggesting several higher sea levels in previous times and the widespread sand dunes, now eroded by the ascending sea, testify to a much lower sea level than that of today during the glaciations, and a very arid climate capable of reworking and redistributing the carbonate-rich sands from the exposed reefs towards inland.

7.3 Trindade Archipelago

7.3.1 General Aspects

The most recent, heterogeneous and topographically varied volcanic island of Brazil, Trindade, still remains an open area for research, since its early discovery. The island is located more than 1,140 km from the Brazilian coast, being the most isolated oceanic island in Brazil, and at the lowest latitude (Fig. 7.2).

The climate is rather equable, but irregular and wetter than Noronha. The wettest months are April and May. The islands possess a great climate variation with altitude, ranging from semi-arid to humid tropical, although there is no climate record from the higher plateau, where frequent cloud condensation results in greater moisture and vegetation growth. Strong winds are typical throughout the year, coming from SE and NE, the latter especially in summer.

The Trindade island was visited by explorers and scientists participating in the expeditions of James Cook in 1775, James Ross in 1839, the Challenger ship cruise in 1876, and La Perouse in 1887 (Almeida 2000). Prior (1900) examined the geological material collected by the expedition of James Ross, highlighting the volcanic nature of the island and its resemblance to Fernando de Noronha. The Brazilian João Alberto expedition in 1950 represented a pioneer study of geology and soils, carried out by Veltheim, Andrade Ramos

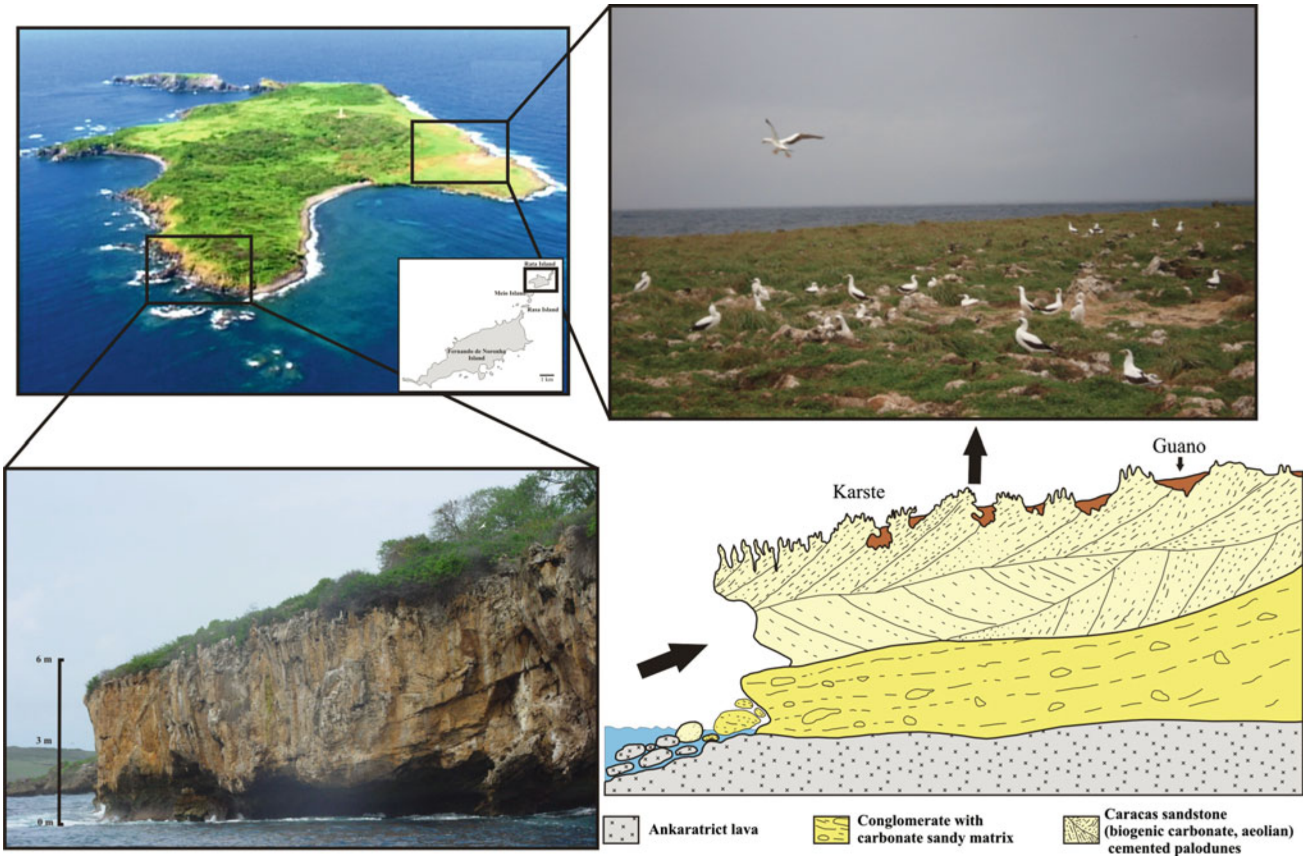

Fig. 7.4 Coastal landform at the Rata Island, showing the marine platform supported by lava, overlain by a sequence of conglomerate to aeolian calcareous sandstone (cemented paleodunes). The latter has been strongly dissolved by acid solutions and guano, giving way to typical karst features with lapiez, unique to the Brazilian oceanic islands

and Paul Vageler (Veltheim 1950), while Almeida (1961) published a seminal study of the geology and geography of Trindade.

The island is entirely volcanic, emerging from the oceanic floor with no relation to the continental shelf, forming an easternmost outpost of the Vitória-Trindade volcanic oceanic chain, aligned east-west. By far, the most important geological contribution is that of Almeida (1961) and his large-scale geological map (1:10,000) is very detailed and consistent. This author recognised five distinct volcanic phases, typified by characteristic lava outpourings.

The Trindade Complex forms nearly 85 % of the exposed rocks of the island, comprising a heterogeneous assemblage of pyroclastics and eruptives (Almeida 1961, 2000). They represent the oldest volcanism and have been drastically eroded. The original volcanic structures have been greatly worn down, and thick talus masks the contacts, while the rocks are apparently deeply weathered. The pyroclastics are poorly stratified deposits with 120 m thickness and are found at Portugueses beach, Pico Desejado, and Vale Verde. Phonolitic pyroclastics include lapilli-tuffs, tuff-breccias and breccias.

Some 16 prominent phonolite domes and necks can be recognised (examples in Fig. 7.5), of which the largest, Morro Branco, is 450 m in diameter. Monument is an extraordinary structure that rises 400 m sheer from the sea and was claimed by Almeida (1961, 2000) to be probably one of the world finest examples of a volcanic neck. Columnar jointing is a notable feature of many necks, e.g. Pico Vigia, Preto, Desconhecido, resembling small replicas of the famous Devil's Tower, Wyoming, U.S.A.

The oldest volcanic episode, that of the tannbuschites of the SW, is represented by fluidal lavas forming fine-grained dykes, in which the abundance of bombs and volcanic glass indicates a process of fire fountaining. The phonolite peaks seem to have more than one origin. Some appear to be monolithic viscous lava intrusions of cylindrical form (Almeida 2000). Other pinnacles of phonolite correspond to cones with a much great diameter than feeding conduits. These bodies have diameters much greater than the monolithic intrusions—up to 450 m. The best examples are the Picos Grazinas (Fig. 7.5), Pontudo, Vigia and Desconhecido. The emission of these very viscous phonolitic lavas to form necks and domes was accompanied by violent explosions,

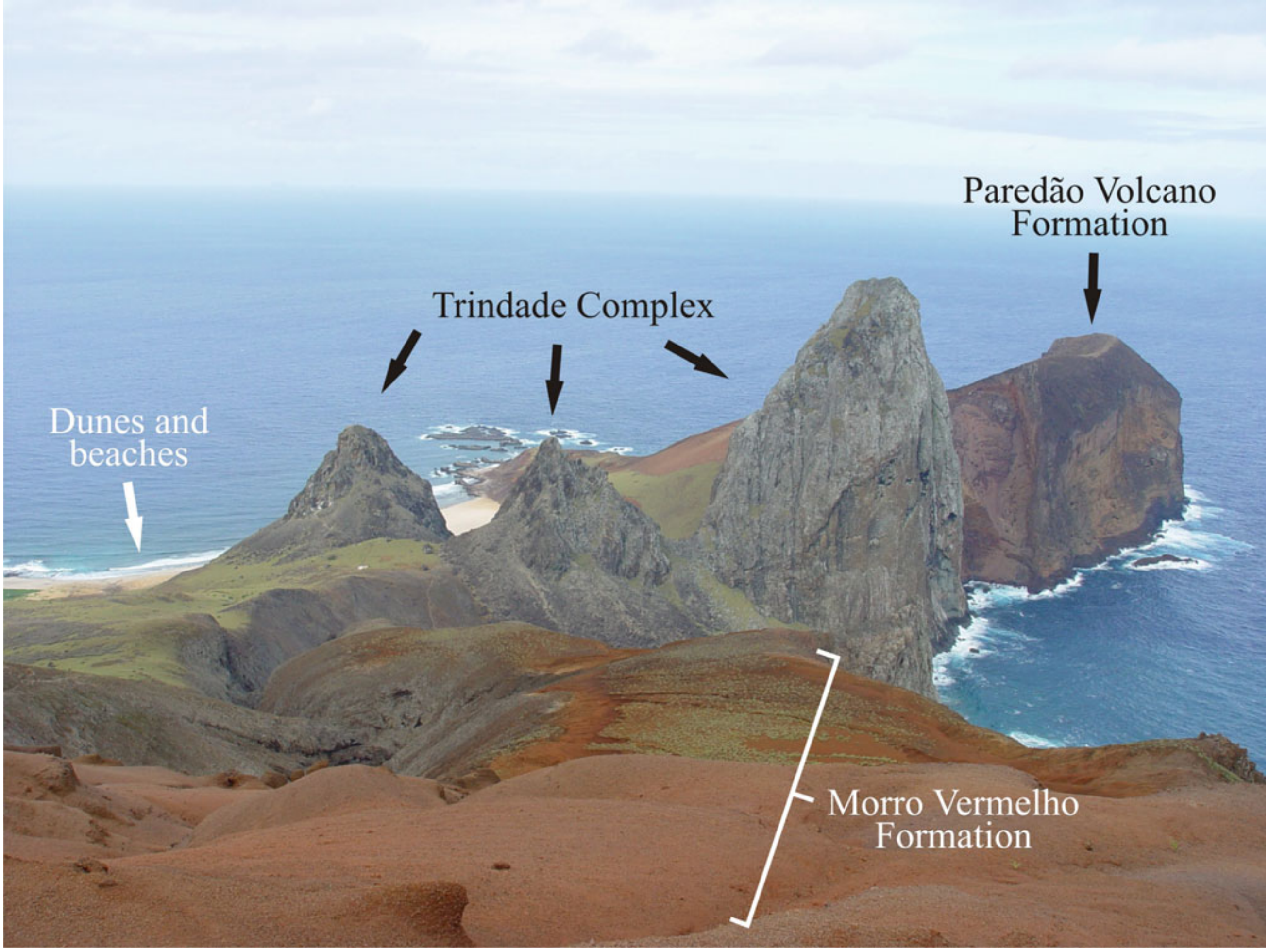

Fig. 7.5 Panoramic view of the Vermelho Valley (Morro Vermelho Formation) with its deeply incised canyon cutting on Late Quaternary lava flows and pyroclastics; in the background, we can observe a sequence of resistant phonolitic necks and domes (Trindade Complex), from *left* to *right*: Lourdes, Vigia and Pão de Açucar; a northern face of Paredão Volcano, entirely supported by red pyroclastics and Tartaruga beach with calcarenitic sandstones and dunes

forming the pyroclastics which constitute the greater volume of the island (Almeida 1961, 2000).

The Central Plateau comprises a succession of phonolite, grazinite and nephelinite flows, intercalated with pyroclastics of the same composition, called the Desejado Sequence. Between Pico Desejado and Portugueses beach, the thickness reaches 400 m towards the west. Topographically, the formation is represented by a plateau with gently sloping volcanic beds. Rising above this Central Plateau are the highest peaks of the island, São Bonifácio, Trindade and Desejado, formed by phonolitic flows up to about 100 m in thickness.

The phonolite and analcite-phonolite flows are resistant rocks and maintain the altitude of the plateau. West and south of Pico São Bonifácio nephelinite flows occur. The phonolites, much more common than the nephelinites, are typically massive, homogeneous rocks, but the top and base of flows become vesiculated and filled with amygdales (Almeida 1961, 2000). Vertical contraction joints are in the lower part of the sequence. Phonolite flows may be up to 16 m thick, and in the upper Cachoeira valley, scarps extend for hundreds of metres with little variation in thickness. Pico Desejado comprises phonolite flows some 160 m thick on the north-eastern, but much less on the western slope.

After the alkaline volcanism of the Desejado Formation, a long cycle of erosion took place. Then, volcanic outpouring reactivated, giving place to the Morro Vermelho Formation (Fig. 7.5). The volcanic and pyroclastics of this phase are the products of a single and continued series of explosions and outpourings from a centre located in the upper Vermelho valley, near Morro Vermelho. After the older phases of volcanism, fluvial erosion carved out this deeply incised valley, bordered by necks and domes rising above marginal interfluvial areas built of pyroclastics and eruptives of the Desejado phase. The Vermelho volcanism filled the valley with more than 200 m of ankaratritic flows and intercalated pyroclastics of the same composition (Almeida 2000).

The flows poured down north-eastwards towards the Andrade beach, where they are well exposed in cliff sections. While the Vermelho volcanic are limited to the eastern part of the island, it should be noted that ankaratritic flows also occur at Paredão volcano (Fig. 7.5), being of younger age.

The pyroclastics are mostly lapilli-tuffs, with blocks and bombs, which change locally into tuff-breccias and agglomerates. At Point Pedra, ashy tuffs are exposed in the cliffs. The granular components of these pyroclastics include ankaratrite fragments of angular shape, resulting from explosive fragmentation, to form driblets, bombs, typical “Pelée tears” and blocks (Almeida 2000). Blocks may exceed 1 m in diameter, and bombs vary from 3 to 8 cm in diameter, the latter having vesicular or even scoriaceous interiors with vitrified crusts more than a centimetre thick. The pyroclastics are highly porous and subject to rapid weathering, with a thickness of 50 m.

Volcanism was centred in the interior of the island in a large depression carved out of the Complex and Desejado rocks, and the eruptions were focused on the upper slopes of this depression. The ankaratritic magma was very fluid and had large gas content, so that emissions were largely in the form of pyroclastics, whose components were expelled into the air in a pasty condition, similarly to a fire fountaining (Almeida 2000).

Morro Vermelho is an eroded remnant of this ankaratritic pyroclastic accumulation, but located at a higher altitude than that attained by ankaratritic flows, does not have a lava cover. The emerging flows spilled downwards into the depression as several “rivers” of lava directed to the coast. In the consequence of the Vermelho volcanism, all the area between Pão de Açúcar and Pico Desconhecido now constitutes high relief, dropping down steeply to the southern coasts.

The next volcanic cycle was the Valado Formation. In the vicinity of Valado Point, on the NE coast, are the dark flows interbedded with deposits of a large cone of dejection. Here, there is an extensive stretch of talus deposits leading down to the coast, indicating the proximity of a vent where tanbuschitic filaments, bombs and smaller clotted masses were expelled (Almeida 2000).

The pyroclastics comprise lava fragments of various forms. The present thickness of the agglutinated pyroclastics is ca. 20 m, but originally it must have been thicker. These agglutinated deposits also occur in the Vermelho formation and at Paredão Volcano, of older and younger date, respectively. The slopes are clothed by talus deposits from a large dejection cone which evidences a recent volcanism.

The rocks of the Valado formation and their spatial relationships indicate that the coastline rose sometime before the onset of this volcanic phase, and a vent appeared through which very fluid lavas in moderate volume were extruded.

The latest volcanic phase is that of Paredão Volcano, which represents the only part of a volcano to be seen in Brazil (Fig. 7.5;). The volcano structure is the eroded remnant of a much larger structure which was rapidly attacked by marine erosion. The crest of the crater rises some 217 m above sea level. Except in its NE part, where ankaratrite flows are exposed, the structure is formed entirely of pyroclastics.

The pyroclastics chiefly comprise lapillitic tuffs, as blocks, bombs and driblets, associated with tuff-breccias and agglomerates. Ashy tuffs, ash and lapilli are also present. Blocks and bombs are in places highly vesiculated and become scoriaceous where attacked by the waves. Dips of 40° are visible. The most spectacular exposures are seen in the cliffs the vicinity of the tunnel that cut across the volcanic edifice, at its entrance. Here, a prominent marine terrace is located, where resistant, quite well-stratified beds of lapillitic tuffs, with enclosed bombs and blocks, pass locally into tuff-breccias and breccias, the transition being either gradual or abrupt.

The ankaratrite flows poured down towards the north and are exposed in the Tartarugas Bay area, both along the cliffs and up to 300 m inland. In general, these lavas are highly vesiculated, become scoriaceous in the upper part of individual flows, favouring rapid weathering into brownish-yellow earthy material. Veltheim (1950) maintained that pillow-lava structure occurred in these lavas, but Almeida disagreed, claiming this was merely a form of spheroidal weathering, which indeed did give a superficial appearance of pillow structure. The flows at Tartarugas beach dip angles of 6° to 12° towards the sea.

The Paredão rocks display many large vertical joints which can extend across the full height of the great walls. In plan, the joints show a radial pattern, presumably related to compression within the vent. It is the close vertical spacing of the joints rather than the friable nature of the pyroclastics which enabled the sea to excavate the large tunnel opening here, a remarkable geomorphological feature of Trindade.

The Paredão Volcano rose from a shallow marine platform to the east of Pão de Açucar and Tartarugas. The base of the volcanic accumulations occurs near sea level on a marine terrace 3 m above the sea. This small initial elevation was rapidly built upon to form a large “apron” to the east of these peaks. Paredão was built as a scoria cone, with which the ankaratrites flows were associated. Indeed, most of the magma volume was expelled as ejecta in the manner of fire fountaining, raising a cone some 200 m in height, with a crater radius of some 300 m (Almeida 1961, 2000). The abundance of bombs, driblets and agglomerates shows that the magma, highly charged with gases, burst forth in clots which accumulated as a cone. As blocks are few, we presume that the explosive action was not violent.

Paredão is presumed to have been of Strombolian type, which likely also applies to the Paricutin, México eruption of

1943 and the Ilha Nova, Azores, eruption of 1957. Such volcanoes may be active for weeks, months or years, but Paredão had a short life, probably months or even weeks. This last volcanic phase of Trindade probably occurred in post-Glacial times, as dated by Cordani (1970) for around 5,000 years B.P.

On many beaches, cemented calciferous sandstones (calcarenites) occur, which consist mainly of fragments of calcareous algae with rather unstable mineral fragments, such as sanidine (Fig. 7.5). The detrital components of these sandstones are identical to the sandy beaches of the island today. These calcarenites are scattered flat platforms located 2–3 m above the present sea level, being very similar to those described in Fernando de Noronha by Almeida (1955). These features are former carbonate-sand dunes, which, under the action of south-east winds, moved towards the higher parts of the island (Schobbenhaus et al. 1984). Field observations indicate that most beach sands are current products of erosive reworking of calcarenite platforms that surround the island (Schaefer et al. 2005). Similar features have been described for Rata Island in the Fernando de Noronha Archipelago (Oliveira 2008).

Clemente et al. (2006) made the first characterisation of landforms and soils of the Trindade Island, emphasising chemical and physical properties in different geoenvironments. Soils in Trindade are the result of lithological, topographical and vegetation influences, frequently in close interplay.

Soil chemical, morphological and physical analyses were performed and the results indicate the occurrence of unique features that suggest an endemic character. The pedodiversity on Trindade is primarily related to the parent material and topographical variations. Soils generally have high fertility, particularly in terms of calcium and phosphorus contents associated with bird excreta inputs (Firme Sá 2010). On the southern side of the island, with a cooler and wetter climate, narrow valleys and steep slopes shelter a more exuberant vegetation of giant ferns, with accumulation of fibrous organic material even on steep slopes, forming atypical Histosols. Soils at an altitude of over 400 m are more acid and nutrient-poor, but phosphorus contents are still very high, which is attributed to bird activity (ornithogenesis), similar to Rata (Fernando de Noronha) and Abrolhos islands. On the northern side of the island, where semi-arid to tropical dry climates prevail, soils are shallower, nutrient-rich and highly eroded, with the dominance of Litholic or Regolitic Neosols. Some pedological features of Trindade soils prevent an appropriate fitting by the Brazilian Soil Classification System, calling for adaptations of various classification levels for an adequate classification (Clemente et al. 2006).

7.3.2 The Geomorphology of a Volcanic Island: A Rich Assemblage of Morphotectonic Features

Trindade can be divided into six basic geomorphological units (Fig. 7.6).

The Central Plateau (I) (Fig. 7.7), with gentle slopes, generally above 350 m, is formed mainly by alkaline rocks (phonolite, granizite and nepheline flows) with intercalated layers of pyroclastics, supporting a high-level structural planation surface. The highest crest at the plateau is the main watershed, and the porous nature of the saprolite accounts for the intense water recharge of Trindade, helping to maintain small drainage channels, now greatly impacted by long-term erosion. Several phonolitic Domes and Pinnacles (II) rise above the plateau (Fig. 7.7), separated by deeply incised ravines or valleys. They represent nuclei of resistant volcanics and plugs. The most outstanding prominence is the inaccessible Obelisco. Volcanic slopes (III) (Fig. 7.7) are basically formed by pyroclastics and connect the edge of the Central Plateau with the marine terraces or shorelines. Several phonolitic necks and domes rise conspicuously above the steep

Fig. 7.6 Panoramic view of six geomorphological units of the Trindade Island: I—Central Plateau; II—Domes and Pinnacles; III—Volcanic Slopes; IV—Ankaratritic Plateau; V—Phonolitic necks and domes arc, and VI—Paredão Volcano

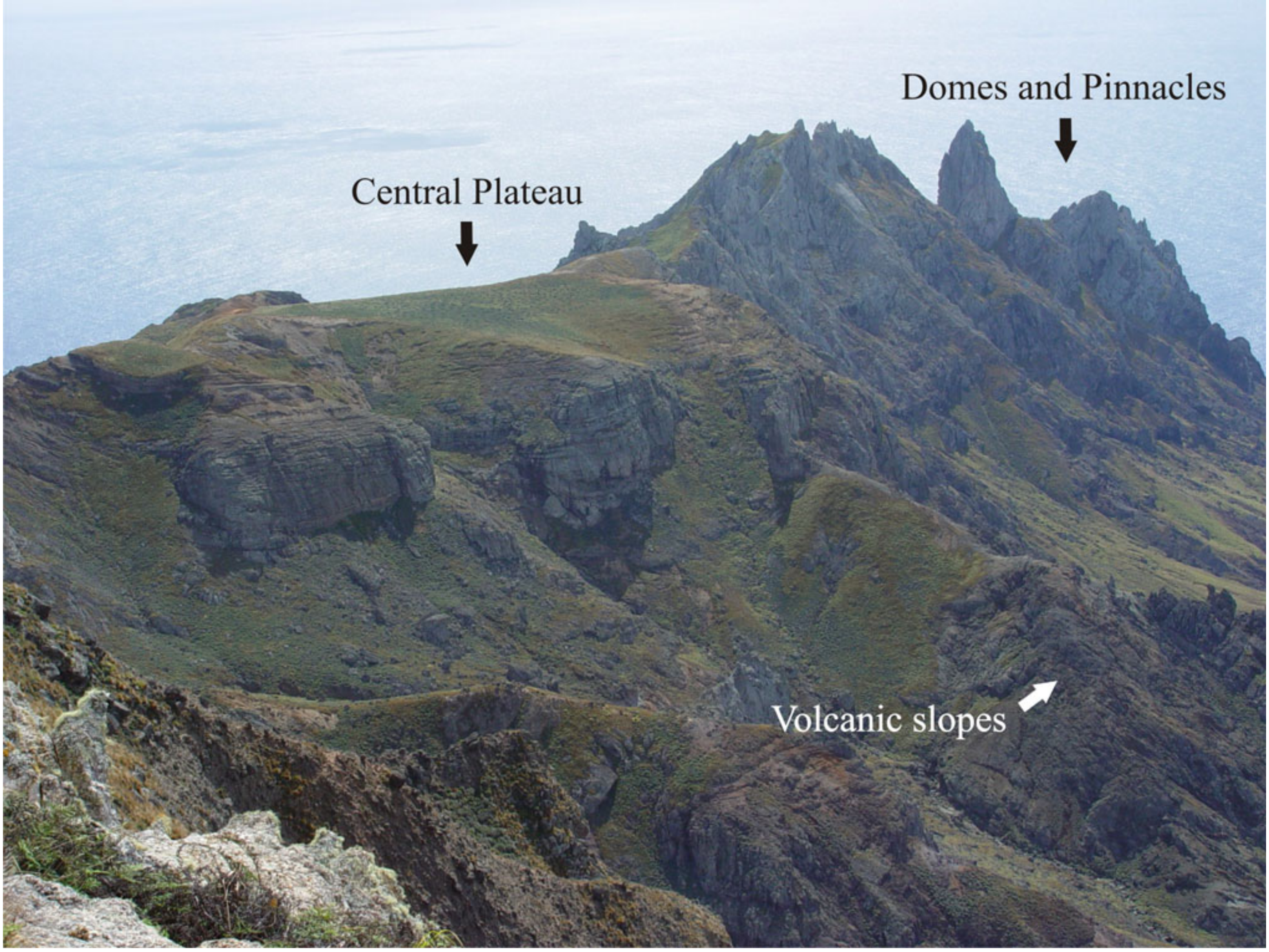

Fig. 7.7 Central (Desejado) Plateau from the Trindade Peak, highlighting the flat top cutting across phonolitic flows and bordered by steep talus cones. In the background, domes and pinnacles above the plateau

slopes, the latter heavily eroded. The Crista de Galo, at the northern extremity, is really a narrow finger of the Central Plateau and also includes the volcanic slopes. From the high axis of the plateau, the land drops steeply down to the E and W in a series of concave-shaped scarps. A distinct NW grain is evident here, with fractures, dykes and the topographic crest all trending in this direction. The Ankaratritic Plateau (IV), in the east, is a concordant feature inclined towards the NE, descending from an elevation of some 500 m at Morro Vermelho down to 40 m, with a perfect match between the slope and the dip of the lava flows (Fig. 7.5). Several ravines drain this surface directly down to the coast, where ankaratrite cliffs border the sea. As previously mentioned, the upper part of the Vermelho valley is filled with pyroclastics of the Vermelho and Paredão formations. Phonolitic necks and domes arc (V) separate the above plateau from the Paredão volcano to the E. Before building of this volcanic pile, these necks and domes formed the eastern extremity of Trindade. Paredão Volcano (VI), a notable morpho-structural volcanic feature, represents the ruins of the youngest volcanic structure in Brazil (Figs. 7.5 and 7.6).

Marine erosion has been chiefly responsible for wearing away of the Paredão Volcano. On the Central and Ankaratritic Plateaux, chemical decomposition has progressed much farther than erosion and mechanical disintegration, resulting in the regolith of moderate thickness, mantling the gentle slopes and undulated terrain.

The scarps and slopes surrounding the Central Plateau, as well as the phonolitic peaks and the Paredão volcano have all evolved through the process of sudden and rapid downhill movements of detritus. While the majority of such movements occurred in the dry state, under the action of gravity, running water also played its role. Around nearly all steep necks and domes, aprons of talus deposits are spread out lower down, where irregularly shaped, angular blocks of all sizes have moved downhill.

Active marine cutting back of the cliffs maintains steep, longitudinal profiles for water courses. The valleys carry water only during the wet period, when they become short-lived torrent, capable of moving rubble which has fallen off the side slopes under the action of gravity, and then down the valley by fast-flowing streams.

The distinction between mass gravitational movements and torrential movements is not always easy, for the relatively short distances of fluvial transport mean little rounding of detritus, as well illustrated by talus and alluvial cones. Materials that constitute these cones differ little from the pyroclastics and eruptives from which they originate, being merely the disintegration products thereof.

All slope and alluvial depositions are not fully active at the present times, and this would seem to indicate former geomorphological processes quite different from those of the present-day. The relatively large extent and thickness of the detrital cover accumulated towards the shores (Fig. 7.8), now experiencing rapid erosion, suggest a previous lag deposition and an inland relief with mass movements unable to reach the present sea level. After the deposition of the mantle debris on the lower slopes adjacent to the shorelines, progradation resulted in slopes undergoing abrupt decrease in declivity, with consequent deposition.

Since the present mass movements and torrential transport look competent to move any large-size detritus from upland sources down to the coasts, it is assumed that in former time, climate was considerably drier than at present, thus reducing stream volumes, stream competency and also reducing the lubricating medium for gravitational movement.

Although aeolian erosion and deposition are less important compared to fluvial and marine processes, or compared with Noronha Island, we do have evidences of wind erosion in Trindade. The NE slopes of Morro Vermelho, formed of

Fig. 7.8 Extensive and thick debris-slope deposits accumulated towards the shores

Paredão tuffs, are subjected to intense deflation, giving rise to small Yardangs. Polishing and characteristic striation of ankaratritic flows can be seen in the Tartarugas region. At Tartarugas, Andrada and Cabritos beaches, we find small dune accumulation. Dunes up to 45 m above sea level are observed, and a dune 120 m in length and 10 m high lies at the base of Picos Tartarugas and Lourdes.

The young, irregular coastline is pounded by great waves having a very long fetch, with very stormy seas during winter months. The coast was carved principally by subaerial processes when sea level was lower than at present, but the narrow, discontinuous abrasion platform was sculptured at present sea level.

At no time was there was any alluvial deposition by streams, and the littoral is basically the result of marine processes. Strong wave action on the marine platform, with vigorous cliff recession, facilitated the formation of detritus which was carried seawards on to the platform. Thus, beaches are relatively few, narrow, and generally made of pebbles accumulated in privileged localities, and full of dark minerals.

The scale at which these process operated naturally varied, and thus along the NE coastline scarps have receded farther, beaches are more frequent and larger, with sandy and pebbly beaches, dunes and reefs. Elsewhere, only at Principe Bay is the littoral well developed, although marine erosion has operated differently here. The more resistant phonolitic masses of Cinco Farilhões and South Points, Morro Branco and Pão de Açucar, all rising steeply from deep waters, have caused significant wave deflections. Between these masses, the tuffaceous sector form gentle sloping coasts, furnishing much detritus to form pebbles on the beaches.

The abrasion platforms are relatively poorly developed in Trindade, testifying to the younger ages of geological events in Trindade. Between Calheta and Pico Tartarugas is an abrasion platform, exposed above low tide, made of ankaratritic lavas upon which lie beach sands at an elevation of 3.2 m above the present mean sea level. Lowering of sea level exposed this platform over which erosion products more than 4 m thick were deposited. The beach was formed by agitated seas during high tide bringing carbonate-rich sands from deeper water. This is confirmed at Andrada beach, where calcareous-cemented sandstones (beachrocks) lie between 2.8 and 3.5 m above the present sea level. At Paredão, especially where the tunnel opening occurs, a marine terrace 3.5 m above present sea level also can be seen.

The submarine terraces at −47, −59 and −77 m off Trindade have close correlates with similar terraces on the continental platforms of the world, which most frequently occur at depths of 29, 47.5, 62.5, 79.2 and 91.5 m. This suggests that submerged terraces of Trindade are of glacio-eustatic, epeirogenic or mixed origin. Almeida (2000) believed these terraces were sculptured during oceanic volume fluctuations related to the glacial–interglacial episodes of the Pleistocene.

7.4 Conclusions

1. The Brazilian oceanic islands are privileged places for studying unique landforms, evolved under an active tectonic setting and humid to semi-arid climates of marine influence.
2. The landforms of Fernando de Noronha are older, and extensive weathering occurred prior to general erosion of the less resistant rocks and saprolites.
3. Phonolites necks, pinnacles and domes are the most prominent landforms on both islands, owing their existence to structural resistance and wider jointing and fracturing.
4. Late Quaternary volcanism at Trindade resulted in the preservation of younger volcanic features, such as caldera remains, volcanic platforms and slopes, lava and scoria fields and dark-sand beaches formed by high contents of primary minerals such as magnetite, as well as storm beaches of large clasts (cobbles).
5. Trindade and Noronha islands show marked polyphasic aeolian features at some coastal sectors, with sand dunes of bioclastic carbonates, the latter of greater extension in Noronha than in Trindade.
6. Uplifted marine terraces are found on both islands, associated with former higher sea levels. In contrast, the presence of submerged terraces at Noronha and Trindade is related to a combination of glacio-eustatic variations (low sea levels) and epeirogenic uplift.
7. In Noronha (Rata Island), there is unusual case of oceanic karst landscape developed on calcareous sandstone, with abundant lapiez and dissolution features.
8. Trindade and Noronha have ornithogenic soils of great importance for paleoecological studies of former bird colonies in these isolated islands.
9. The most prominent landforms are structural and tectonically controlled, and the degree of erosion in Noronha advanced much farther than in Trindade, exhuming preexistent volcanic necks and similar structures, forming complex and impressive landform scenery.
10. Trindade reveals unique, endemic landscapes formed by pure stands of arboreal ferns (Cyathea sp.), where deep organic soils developed. Fluvial erosion is very limited, but there is evidence of a former greater importance of run-off in Noronha and Trindade.

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The Lençóis Maranhenses: A Paradise of Dunes and Ponds

8

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Abstract

The Lençóis Maranhenses, located in the coastal zone of Maranhão State in north-eastern Brazil, is home to one of the largest coastal dune areas formed in the Quaternary. Because of the exuberance and diversity of the Lençóis Maranhenses ecosystems, a part of this area was transformed into a federal conservation unit called The Lençóis Maranhenses National Park (Parque Nacional dos Lençóis Maranhenses; PNLM). The vast fields of white sand dunes interspersed with green and blue ponds and associated with 'restinga', deserted beaches, warm water rivers and exuberant mangroves form beautiful landscapes that attract increasing numbers of tourists. The origin and development of the Lençóis Maranhenses dune fields is related to, among other factors, climatic and sea-level variations, as well as the accumulation of sediment associated with the regime of waves, currents and tides in this area of the Maranhão coast. The results of dune morphodynamics studies conducted in the south-eastern sector of PNLM indicated migration rates of 4–25 m/year as a function of climatic conditions and natural barriers. The evolutionary model proposed for Lençóis Maranhenses identified four linking areas where dune sands are in continuous motion. Regarding the geochronological aspects, the ages of the stable dune fields suggest at least three alternating phases of strong wind activity followed by periods of high humidity, resulting in the stabilisation of dune forms, primarily during the Holocene period.

Keywords

Dune fields • Ponds • Lençóis Maranhenses • Maranhão/Brazil

8.1 Introduction

The Lençóis Maranhenses, located on the eastern coast of Maranhão State (Fig. 8.1), is distinguished as the most remarkable coastal dune field in Brazil; this field developed over the Late Quaternary. In this region, generations of vegetation-fixed fossil dunes can be observed along with recent dunes, which are relatively close to the shoreline and, in some places, encroach on the earlier dunes. Because of the exuberance and diversity of the ecosystems along the Maranhão Coast, north-eastern Brazil, on 2 June 1981, the Lençóis Maranhenses National Park (PNLM) was created. The PNLM is a geological site in Brazil that comprises 155,000 ha and a 270 km perimeter of peculiar nature and size, thus making it suitable to studies concerning its genesis, which has been associated with the local wind dynamics. The crystalline interdune ponds are among the most visited morphological traits in the park (Fig. 8.2).

The Lençóis Maranhenses region is characterised by extensive beaches, sand sheets, dune fields, rivers, mangroves, lagoons and 'restingas' (beach ridges). This region

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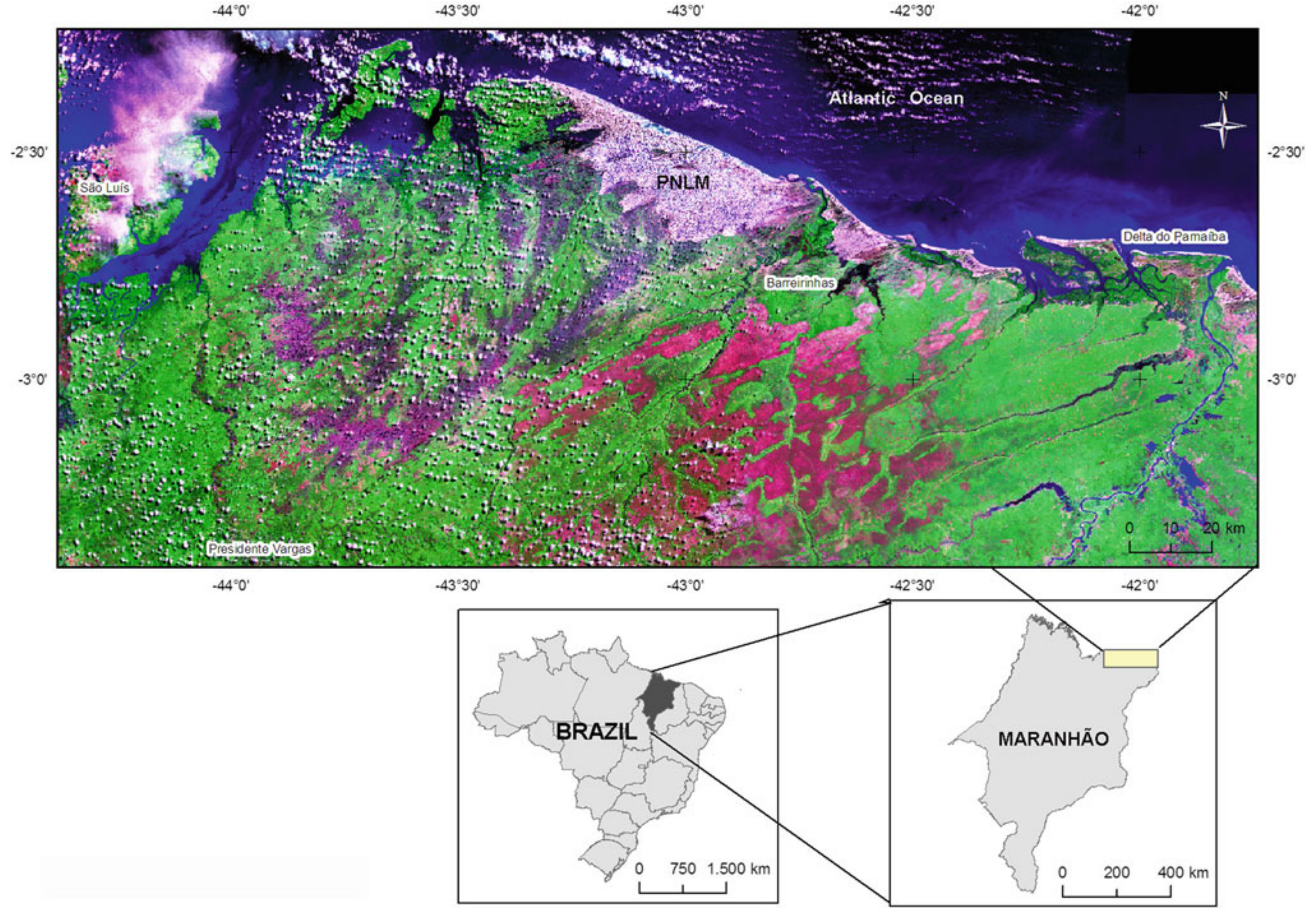

Fig. 8.1 Satellite image of the Lençóis Maranhenses region, located between São Luis and the Parnaiba Delta. *Source* Santos (2008)

has potential for the development of nautical activities, such as swimming in the ponds, waterfalls, rivers and sea, walks on the beaches and dunes, photography and enjoyment of the landscapes, sunsets and bird watching (local and migratory species). In the areas surrounding the PNLM, surfing, canoeing, adventure tourism, rustic camping, horseback riding, and all-terrain vehicle (ATV) and water tours are common, in addition to flights in small aircraft or helicopters to admire the beauty of the local landscape. Given its diverse morphological features and natural resources, the Lençóis Maranhenses (Fig. 8.2) is increasingly recognised as a tourism attraction for nature lovers.

8.2 Geoenvironmental Characterisation

The Lençóis Maranhenses are bounded to the north by the Atlantic Ocean, to the south by the dissected tablelands of the Barreiras Formation, to the east by the Parnaíba River (Piauí State) and to the west by the São José Basin (Maranhão State; Fig. 8.1) and the Itapecuru, Munim and Periá rivers. Geologically, this region is located in the Barreirinhas Basin (itself formed during the Cretaceous period), which mostly comprises the north-eastern portion of the state of Maranhão. This sedimentary basin is bordered to the north by the Atlantic Ocean and, in the south, by a series of normal faults and the Férrer-Urbano Santos Arch. Eastward, the basin is limited by the Piauí Graben and the Parnaíba Plateau, while westward, it is limited by the Ilha Nova Graben.

Regionally, the Férrer-Urbano Santos Arch constitutes one of the most important tectonic structures in the emerged basin area. According to Gonçalves (1997), this arch corresponds to a high crystalline basement structure that surrounds the Barreirinhas-São Luís and Barreirinhas-Maranhão basins and originated from fissural volcanism that occurred at approximately 120 Ma. The emerged area of this basin was, according to Pamplona (1969), calculated to be 15,000 km^2 and approximately 250 km long by 60 km wide, with a maximum depth of approximately 7,000 m and of Cretaceous age (Albian-Campanian). In terms of geostructure, the Barreirinhas Basin was formed on the equatorial margin in the Late Cretaceous from the rift that caused the separation of continents (South American and African plates) and consequently the emergence of the Atlantic

Fig. 8.2 A partial view of the fields with mobile dunes in the Lençóis Maranhenses National Park, Maranhão State/Brazil (Photograph by Meireles Junior)

Ocean (Veiga Junior 2000). The crystalline basement contains gneisses, granites and quartz-mica schist of Precambrian age. The Cretaceous sediment package (terrigenuous clastic continental) from the Canárias Group (Feijó 1994) of Albian age overlaps these rocks. Next, the Caju group represents a marine transitional sequence characterised by Albo-Cenomanian age (100 ma) clastics and carbonates, representing the beginning of marine sedimentation in the basin. These sequences are bounded by unconformities caused by declining sea levels. According to Feijó (1994), the Humberto de Campos Group, which overlaps the Caju Group, comprises shales, fine sandstones and carbonates that represent the passive phase of the basin's tectonic process. The Pirabas Formation (Upper Cretaceous/Tertiary) is above this group and corresponds to a 3,500-m-thick layer of rocks formed of conglomerates, continental and marine sandstone, shales and marine limestones (Brown et al. cited in Gonçalves 1997) that developed throughout the basin and cover the Cretaceous sediments (Pamplona 1969). The Pirabas Formation crops out in restricted areas of the basin. The Quaternary sequence, formed of sediments deposited in fluvial, coastal and aeolian environments, rests unconformably on the thick layer of Cretaceous to Tertiary rocks. The Quaternary sediments of the Açuí Formation, comprised predominantly of quartz sands, virtually cover the entire Barreirinhas Basin. The maximum thickness of the Quaternary sequence varies from 15 to 50 m (Pamplona 1969).

Geomorphologically, the area in consideration, according to publications from the RADAM (Brasil 1973; Maranhão 2003) projects, is located in the Lençóis Maranhenses geomorphological unit. This unit comprises an extensive coastal plain characterised by mild to moderately undulated relief, in which large areas of mobile and fixed dunes of various shapes and sizes are commonly found and where barchan, parabolic and oblique dunes stand out, along with chains of barchan, parabolic and transverse dunes. In addition to the dunes, wind deflation plains, dune beds, 'restingas', sand spits, sandy banks and terraces, ponds, lakes, lagoons, river islands, and flood and tidal plains with or without the presence of mangrove vegetation are also present in this unit. The coastal plain in which the PNLM is located contains approximately 70 km of deserted white beaches with pristine waters. The PNLM dune field has some of the typical features of classic deserts, including temporary rivers (wadi), intermittent ponds, sand sheets, dunes and dune displacement paths (current and ancient) that are, in some cases, well preserved and laterally bounded by ridges disposed as linear tracks (Santos 2008). In addition to these features, the seasonally flooded depressions in the towns of Baixa Grande and Queimada dos Britos, located in the central area of the dune fields, are equivalent to classical oases. However, the use of the term 'desert', especially by the media (newspapers, magazines and TV), is not conceptually appropriate according to Feitosa (2005) because, geographically, deserts exhibit total rainfall levels of less than 200 mm/year, whereas the Lençóis Maranhenses region receives a total rainfall level that usually exceeds 1,500 mm/year.

According to Gonçalves (1997), Muehe (1998), MMA/IBAMA (2003) and Santos et al. (2009), the genesis of both active and fixed dune fields in PNLM is closely related to the sediment selection consequent to the retrogradation of the Barreiras Formation sediment deposits. This retrogradation and consequent enlargement of the continental shelf, caused by marine transgressions that have occurred since the Pleistocene and are associated with the input of fluvial sediments originating from major rivers such as the Parnaíba and Preguiças, created favourable conditions for the establishment of this unique landscape in Brazil.

An explanation for the regional sand abundance founded in the studied area is presented by Santos (2008). Presently, a complementary explanation is given. This abundance stems from the Parnaíba River deltaic sand deposition, both present and sub-present (Fig. 8.1), as evidenced by the many river mouths and corresponding deltaic lobes, associated with coastal sands and occurring over a large extension of the coastal zone east of the studied dune fields. It is reasonable to assume that, during the last sea transgressive period, a large amount of sand became available to be moved landward by the rising transgressive frontal wave system and associated currents. Those sediments are quartzous sands, dominantly, because the continental platform, after being progressively submerged, was the place where occurred underwater mechanical abrasion and dissolution of other minerals eventually composing former deposits brought to the platform by the Parnaiba River. Therefore, sands of several granulometric classes were disposed on the shoreface by the wave breakers operating under a 2- to 4-m-amplitude tidal system. Finer sands were transported to mainland from this renewable sand source the beach via the constantly NE blowing trade winds system. This complex geomorphologic system is compatible to the presence of the extensive dune fields of the Lençóis Maranhenses.

The areal hydrography is characterised by the presence of bays, rivers (perennial and ephemeral), ponds and lagoons; in particular, the São José, Tubarões and Tutóia bays deserve greater emphasis. The main rivers in this area are the Itapecuru, Munim, Periá, Grande, Negro, Preguiças, Cangatá, Barro Duro and Parnaíba. According to several authors (Brasil 1973; Gonçalves 1997; Santos et al. 2005; Santos 2008), the Parnaíba River, located in the eastern study area, is among the main sediment sources for the Lençóis Maranhenses region. In contrast, the Preguiça River is a tourism route because of beautiful scenery of the area that spans from Barreirinhas (the main regional town with tourism infrastructure) to the villages of Mandacaru or Atins, which are both located at the river mouth (Fig. 8.3). Along an exploratory route, alluvial plains, riparian forests, dune fields, mangroves, beaches, river islands and a sandspit at the mouth of the Preguiças River can be observed. It is noteworthy that in the village of Mandacaru, situated on the left bank of the above-mentioned river, there is a 45-m-high lighthouse built by the Brazilian Navy in 1940; accessible by stairs, this lighthouse provides a 360° panoramic view of the coastal plain (Fig. 8.4).

The Negro River, which is located in the central area of the conservation unit, is the only river that transverses the extensive PNLM mobile dune field from south to north. The drainage network south-east of the mobile dune field displays both perennial and ephemeral rivers, some of which comprise a radial centrifugal drainage, indicating structural control over their development.

Numerous interdune, temporary and/or permanent freshwater ponds can be found in the depressions within the active dune field; these are filled by rainwater or the upwelling of groundwater and display different shapes, sizes and depths (Santos et al. 2009). During rainy seasons, the interdune ponds within the mobile dune field interconnect by small intermittent drainage channels that carry flow towards the beaches. The wind migration speed inside the dune field is reduced due to the presence of interdune ponds that hinder dune displacement, especially during the rainy season. This wind movement deceleration was also observed by Claudino-Sales and Peulvast (2002) in the dune fields in Ceará State (Brazil). Permanent ponds also surround the active dune field; these are formed by contributions from small streams (e.g. Lagoa da Colher, Salgadinho and Taboa) or by the damming of rivers (e.g. Esperança and Betânia ponds). One of the most famous ponds in the Lençóis Maranhenses region is the Caçó, which is located approximately 70 km from the coastline to the north and is 5 km long, 200–500 m wide and 10–12 m deep at maximum (Gurgel 2002). However, the largest lake in the Santo Amaro Park is formed of rainwater from the aquifer and the Grande River. Clear water ponds are present in the Lençóis Maranhenses region (Fig. 8.5a, b). These still-pristine ponds are widely explored tourist attractions with tours conducted by local agencies and tour guides, where tourists usually enjoy swimming.

According to the phytogeographical system established by the IBGE (1992), the PNLM vegetation is characterised as primary system (natural), framed by the classification of the areas of pioneer formations, which on a regional scale comprises vegetation with a marine influence ('restinga'), vegetation with a fluvial–marine influence (mangrove), vegetation with a fluvial influence (Alluvial Communities) and grassland vegetation and 'cerrado' (savanna type). In the Lençóis Maranhenses, vegetation predominantly covers the

Fig. 8.3 Aerial view of the Caburé beach and Preguiças River, located in the damping zone of the Lençóis Maranhenses National Park—MA/Brazil (Photograph by Meireles Junior)

coastal plain around the free dune field; this vegetation is named 'restinga' (Fig. 8.6) and mainly comprises species of 'cajuí', *Anacardium microcarpum,* L.; cashew, *Anacardium occidentale*, L.; cocoplum, *Chrysobalanus icaco*, L.; and 'murici', *Byrsonima* sp., among others. The fluvial–marine plain exhibits the red mangrove, *Rhizophora mangle* L., *Rhizophoraracemosa* G.F.W. Meyer; black mangrove, *Avicennia germinans* (L.); and Stearn and white mangrove *Laguncularia racemosa* (L.) Gaert in the lower reaches of the Periá and Preguiças rivers (Santos 2007). Inside the park and in its surroundings, typical 'cerrado' species can be found, including the 'pequi' fruit, *Caryocar cf. coriaceum* Wittm; soursop, *Annona muricata* L.; 'ameiju', *Duguetia echinophora* R. E. Fr; and mangaba, *Hancornia speciosa* Muelle. Arg.

When comparing PNLM flora with other 'restinga' environments on the Brazilian coast, it is possible to observe the existence of endemic species such as *Polygala adenophora* and *Hybantus solccolaris*, which are found in the town of Queimada dos Britos (MMA/IBAMA 2003). It should be noted that, in addition to hydrography, the vegetation in the PNLM area is crucial to reduce dune migration rate in certain sectors of the park, as well as to the maintenance of local biodiversity.

The climate of the Lençóis Maranhenses region is characterised as megathermal tropical, hot and humid to subhumid. The mean annual temperature is relatively high, reaching 27 °C, while the maximum mean temperature ranges from 31 to 33 °C (Maranhão 2002). The area is subject to the marine equatorial air mass and the convergence of trade winds from the north-east and south-east, resulting in a maximum rainfall regime in the summer (January–July) and a minimum regime in the winter (August–December). Approximately 90 % of total annual rainfall occurs during the period from February to May (Fig. 8.7). During the dry season (i.e. from August to December), only 10 % of total annual rainfall occurs (Maranhão 2003). This situation leads to differentiation in the landscape of this aeolian sedimentary system.

The annual rainfall in Barreirinhas is relatively high, 1,623 mm on average (MMA/IBAMA 2003). However, the atmospheric circulation dynamics throughout the Maranhão coastal zone, which is subject to the interference of the intertropical convergence zone (ITCZ), cause great variations in the total annual rainfall. This is exemplified by the rainfall levels in Barreirinhas during the years of 1974 (3,118 mm) and 1983 (623.3 mm). According to Brasil

Fig. 8.4 View of the Preguiças lighthouse, situated in the village of Mandacaru, which allows viewing of the river, beaches, islands, mangroves and dune fields (Photograph by Meireles Junior)

(2001), the winds are predominantly in the NE, ENE, E and N directions on the eastern Maranhão coast, where wind speeds range from 6.1 to 14.1 m/s according to studies conducted during the PNLM management plan.

According to data from the Directorate of Hydrography and Navigation of the Brazilian Navy (Divisão de Hidrografia e Navegação; DHN) and the Marine Forecast, which is provided by the Centre for Weather Forecasts and Climate Studies (Centro de Previsão de Tempo e Estudos Climáticos; CPTEC; www.cptec.inpe.br/ondas/tabuas_mares/), the region between the mouth of the Parnaíba River to approximately the Tubarões Bay (Primeira Cruz, MA) has a mesotidal (ranging from 2 to 4 m), semi-diurnal-type regime that increases towards the city of São Luís (located on Maranhão island) and is subjected to a macrotidal regime (ranging > 4 m). This mesotidal regime is responsible for the significant width of local beaches, where the fine-grained quartz sands, once dried, are transported towards the mainland during low tide. According to Bittencourt et al. (2003), the predominant wave front directions in the area from the Paraíba River mouth to Santana Island are N90 and N45, with wave heights of 0.5–1.0 m. The areal coastal drift from the east–west direction is caused by the incidence of waves oblique to the coastline.

In the PNML rural zone, human occupation is discontinuous, clustered along nearby rivers and access trails, and consists of predominantly small properties of less than 10 ha or small villages that are characterised by their rusticity. The largest population agglomerations are found and more public services are provided in the municipal headquarters, which are located outside the conservation unit.

The Lençóis Maranhenses regional economy is predominantly based on agriculture, artisan fishing, handicrafts and, most recently, tourism. Handicrafts (continuous growth) and tourism (with its many variations) are responsible for the majority of employment and income generation in the private sector of the Barreirinhas Municipality. In the last 5 years, tourism has become increasingly dynamic as a result of improvements to access roads and the establishment of hotels and tourism agencies to serve the increasing numbers of tourists (domestic and foreign) who are attracted by the exceptional beauty of the PNLM, which has been widely publicised (Santos and Xavier-da-Silva 2009).

Fig. 8.5 Partial view of the Lagoa Azul (**a**) and interdune ponds (**b**), located in the mobile dune field of Lençóis Maranhenses National Park/ Brazil (Photograph by J. Santos)

8.3 Evolutionary Model of Dune Fields in Lençóis Maranhenses National Park

The Lençóis Maranhenses region comprises extensive fields of dunes and palaeodunes that exhibit geological and geomorphological characteristics similar to those of other dune fields along the northern coast of north-eastern Brazil. In this context, four zones occur in PNLM and its surrounding areas; these are represented as the supply zone, input zone, retention zone and output zone.

8.3.1 Supply Zone

According to Palma (cited in Muehe 1998), the continental platform in front of the Lençóis Maranhenses region, which mainly receives sediment from the Parnaíba Delta, is 70–80 km wide, having up to 80 m depths. Its cover is made predominantly of sand that forms waves or underwater dunes that move westward, according to the predominant direction of the longshore drift. Thus, the great amount of sand transported by the waves and longshore drift is deposited onto the beaches of both the small and the large

Fig. 8.6 'Restinga' vegetation at the edge of the mobile dune field in the Lençóis Maranhenses National Park (Photograph by N. Santos)

Lençóis Maranhenses. The 70-km extension beaches in front of PNLM are dissipative, with a small slope, a width of 200–400 m, and multiple breaking waves. The sediments comprise predominantly well-sorted medium (0.354–0.250 mm) and fine-grained sands (0.177–0.125 mm). The significant beach area (approximately 20 km^2) receives material from the inner continental shelf and the drainage systems of the Parnaíba and Preguiças rivers (Santos et al. 2005).

Therefore, the sandy sediments deposited onto the beach surfaces, which are exposed daily during the mesotidal cycles (every 12 h), are remobilised into the interior of the coastal plain by the unidirectional winds of the NE quadrant (Gonçalves et al. 2005).

8.3.2 Input Zone

Above the beach environment, particularly in the northern sector of the PNML, there is a large wind deflation plain with a width of 1.0–2.5 km through which the sand beach is transported. During the rainy season (January–July), this plain is characterised by a high density of ponds, temporary lagoons and intermittent bodies of water, which significantly reduce the wind transport. During the dry season (August–December), along with a lowering of the water table, loose sands occur, from which sand sheets originate. These features can be described as a sandy surface of negligible relief that advances as a mantle into the dune field (Barbosa 1997) without exhibiting a slip face (McKee 1979). In the eastern sector of the PNLM, the deflation plain is characterised by the presence of herbaceous vegetation (grasses) and the rare occurrence of sand sheets due to the natural barrier formed by the existing sand spit at the mouth of the Preguiças River, which is responsible for interrupting sediment input into this sector of the park and hence the accumulation of sediment on the right bank of the river. From interpretations of aerial photographs taken from 1976 to 1999 and high-resolution satellite images from 2004, dune beds (displacement paths) can be clearly observed over the deflation plain (Fig. 8.8), indicating the crossing point of the mobile dunes (current

Fig. 8.7 Aerial view of the mouth of the Preguiças River with the presence of a barrier island, sandy beach, traces of dune migration, wind deflation plain and transverse dune field comprising interdunes ponds in the Canto do Atins, located within the Lençóis Maranhenses National Park, Maranhão/Brazil (Photograph by Meireles Junior)

and ancient). Therefore, the presence of sand beds suggests that most of the volume of sand present in the mobile dune field was transported as barchan-type dunes, which in turn suffered deformations of their original morphology to become barchanoid, transverse, oblique and/or parabolic dunes (Santos et al. 2005).

8.3.3 Retention Zone

This sub-system is the most representative of all studied subsystems and can be divided into current and ancient retention zones. The current retention zone comprises mobile dunes of moderately undulating topography with ridges of up to 61 m high. The mobile dune fields are predominantly characterised by fine, well-sorted sediments and are oriented in a NE/SW direction (Santos 2008). Various interdune ponds and first- and second-order drainage channels can be found within this system. The height and volume of the dunes increase as the dunes advance into the coastal plain, with migration rates ranging from 4 to 25 m/year. The lack of significant wind variation in the same quadrant causes the pilling of barchans, which initially originate from the barchanoid chains and later from the transverse dunes. Barchan chains (barchanoids) are formed from the side union of barchans dunes and are the main type of dune found in the PNML (Fig. 8.9). In addition, during the rainy season, the flow in small interdune channels increases within the dune field, from which a chain of oblique dunes emerges as a result of the transformation that occurred in the barchanoid chains (Gonçalves et al. 2003).

'In situ' observations have shown that the increased amount of sand available in this sub-system is inversely related to the distance from the source. In other words, dunes height increases with the distance from the supply zone. This phenomenon was also observed in the dune fields of Paracuru, Ceará State (Castro 2001). From comparisons of multitemporal aerial images, it was observed that the inner dunes next to the fixed dune field had a lower migration rate (4 m/year) because of various environmental factors. Those factors include the larger volume and size of the dunes, an increased density of interdune ponds, the presence of drainage channels that border the mobile dune field, significant distances from the source area, the greater occurrence of vegetation in the inner sectors of the park and considerable amounts of wetlands on the current migration paths during the rainy season.

Fig. 8.8 View of a barchanoid chain with an interdune ponds within the Lençóis Maranhenses National Park, Maranhão/Brazil (Photograph by J. Santos)

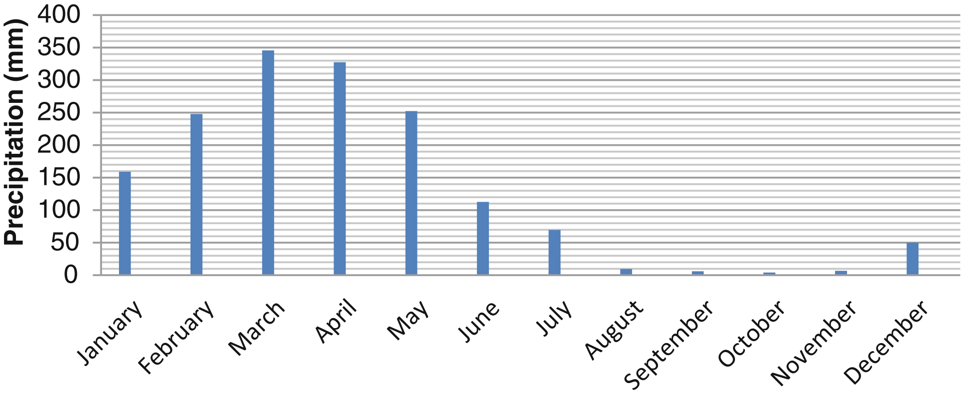

Fig. 8.9 Monthly mean precipitation in the Barreirinhas Municipality (1967–1991)

The fixed dune fields, which are also called inactive or fossil dunes (Thomas and Shaw 1991), are stabilised by tree and shrub vegetation and may feature sharp or subdued morphologies; these comprise the largest dune field on the coast in Maranhão State. In the inner portion of the PNLM, the mobile dune field advances over an ancient dune field. The main geomorphological sand features identified at are migration paths of former dunes, dissipation and parabolic dunes, barchanoid and transverse dune chains. At the Lençóis Maranhenses, parabolic dunes can be classified as single or composite, according to Pye (1993). According to the dating of diatoms found in the Caçó pond, Nascimento et al. (2003) identified three significant dry periods within the last 21,000 years: 21,000–18,000 years BP, 13,200–12,600 years BP and 5,050–3,990 years BP. According to Santos (2008), the similarity in the ages observed in three dunes (3,840, 3,600 and 2,730 years BP), which were more internalised and relatively far apart, suggests that during the period between 3,000 and 4,400 years BP, there was significant wind activity in the Lençóis Maranhenses region that may have abruptly stopped due to the change to a wetter climate, thus causing the fixation of these dunes. This hypothesis coincides partially with the results of Sifeddine et al. (2003) and Nascimento et al. (2003). The presence of vegetation-fixed barchanoid and sharp transverse dunes near Barreirinhas can be considered as an indicator of such climate changes on the coast of Maranhão. Notably, the only mobile and inactive dunes of the Holocene age were found in the inner area of PNLM. However, outside the park boundaries, Santos (2008) found two dunes of Pleistocene age (12,000 and 23,800 years BP). This result may indicate the development of multiple dune fields from pulsations that occurred from before the last glacial maximum (LGM) to the present day.

8.3.4 Output Zone

The term 'output zone' was used by Castro (2001) to define environments buried by aeolian sediments (dunes) and subsequently subjected to fluvial transport towards the sea. In the PNML, the aeolian sediments are mostly found in the inner areas of dune fields. However, along the western boundary of the survey area, the Negro River is mainly responsible for a small portion of aeolian material that is transported towards the sea, especially during the rainy season when the flow rate increases. However, considering that the river is small in comparison with the extent of the dune field (current and ancient) and that, consequently, the flow of sediment towards the sea is small (during the dry season), the Negro River is not a significantly important output zone in terms of sand transport in the wind system.

8.4 Conclusions

The mobile and fixed dune fields, characterised as barchans, barchanoid, transverse, parabolic dunes and sand sheets, significantly cover the Brazilian coast, with the maximum presence along the Maranhão coast. Notably, both rivers and gorgeous interdune ponds with their blue and green waters, located within the mobile dune fields of the Lençóis Maranhenses region, are key to the development of local tourism. They also control wind movement and thus hinder the migration of dunes over palaeodunes and sub-current wind deflation plains, which are situated contiguously in front of mobile dunes. In general, it can be inferred that wind dynamics is strongly influenced by the meteorological phenomena that occur in this sector of the Maranhão coast, as the annual dune progression is inversely proportional to rainfall in the region (i.e. the higher the amount of rainfall, the lower the dune migration rate). Other conditions that favour wind dynamics in the PNLM include reasonable coastal dynamics, represented by waves, currents and tides (mesotidal/semi-diurnal); the presence of two well-defined seasons, with a dry period of 4–6 months and higher wind speeds during this period; an E/SE shoreline orientation standing obliquely to the directions of the waves and prevailing winds from the NE; the presence of significant sedimentary stocks on the inner shelf that are associated with sands deposited by local drainages (Parnaíba and Preguiças rivers) and longshore drift and the existence of dissipative beaches of fine sand with widths of up to 500 m that are exposed to wind action for approximately 12 h daily.

The presence of both relatively well-preserved transverse and barchanoid chains (sharp morphology) in the inner fossil dune fields suggests a recent change to a wetter climate that favoured the fixation of these wind forms in the Lençóis Maranhenses region. Finally, sustainable tourism development is expected for this important tourist attraction in Maranhão State because this exceptional natural beauty of the PNLM makes this region one of the finest wildlife sanctuaries in Brazil, which will be enjoyed by current and future generations.

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One Island, Many Landscapes: Santa Catarina Island, Southern Brazilian Coast

9

Edna Lindaura Luiz

Abstract

The Santa Catarina Island, with an area of 424 km^2, features beautiful landscapes created by different landforms of continental and coastal environments, formed under the influence of a humid subtropical climate. Elevations built of crystalline rocks surround lagoons, beaches, and mangroves, whose different dynamics and evolutionary histories are linked to fluctuations in sea level, erosion, and sedimentation events resulting from different geomorphological processes such as coastal and tidal currents, wind, gravity, stormwater runoff, rivers, and mass movements. On the portion of the island closest to the mainland, the sea is calm and mangroves have formed in the coves, whereas sandy beaches accompanied by lagoons and dune fields and separated by rocky shores delimit the coast on the ocean side. The prominent and impressive landscapes of Santa Catarina Island include the following: the Lagoa da Conceição group: Conceição lagoon, dune fields of Joaquina and Joaquina beach; Lagoinha do Leste beach; the sand spit of Daniela (Pontal da Daniela); and the Itacorubi mangrove.

Keywords

Santa Catarina Island • Coastal landscapes • Lagoons • Mangroves • Sand spit

9.1 Introduction

The Santa Catarina Island is located off the coast of the state of Santa Catarina in the South Atlantic Ocean. Its entire territory belongs to the municipality of Florianópolis, which is the capital of the state of Santa Catarina. The island is near the mainland and separated from it by a small stretch of calm waters, the North and South bays, which are divided from one another by the Estreito isthmus (Fig. 9.1). The island has an elongated shape, with hills and mountains that follow a roughly NE–SW alignment, consistent with the pattern of predominant regional tectonic lineaments. These elevations are built of granitic Precambrian rocks with dikes of basic rocks (diabase) and volcanic and subvolcanic acid rocks (rhyolites, rhyodacite, and ignimbrites) (Zanini et al. 1997).

The predominant climate is humid subtropical with more abundant rainfall during summer and spring. No dry season occurs in the region. Rainfall ranges from 197 mm in January to 82 mm in July. The average temperature varies from 18 to 24 °C, with colder days in winter caused by the arrival of polar air masses from the south.

Significant humidity favors chemical weathering; however, considerable resistance of the rocks, most of them quartz-rich, produces weathering mantles and soils that are not very thick. Rock blocks are present in the interior of the most weathered masses. These boulders are often exposed and precariously balanced on the hillsides and inside drainage channels. Forest clearing on the hillsides and human occupation can lead to accidents involving the fall and slide of these boulders.

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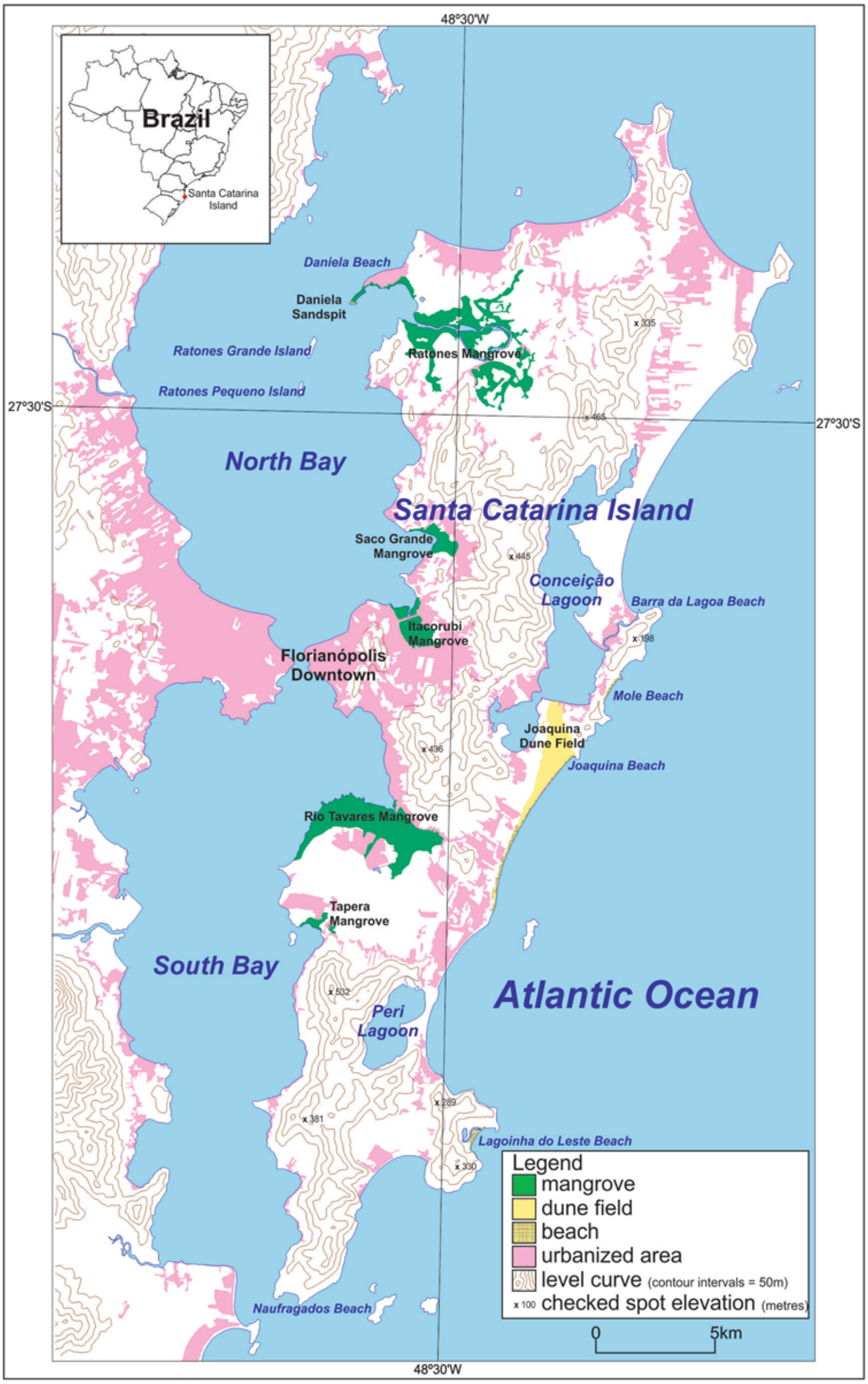

Fig. 9. 1 Santa Catarina Island, including the locations of Conceição lagoon, Joaquina dune field and beach, Daniela beach, Lagoinha do Leste beach, and the Ratones, Saco Grande, Itacorubi, Rio Tavares, and Tapera mangroves

Surrounding the crystalline massifs is an extensive sedimentary area of Quaternary age that consists of deposits from marine, lagoonal, eolian, and estuarine environments, developed and reworked at different sea levels (Luiz 2004). The Lagoa da Conceição (Conceição lagoon) and Lagoa do Peri (Peri lagoon) are located in the eastern portion of the island and are both very extensive, presenting evidence of sea-level changes from the Pleistocene until today.

9.2 Human Occupation of Santa Catarina Island

The first reports about the Santa Catarina Island are dated from the early sixteenth century and were made by Spanish, French, and Portuguese navigators of ships anchored in the region because of the sheltered position of the harbor. Often, deserters and exiles were on the island, besides shipwrecked persons. Shipwrecks were common at the south end of the island, in front of where the "Naufragados beach" (Shipwreck Beach) is today, because of strong currents and storms.

At that time, the island was inhabited by Indians carijós, branch Guarani, who lived by hunting, fishing, gathering shellfish, fruit, and roots. They have also practiced cultivation of certain plants, especially cassava, which was a very nutritious food. These natives disappeared from the region because of the persecution by European navigators and due to communicable diseases. The records of the presence of indigenous groups include the oldest lithic workshops and huge mounds of shells and earth located along the coast called "sambaqui," where burials and artifacts can also be found. In the seventeenth century, there was a colonization attempt of the Santa Catarina Island by Portuguese coming from an already established colony on the coast of the current state of São Paulo, but the company did not prosper because it was attacked by pirates a few years after settled.

A Portuguese colonization became more effective, and higher population contingent arrived in the mid-eighteenth century, consisting of migrants from the islands of the Azores and Madeira. This initiative was due to the fact that at that time, Portugal and Spain were at war in the region of the River Plate estuary to have possession of the region and the Santa Catarina Island was one of the last sheltered ports before reaching the area of conflict. Portugal also wanted to consolidate their domains in southern coast of the colony of Brazil. The Azorean Portuguese effectively colonized the territory of the Santa Catarina Island, occupying sandy coastal plains, alluvial plains, and slopes of the crystalline hills. To survive, they practiced subsistence agriculture, extensive cattle ranching, fishing, and mollusks and crustaceans extraction (Fig. 9.2).

Fig. 9.2 "View of Desterro" by Joseph Brüggmann, painting of 1867. The painting shows the village of Desterro (current city of Florianópolis) in the mid-nineteenth century, with the crystalline hills surrounding the North and South bays

Agriculture was adapted to climatic and soil conditions of the region and followed many practices held by the Indians before, as setting fire to the bush after planting and cultivation of cassava. Cassava has been widely planted in coastal sand terraces and on the sandy coastal plain with poor soil, because it is rather undemanding. From this plant, it is possible to make flour, which motivated installation of many "flour mills." In addition, corn, beans, coffee, and cane sugar were planted, especially on hillsides. The slopes, alluvial plains, and marine terraces were also occupied by pastures for cattle. On some beaches, communities specialized in fishing were established; however, there was always the practice of agriculture and livestock, but to a lesser extent.

These forms of human occupation of the island remained until the 1970s. Deforestation for plantation was cyclical, because when the soil was no longer productive, it was abandoned and new areas with native vegetation or those subject to regeneration previously were deforested for new plantations.

This practice caused the disappearance of many ecosystems and soil erosion, with the occurrence of runoff processes of high energy. Probably, this type of land use throughout time has generated large sediment yield for the channel heads and rivers present on the slopes and in the plains of the island.

In the second half of the twentieth century, the Santa Catarina Island began to be sought after by tourists because of its beautiful beaches and landscapes. One of the facts that motivated tourism was easy access to the island, because at that time a highway linking Brazil from North to South, the BR 101 highway, was built and it passes close to the mainland shoreline. A large amount of people migrated to the island in search of natural beauty and the jobs generated by tourism.

Another factor was the creation of various organs of public administration which also generate jobs. Thus, currently, agriculture, livestock, and fisheries have almost disappeared in the Santa Catarina Island and urbanized areas are increasing every day. Forests began to expand again on the hillsides, as did the coastal sandy vegetation (Brazilian restinga) on plains and sandy terraces; it is also possible to see an increase in the number of animal species that had almost disappeared. However, urbanization also creates problems, since it occurs to the detriment of areas with native ecosystems and causes heavy burden of pollution, especially for water.

9.3 Landscapes of the Santa Catarina Island

The combination of crystalline massifs with sedimentary feature of various environments with an open sea to the east and the calm sea of the bay to the west has created a unique and diversified landscape on the 424 km^2 that constitute the Santa Catarina Island. Several of these landscapes are further described here because of their scenic beauty and geomorphological features.

9.3.1 The Landscape of the Top of Lagoa Hill (Morro Da Lagoa Da Conceição)

This landscape is one of the most representatives for the island in terms of its scenic beauty and geomorphology. It features a view of the Atlantic Ocean, the Joaquina and Mole beaches, the Joaquina dune field partially covered by restinga vegetation, and the crystalline highs covered by the Atlantic Forest. Crystalline highs anchor the sedimentary deposits that close the Conceição lagoon (Fig. 9.3). Various geomorphological processes have created this landscape which is the most famous postcard theme.

Crystalline rock highlands are modeled in anorogenic granites of Neoproterozoic age which intruded as batholiths (Zanini et al. 1997). These granites are isotropic rocks that are approximately 600 million years old, composed of plagioclase, K-feldspar, quartz, and biotite (Zanini et al. 1997). The elevations are hill-shaped with angular hilltops and wide and steep slopes; they are approximately 300 m high but reach 493 m at Morro da Costa da Lagoa (the Lagoa da Conceição Coastal hill). Many rock slopes reach the ocean to form rocky shores, allowing the observation of geological structures and lithological features. The steep hillsides have shallow soil with granite boulders immersed in sandy–clayey material. Even with the shallow soil, the Atlantic Forest covers these hills. Many small rivers run from those hillsides into embedded valleys and flow into the Conceição lagoon or into the Atlantic Ocean. The waters are crystal clear and pure; however, these rivers may experience torrential flows during episodes of heavy rainfall and carry large amounts of sediment to its mouth during such events.

The crystalline highs border the Conceição lagoon and serve as a trap for marine sedimentation and the construction of the beaches of Joaquina and Mole. The Lagoa da Conceição extends for 13.5 km and is approximately 20 km^2 in area (Muehe and Caruso 1989). The lagoon connects to the ocean by a sinuous channel in its northern portion that travels to the Barra da Lagoa beach.

Previous studies have associated the formation of Conceição lagoon with the marine transgression event from 120,000 years BP (Muehe and Caruso 1989) when the sea level was 8 ± 2 m higher than today (Suguio 2001). The presence of rocky outcrops on the shores of the Lagoa da Conceição along the foothills of crystalline highs may indicate an ancient rocky shoreline. After the maximum transgression, the sea level began to decrease until approximately 18,000 years BP, leading to the formation of a sandbar to the

Fig. 9.3 Landscape from the top of Lagoa da Conceição hill. The Conceição lagoon is limited by crystalline highs and sandy sedimentation areas. The Atlantic Forest covers the hills, protecting them from erosion. (*Photos* E. Luiz)

east of the crystalline highs, which isolated the lagoon. The lagoon may have dried out as the result of the maximum marine regression that occurred contemporaneously (Muehe and Caruso 1989), when the sea level was approximately 120–130 m lower than today (Suguio et al. 2005).

During the Holocene (at 5,100 BP), a new marine transgression occurred, and the sea level rose approximately 2.5 m above the current level. This caused the lagoon to refill with water, and a new sandbar was created further east at the time of subsequent marine regression, whose peak was at 2,500 years BP. Therefore, there are currently two sandbars between the lagoon and the Atlantic Ocean that were formed during different transgression/regression episodes and are separated by a lower area of marsh. At the external strand close to the Atlantic Ocean, the Joaquina, Mole, and Galheta beaches—in addition to the lagoon coast (Barra da Lagoa)—are currently developing; the Galheta beach and the lagoon coast are not visible from the top of Morro da Lagoa.

The Joaquina beach is very long with a dissipative beach profile (Torronteguy 2002) and a gentle average slope of 2.5° (Fig. 9.4). It consists primarily of well-selected fine sand (Peixoto 2010) that mainly comprises quartz but has yellowish color because it also contains shell fragments. The waves have high energy, especially in the northern sector close to the rocky shore; these waves turn the Joaquina beach into one of the most popular surf spots on Santa Catarina Island.

The rocky coastline of the Joaquina beach is composed of granites with diabase intrusions, which are easy to see because of its length and the thin weathering mantle on the rocks—wave action and rains quickly remove weathered materials. The diabase rocks also contain visible ancient sharpening grooves from pre-colonial human occupation.

At approximately 1 km in length, the Mole beach is shorter than the Joaquina beach and is located further north. It is steeper than the Joaquina beach because it consists of medium

Fig. 9.4 Joaquina beach and part of the Joaquina dune field. View from north to south. This sector of the dune field is formed by blowout, a result of the migration of sand to the north. This migration occurs because of the action of the south wind, the most active in the area. The Joaquina beach is very long and is very popular for the practice of surfing. (*Photo* E. Luiz)

to coarse sand. The average slope of the beach is 8°, but can reach 16° (Heidrich 2011). The name of the beach—"Mole" means "soft" in Portuguese—is related to the coarse and fluffy sand that is soft to walk on. The sand of the Mole beach also has shell fragments in its composition.

The Mole beach has a strong swell, particularly from the east quadrant, and is also popular with surfers. It has a variable profile throughout the year depending on meteorological and oceanographic conditions. From fall until spring, cold fronts from the south cause waves and storm tides on the coast of Santa Catarina Island and drastically change the profile of its sandy beaches, including the Mole beach. Heidrich (2011) classifies Mole beach as an intermediate beach.

The dunes of Joaquina comprise a transgressive dune field that has most likely been active since the Pleistocene (Bigarella 2000) (Fig. 9.5). It is approximately 3.5 km in length and its width varies between 2.0 km in the south and 1.2 km along the banks of the Lagoa da Conceição (Caruso 1993). The dunes advance into the lagoon causing siltation and forming a lagoon beach with a very smooth slope.

The wind direction in the region is primarily NE, but the dune field is mostly influenced by the storm winds coming from the southern quadrant as a result of the barrier formed by the crystalline massif of the Joaquina hill to the north. Bigarella (2000) performed measurements in a parabolic dune in the Joaquina dune field over a 20-year period, from 1975 to 1995, and confirmed the advance of the dune crest to the NE.

Fig. 9.5 Joaquina dune field. **a** Overview of the dune field from the Lagoa hill. *Note* that the dunes are accumulating on the crystalline hills. **b** Detail of the dunes within the dune field. These are transverse dunes becoming parabolic dunes in some sectors. (*Photos* E. Luiz)

The dunes in the area are reverse, transverse, and parabolic; in addition, there are dunes superimposed on the crystalline slopes of the Joaquina hill and blowouts in the rear of the main direction of dune migration. There are many depressions in the blowout area, which sometimes become filled with water during episodes of heavy rainfall and form small natural pools.

9.3.2 Lagoinha do Leste Beach

This beach is located in the south–east of the island on the Atlantic Ocean side. The landscape consists of a beach and a small sandy plain located between rocky shores and surrounded by crystalline slopes covered by Atlantic Forest (Fig. 9.6).

The crystalline highs surrounding this area are modeled in granitic and acid volcanic rocks: lava flows and dikes of rhyolite, rhyodacite, and dacite, in addition to the presence of pyroclastic rocks developed as tuffs and lapilli tuffs that form ignimbrites (Tomazolli and Pellerin 2001). These rocks exhibit quartz and feldspar phenocrysts in a very fine or vitreous matrix. The dikes cut the volcanic rocks and the granite. These granitic and volcanic acid rocks are approximately 507 million years old (Zanini et al. 1997).

The crystalline massifs are approximately 300 m high with steep slopes and suspended valleys that constitute the predominant relief; however, there is a hanging circular valley carved on the slopes. This valley has a knickpoint which is a site of a beautiful waterfall. The river that has carved the valley is dammed by sandbars and dunes at its mouth and forms a sinuous freshwater lake in the plain at the foothills of the crystalline slopes. Thus, the beach is named ‘small lagoon of the east’ (Lagoinha do Leste).

During storm events with strong waves and high tides, the sandy coastal barrier is breached and the small lake is emptied. This phenomenon also occurs during heavy rainfall that increases the river flow (and consequently its energy) and thus overtakes the sandy shore at its mouth.

Sand ridges created during marine transgression and regression episodes of the Pleistocene and Holocene constitute the sandy plain. The older of these sandbars is anchored at the foothills of the crystalline highs, and it contains brownish, middle-grain sand, subject to eolian reworking and contamination by immature colluvial

Fig. 9.6 Landscape of the Lagoinha do Leste beach. The lagoon is formed by damming the mouth of a river that descends from the hills modeled in acid volcanic rocks. The action of waves, currents, and tides results in marine sedimentation, damming the river. Storm waves or larger river discharge can destroy the depositional area, emptying the lagoon. (*Photo* A. Salgado)

sediments descending from hills. The most recent sandbar has dunes at its top, and the beach is developed at its external edge. The dynamics of this beach is related to coastal drift, currents, and tides, in addition to the river action that feeds the small lagoon.

Because of the intense dynamics linked to meteorological and oceanographic factors, the Lagoinha do Leste beach has fine to medium sands with a profile that varies greatly throughout the year, depending on waves and storm tides that commonly occur in fall, winter, and spring. The beach may also have contributions of thick and immature sediments brought by the river when the sandbar that blocks its mouth is breached. When the river mouth is open, saltwater enters into the lagoon during high tide; however, because of its sinuous shape, this is insufficient for complete salinization. Nevertheless, the lagoon suffers from siltation because of wind action on the dunes that develop in the crest of the sandbars.

Lagoinha do Leste is one of the most inaccessible beaches on the Island of Santa Catarina, which has hampered human occupation. In 1992, the area of the Lagoinha and its adjacent hills were intended to be permanently protected with the creation of the Municipal Park of Lagoinha do Leste (Parque Municipal da Lagoinha do Leste). The combination of outcrops of acid volcanic rocks in the rocky shores on either sides of the beach covered with tropical forest produces a unique landscape.

9.3.3 Daniela Beach (Praia da Daniela)

This beach has calm waters and fine white sand and is located close to the North Bay (baía Norte) at the external side of a sand spit developed from the crystalline massif of the Morro do Forte (Forte hill) in the north. The sand spit advances in ENE–WSW direction and diverts to SW at its distal portion toward Ratones Cove (Enseada de Ratones) and Ratones River (Rio Ratones) estuary. The sand spit is aligned with the islands of crystalline highs—Ratones Grande and Ratones Pequeno—located in the North Bay (Fig. 9.7).

These islands were named Ratones (rats in Spanish) because in the eyes of Spanish sailors of the seventeenth and eighteenth centuries, they resembled rats standing on the

Fig. 9.7 Daniela beach is situated on the outside of a sand spit. This beach has calm waters and no waves because it is located within the North Bay. It has fine white sand and gentle slope. (*Photo* E. Luiz)

water. Because the mouth of the Ratones River is in front of these islands, the river was given the same name.

The inner portion of the sand spit has finer sediments and encompasses a mangrove forest. The Ratones River estuary contributes with fine sediments to the mangrove. This river has the largest drainage basin of the Santa Catarina Island.

The sand spit is characterized by a series of sandy ridges that grew from a preexisting structure (mainland or island) as a result of the action of currents and waves (Suguio 1992). With respect to the Daniela sand spit (Pontal da Daniela), the tide current formed in the interior of the bay can also be an important mechanism for the formation and evolution of this feature. In this portion of the North Bay, there is a narrow section, and the low- and high-tide waters must pass between the islands of Ratones Grande and Ratones Pequeno on one side and through the northwestern portion of the Santa Catarina Island on the other (Cruz 1998).

The evolutionary dynamics of the Daniela sand spit is significant. In 1938, aerial photographs showed a narrower sand spit with an overall direction toward the south that almost closed the cove of the Ratones River mouth. However, observations of the same profile in aerial photographs from 1978 indicated a decrease in its length, an enlargement in some portions of the sand spit and the diversion of its distal portion to the SW (Mendonça et al. 1988; Diehl 1997).

Diehl (1997) and Mendonça et al. (1988) asserted that there are portions of the Daniela sand spit suffering erosion. It is possible to observe a narrower sand strip on the beach and many dry mangrove tree trunks suffering from the direct action of waves exactly at the site where the sand spit changes direction. However, Marques (2011) has shown through monitoring that there is alternating sections with dominant erosion and deposition processes in sand spit. One section of the sand spit serves as the source of sediments area for the other, in a proximal to distal portion direction, with a strong influence of longshore current.

This area of the sand spit with its intense and unstable dynamics over time should be preserved because human occupation and the construction of rigid structures can compromise the action of modeling agents and the movement of sediments. At present, houses occupy the interior of the proximal and intermediate portion of the sand spit and there are several paths used to reach the beach. These paths harm the restinga vegetation of the front dunes and interfere with natural erosion and the sedimentation pattern of the area.

9.3.4 Coves with Mangrove Ecosystems

In the western portion of the Santa Catarina Island, within the South and North bays, tidal plains are formed with mangrove development, specifically in river mouths located in intertidal areas with little action of waves and tides.

There are at least five important coves in the western portion of the island where rivers flow into estuaries, including the sites of Ratones, Saco Grande, and Itacorubi situated in the North Bay and the Tavares River (Rio Tavares) and Tapera located in the South Bay. These coves are built in coastal recesses formed by the arrangement of crystalline highs and have been silted due to the combination of sea level lowering since the last marine transgression (5,100 years BP) and the sedimentation of rivers and tidal currents.

The peculiarities of the aforementioned sedimentation create muddy and salty soils that are invaded by high tide daily. The tides of Santa Catarina Island are semidiurnal with low oscillation values; high spring tide reaches an average of 154 cm and neap tide reaches 120 cm, whereas for low tide, the average values are 71 cm for spring tide and 106 cm for neap tide (Cruz 1998).

The very presence of vegetation helps fix the sediments brought by tides and rivers, such as the *Spartina montividenses* grass that colonizes the exit of the cove. The roots of this grass form a dense network, capturing sediments that arrive through tidal currents or river flow. In thicker soils, toward the interior of the island, there are typical mangrove tree species, such as *Avicennia schaueriana*, which is more abundant and found in the intertidal area; *Laguncularia racemosa*, which occurs where the soil is firmer and sandier; and *Rizophora mangle,* which is rare in the mangroves of the Santa Catarina Island and is found only in the deeper depressions of the terrain. The *Avicennia* and *Laguncularia* species have pneumatophore roots for respiration in the saturated and saline soil, whereas *Rizophora* have supporting roots to ensure support and oxygenation. The predominance of *Avicennia* species in the island mangroves produces a relative homogeneity in the mangrove forest (Ayala 2004).

The mangrove ecosystem of Santa Catarina Island does not boast as great a variety of species and trees as those that are found in the tropical area of Brazil because the temperatures are lower and the seawater is colder at the latitude of the island. Mangroves cover large portions of Santa Catarina Island and form beautiful and homogeneous green carpets that protect the shoreline from coastal erosion and serve as breeding and shelter areas for different species of mollusks, crustaceans, fish, and birds.

Ayala (2004) has shown in the studies at the Itacorubi mangrove—which has extensive human occupation in its surroundings—that there was an advance of the mangrove area toward the sea by approximately 120 m between 1938 and 1998 in one of the measured sites, in spite of human interference. This study demonstrated the great contribution of sedimentation in this environment even today (Fig. 9.8).

Ayala (2004) also found that the muddy and organic matter sedimentation in the Itacorubi mangrove exhibits thick packages, which change in depth to sandy and clayey–sandy sediments with pebbles until the crystalline basement

Fig. 9.8 Itacorubi mangrove. This ecosystem is expanding on the exit of the cove because of the lowering of sea level during the Holocene and the capture of sediment by grass Spartina. The mangrove is surrounded by a zone of intense urbanization. (*Photo* E. Luiz)

of granite is reached. Moreover, this author also found packages of muddy sediments through surveys of the peripheral area upstream of the current mangrove area and confirmed that this environment is migrating over time toward the sea of the Itacorubi Cove.

9.4 Final Considerations

The Santa Catarina Island has different landscapes in its territory, particularly in its eastern portion close to the Atlantic Ocean and at its western portion close to the calm waters that separate the island from the mainland.

Sedimentation that has occurred throughout the Quaternary and is still active today creates landscapes of great scenic beauty. However, these landscapes are fragile and unstable because they continue to evolve under the actions of agents that created them as well as undergo changes because of the local environmental conditions.

The occurrence of extreme climatic events, which are common in the subtropical climate of the region, causes changes in the configuration of dune fields, beaches, and mangroves through the action of strong winds, current, and tidal storms. In the slopes of the crystalline highs, the combination of heavy rains, slope cuts, and deforestation causes landslides and falling boulders, in addition to the heavy river flows that descend from these hills. These phenomena cause changes in naturally unstable environments and contribute to risk for human occupation.

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10 Antonina Bay and Superagui Island: A Mosaic of Mountains, Coastal Plain, and Atlantic Forest

Leonardo José Cordeiro Santos, Eduardo Vedor de Paula,
and Carlos Roberto Soares

Abstract

The coastal plains of Paraná are located in the south of Brazil and spread over 105 km, with a maximum width of 55 km, fringed with bays, lengthy tidal flats, and sedimentary islands, framed inland by the Serra do Mar mountain ridge. This ridge is one of the highest massifs in Brazil, running from the Espírito Santo State to the Santa Catarina State and considered to be one of the most important scenic landscapes in Brazil. It provides a context to the Superagui Island and the Antonina Bay. They were both important locations in the historical process of occupation of the coastal area of the State of Paraná and for featuring one of the most pristine areas of the Brazilian Atlantic Forest. Several Conservation Units were created, supported by very strict legislation. The Superagui Island is formed by coastal plains with sand strips, created as a consequence of the fluctuation of the relative sea level during the Quaternary. The Antonina Bay, more than just an estuary, should be seen as a part of a large estuarine system, consisting of several bodies of water, interconnected in a complex geological and geomorphological framework. In the Antonina Bay, silting rates are increasing and the volume of newly deposited sediments requires dredging to maintain the operation of the port. Geomorphological consequences include the creation of flat islands in the region, which, although revealing a silting process, offer scenic beauty through the contrast created by the proximity of the mountains to the coastal plains.

Keywords

Paraná coast • Serra do Mar • Coastal plains • Estuary • Environmental preservation

10.1 Introduction

The State of Paraná, one of the 27 federation units, located in the Southern region of Brazil, shows evidence in its 105-km-long coast of the presence of two large geomorphological compartments: the Serra do Mar mountain range and the coastal plains (Maack 2002; Bigarella et al. 1978; Oka-Fiori and Canali 1998). The first one consists mainly of granite massifs, surrounded by complex associations of gneissic and migmatitic rocks. Its height range is between 20 and 1,877 m (Paraná Peak). The coastal plains show a maximum width of 55 km, deeply indented by the Guaratuba and Paranaguá bays (estuaries). They feature several minor compartments, but this chapter will cover the Superagui Island and the Antonina Bay only (Fig. 10.1).

The Superagui Island, with an area of 157.5 km^2, approximately, belongs to the Municipality of Guaraqueçaba. It can be considered an artificial island, since it has been created after

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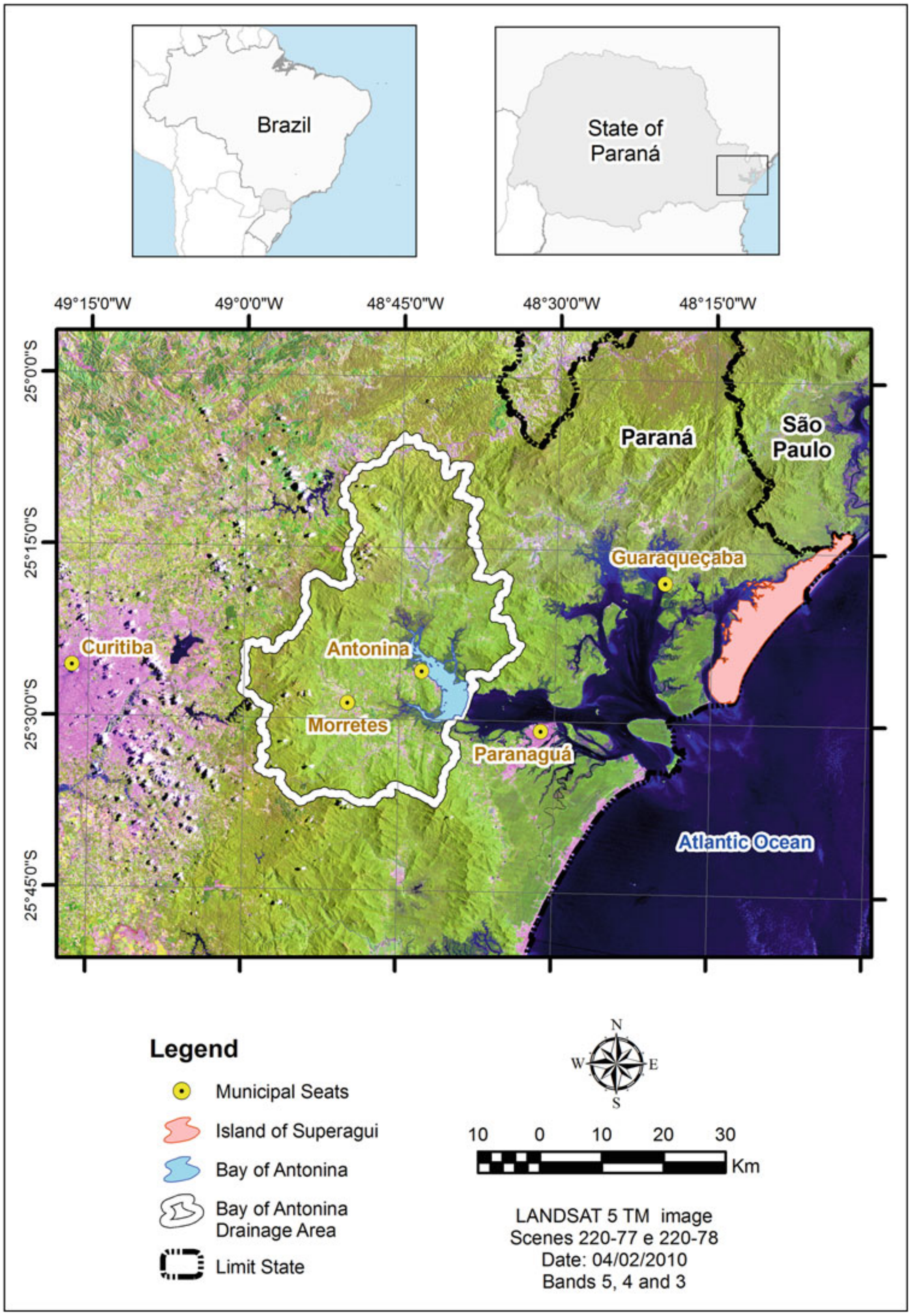

Fig. 10.1 Location Superagui Island and Antonina bay, Paraná's coastal area

the opening of the Varadouro Channel, an artificial channel made through excavating and dredging, separating the peninsula from the continent, back in 1953. Due to the beauty of the scenery (Fig. 10.2), together with high degree of conservation of its environments, Superagui has become Paraná natural and historical heritage in 1970, national park in 1989, biosphere reserve, by UNESCO, in 1991, and natural heritage site, also by UNESCO, in 1999.

Geologically, Superagui consists of coastal plains with coastal strips formed as a consequence of fluctuations of the relative sea level during the Quaternary. These plains are covered with hydromorphic and salic soils, with mangroves present in the estuary portion, located on the west shore of the island.

The Antonina Bay, located in the municipality of the same name, is the deepest inland point, from the coastline, in the Brazilian territory. The bay area is 46.4 km^2, with 7.2 km^2 of

Fig. 10.2 William Michaud (1829–1902). Aspect of the Superagui colony. s. d. Watercolor 26.1 × 32.7 cm. *Source* Taunay family collection donated to state of Paraná government

islands. The area of the hydrographic basin draining into the bay is 1,500 km^2. In the slopes of this basin, we find underdeveloped soils. We also find steep slopes, generally over 30 %, with the highest precipitation records in the State of Paraná, reaching a yearly accumulated reading of over 3,500 mm. This landscape configuration leads to high natural susceptibility to mass movements and the development of erosion processes (Paula and Santos 2009).

In the plains of the Antonina Bay drainage area, we can see the dominance of unconsolidated alluvial sediments associated with hydromorphic soils. Precipitation is also significant, reaching 2,000 mm per annum. In this compartment, besides erosion processes caused by surface runoff due to quick saturation of the hydromorphic soils under abundant rains, we can notice considerable morphological change of the river beds due to the high degree of silting (Paula and Santos 2009).

In population-wise, Superagui has 1,000 inhabitants, considered to represent the “Caiçara”[1] culture, as they originated through miscegenation of Caucasians, of Portuguese, German, Swiss, and Italian origin, with indigenous groups. 35,000 inhabitants approximately live in the Antonina bay drainage area, of which 23,100 live in the towns of Antonina and Morretes.

10.2 Geological and Geomorphological Evolution

On the Paraná coast, there are two main geological domains: the crystalline basement rocks (or shield) and the Cenozoic sedimentary cover. Both rocks and sediments are associated with the main geomorphological units of the region.

The shield of the Serra do Mar mountain ridge is formed by igneous and metamorphic rocks of Pre-Cambrian age, more than 600 million years old. An intense volcanic activity occurred in the South American continent during the Mesozoic, when South America and Africa drifted apart and the Atlantic Ocean was created.

Oozing of lavas through faults and fractures created dikes which are very distinctive features in the Paraná’s inlands, in the Serra do Mar mountain ridge, in the Currais Archipelago and in the hills of the islands of Cotinga and Mel.

Although Serra do Mar features rocks from the Pre-Cambrian and Mesozoic igneous dikes, its current configuration as a continuous tall ridge is much more recent, dating from the Cenozoic, between 65 and 1.8 million years, when continental blocks were lifted through tectonic activity. It is one of the tallest massifs in Brazil, stretching from the state of Espírito Santo to the state of Santa Catarina as a prominent mountain ridge in the SW–NE direction, considered to be one of the most important scenic landscapes in Brazil. Paraná’s coastal plains lie over that older base. The sand pockets on the shore plains were deposited during the transgressions and regressions of the sea level.

A total of 120,000 years ago, a transgressive maximum occurred, with the sea level 8 ± 2 m above the current level. All the current plains were under water, whose limit was the

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[1] Traditional Communities living between the Atlantic Forest and the sea, subsisting upon small production of goods associated with agriculture and fishing.

Serra do Mar slope (Fig. 10.3a). At the time, the region looked like a gulf with scattered islands, with the presence of the ridge, the sea, and lacking well-developed plains.

From 120,000 years ago to approximately 21,500–18,000 years ago, the sea level fell to the current depth of the continental platform of −100 to −130 m. When the sea reached the lowest level, all the submerged area emerged, with the coastline at 190 km east of the current one. At that time, rivers flowed on the current continental platform (Fig. 10.3b).

After that, a new transgression started, peaking at between 5,400 and 5,100 years ago, when, probably, human populations already occupied the region. The sea reached a level of between +2 and +4 m above the current one. This last transgression covered again a part of the coastal plains and Superagui, which was totally submerged (Fig. 10.3c).

As the sea receded to the current level, marine sediments deposited as consecutive coastal strips and intermingled with paleo-estuarine deposits survived, and new deposits were formed, also as coastal strips and estuarine deposits (Fig. 10.3d).

The configuration of the current coastline of Paraná is, therefore, the result of progression (advance) and sweepback (erosion) of the coastline and also of the denudation processes that occurred in Serra do Mar.

Marent (2011) derived the long-term denudation rates investigating fluvial sediments of ten hydrographic basins of the Paraná's portion of Serra do Mar by means of the cosmogenic 10Be isotope method. The results showed that the denudation on the western slope of Serra do Mar is ∼2.4 times bigger than on the opposite slope, leaving, as its main legacy, the sandy plains with coastal strips of different

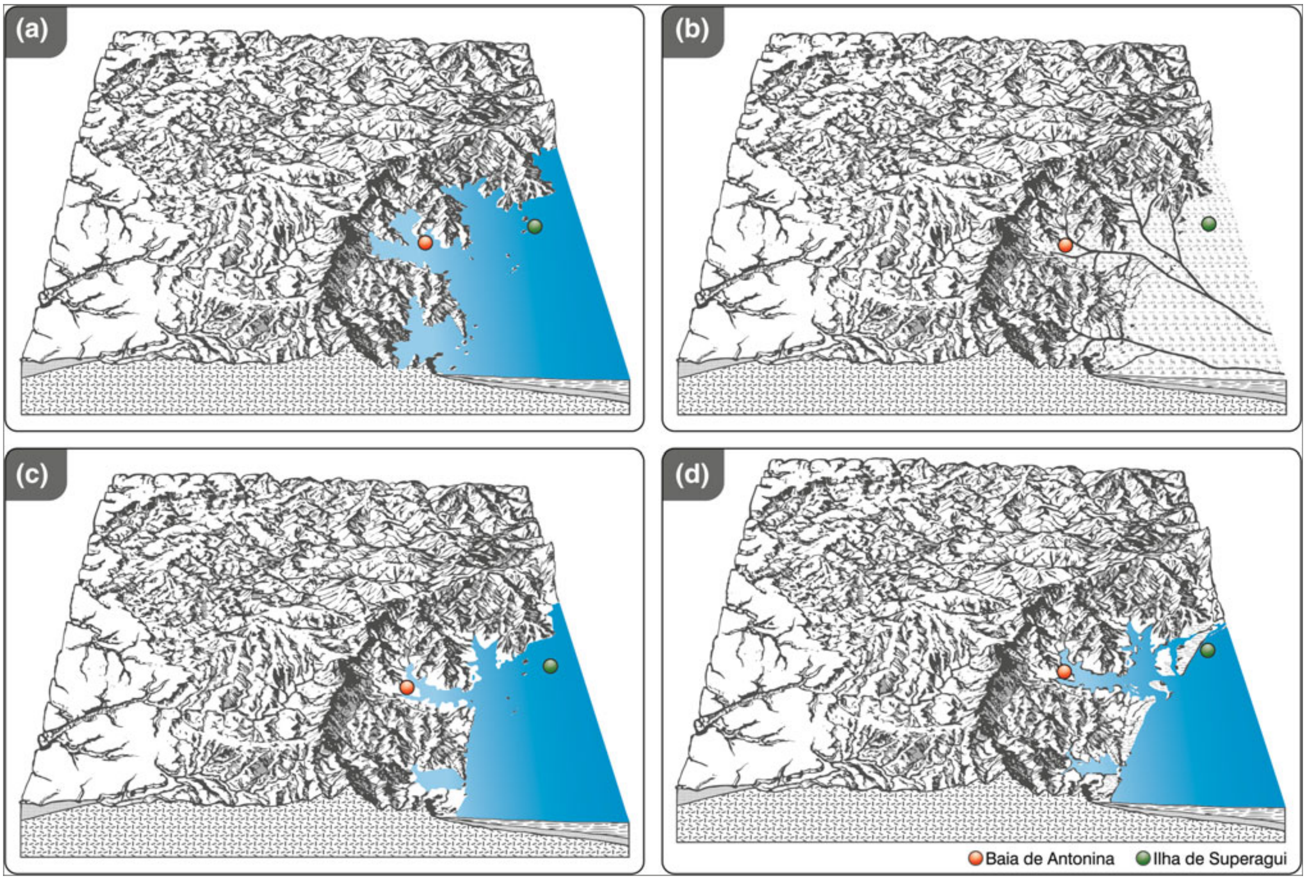

Fig. 10.3 Evolution of Paraná's coastal area in the last millennia: **a** the sea level $8^{\pm 2}$ above the current one, reaching the slopes of Serra do Mar, 120,000 years ago; **b** the sea level 130 m below the current level, between 21,500 and 18,000 years ago; **c** between 5,400 and 5,100 years ago a new sea transgression occurred and the sea reached a level between +2 and +4 m above the current one, eroding part of the coastal plains. **d** Since the transgression mentioned in **c**, the sea level receded to the current level, when beaches and mangroves were formed. *Source* Modified from Bigarella et al. (1978), in Lana and Soares (2012)

heights, and the current beaches and islands result from the reworking of those sediments.

In some cases, erosive processes are further influenced by anthropic actions, such as modifications on the sea bottom through dredging and discharging of dredged material and building activities, such as construction of piers, walls, and dikes.

10.3 The Island of Superagui: Geomorphological Processes and Their Historical Aspects

Along the Paraná's coast, due to its physiographical and dynamic characteristics, three types may be distinguished (Angulo and Araújo 1996): (1) estuarine coasts inside bays, characterized by the existence of sandy and muddy tidal plains, covered with mangrove vegetation, and salt marches; (2) open sea coasts, characterized by the existence of sandy beaches and frontal dunes; (3) coasts with water bodies outlets, which also feature beaches and frontal dunes, having, however, a more complex dynamics than open sea coasts. Tidal currents and waves give a great mobility to these coasts, with the position of the coastline changing by hundreds of meters in a matter of few years. Superagui features all three types (Fig. 10.4).

Praia Deserta (Fig. 10.5) runs in the NE–SW direction approximately, stretching from Barra do Ararapira (the northern state border with Sao Paulo) to the Superagui Channel, and it consists of fine, well sorted sand (Mihály 1997). It is about 20 km long, shaped as an arch. In this arch we can see frontal dunes and coastal strips, which are connected with old beach lines when the sea level was higher. The sediments present in those coastal strips show the content of fines up to 20 %.

The most important variations occur at the northern and southern tips of the island, at Barra do Ararapira and at the mouth of the bay of Paranaguá, respectively. In Ararapira, migration process of the coastline to SW was observed, where the main channel moved 1,200 m in that direction between 1953 and 1980 (Angulo 1993; Angulo et al. 2006). In the mouth region, the advance of the coastline was almost by 300 m in the same time lapse, although interspersed with periods of erosion. At Praia Deserta no significant variations of the coastline were noticed in the last few decades.

Although the Portuguese had already been in the Bay of Paranaguá since the beginning of the sixteenth century, Superagui Island is the first place in Paraná whose occupation by Europeans was documented. Pushed ashore by a storm, Hans Staden, a German, shored in Superagui on the 24 November 1549. The record of his adventures, not published until 1556, contains the first map of that region, a xylograph, reproduced in Soares and Lana (1994).

The effective occupation of Superagui only occurred in the second half of the nineteenth century, when, curiously enough, a Swiss settlement was established in 1852, headed by William Michaud. Not only Swiss immigrants settled, but also Germans, Italians, and French came too. Although the region of Paranaguá was, historically, considered poor to the extreme (Vieira dos Santos 1850), its population concentrated in the towns of Paranaguá, Antonina, and Guaraqueçaba. The Superagui colony was thriving and had its peak in 1879, when the island had 150 houses, from which only 10 belonged to Brazilians (Behr 1997).

Despite the dramatic climate difference with their countries of origin, Michaud and the other immigrant families adapted well to the region and made it very productive, with reports of rice, coffee, manioc, vine, sugar cane being planted, and several devices to process them, as well as of lumberyards, shipyard, winemaking, school and Post Office (Scherer 1988; Behr 1997). Besides his effective leadership, Michaud portrayed the region in numerous water colors, scattered among Brazilian and Swiss museums. Although only few significant material records from this colony survived, such as buildings, the legacy of European peoples still lives in the human features of the current native population, basically fishermen, with blond hair, light-colored eyes, and foreign surnames.

The growth of the Ports of Paranaguá and Antonina in the beginning of the twentieth century, together with the paving of the Graciosa Road and the construction of the Curitiba—Paranaguá railroad linking the coast to the inland plateau, concentrates the occupation in the bay's vicinity. The northern region features good areas of preservation of the coastal ecosystems.

After the appearance of environmentalism in the early 1970s at international level, all of the Paraná's northern coastal region, due to its good state of preservation, turned into several types of conservation units (CUs), pursuant the legislation in force, such as the environmental protection area (Guaraqueçaba EPA), national park (Superagui), and ecological station (Mel Island), among others. Although established years ago, to this day, they never had their management plans implemented.

Despite their ecological relevance, there are still some governmental projects related to the national infrastructure of transportation modals that could change the Superagui region. Highway BR101, which practically runs along the entirety of the Brazilian coast, does not exist in Paraná, due

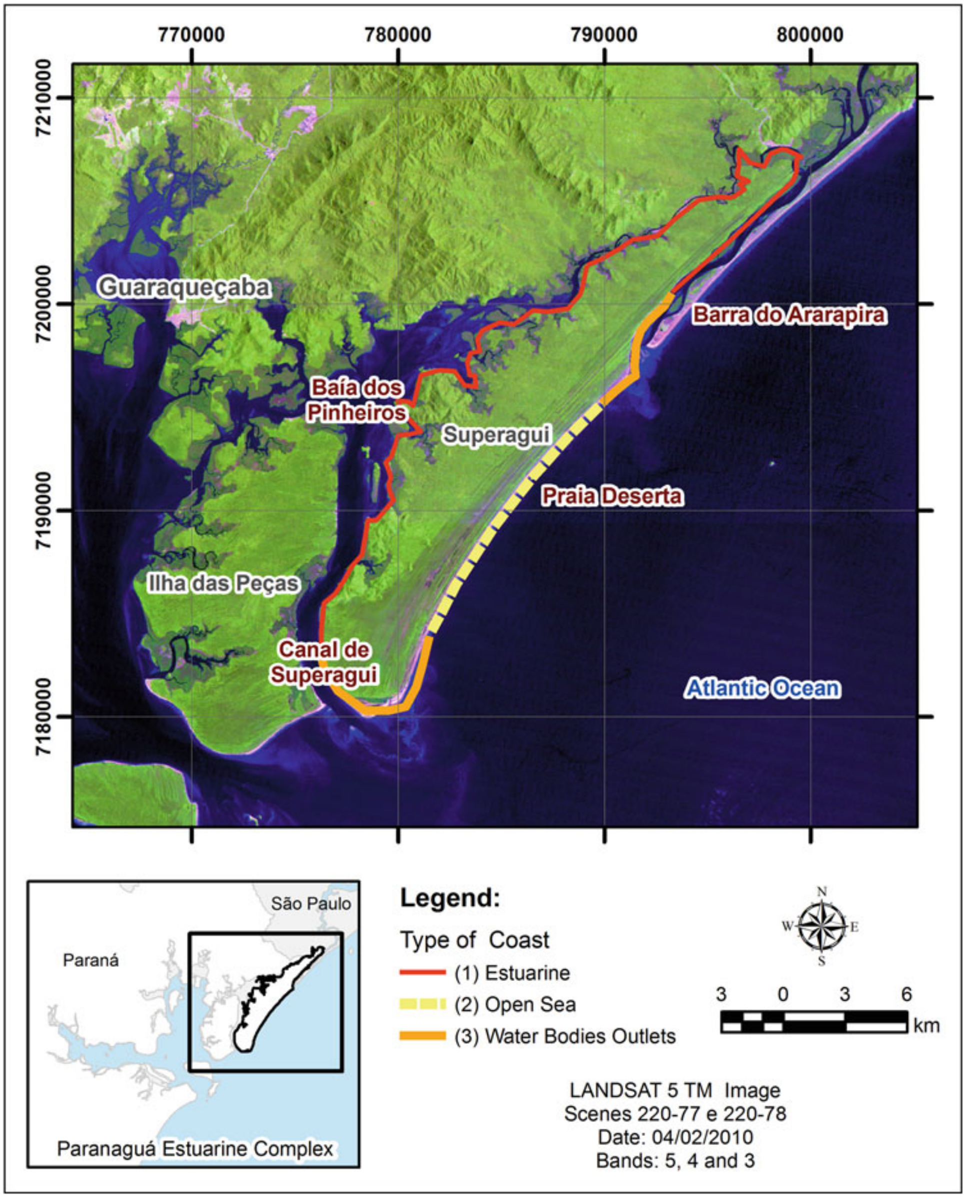

Fig. 10.4 Coastline types of Superagui Island

to the established CUs. Since long ago, there have been projects to link the main ports in the south and southeast of Brazil by road, those being Rio Grande (RS), Itajaí and São Francisco do Sul (SC), Paranaguá (PR), Santos (SP) and Rio de Janeiro (RJ). The highway would have to go through, inevitably, the Superagui region.

10.4 The Antonina Bay

Like many other tropical and subtropical bays in the Brazilian coast, the Antonina bay, more than a simple estuary, should be regarded as a part of an estuarine complex. This complex, known as the Paranaguá Estuarine Complex (PEC), comprises several bodies of water interconnected in a complex geological and geomorphological framework. Long before the arrival of scientists, the Carijó Indians had already a good perception of this environmental reality, as shown by the name they gave to the bay. Paranaguá, meaning sea harbor, sea inlet, or round sea, reflects very well this intuitive perception of an old continental area literally drowned by a raising sea level. This is why its physiographical structures, such as sand banks and flat islands, change continuously with time. They are geologically short-lived and very dependent on the interaction between fresh water from the dense local drainage system and the sea water brought in by the tides (Soares and Lana 2012).

Fig. 10.5 Praia Deserta in the Superagui Island. *Source* LECOST/UFPR

The structure and functioning of landscapes and ecosystems that are parts of the Antonina bay cannot be understood without an understanding of a triple gradient of environmental variations. These are: (1) Salinity gradient—from typical marine conditions at the PEC point of entry to fresh water conditions at its innermost point. This gradient is very evident along the main E–W axis (bay of Paranaguá and Antonina bay), and the secondary N–S axis (bay of Laranjeiras and bay of Pinheiros); (2) Lateral gradients—caused by the addition of fresh water brought in by rivers and creeks slicing the plains, creating an infinity of micro-estuaries, even in the higher salinity sectors at the bay entry; and (3) Time-related gradients—with daily (associated mainly with tides), seasonal (associated with more or less rainy and hot periods), and interdecadal components (associated mainly with the El Niño and La Niña global events). Much is known regarding the daily and seasonal variations, but the variations brought in by the latter, longer-term events are still little studied (Soares and Lana 2012).

Regarding studies directed to the characterization of sediments from the bottom of the Antonina bay, Bigarella et al. (1970, 1978) and Odreski et al. (2003) need to be mentioned. Lamour et al. (2004) published a synthesis thereof, presenting textural maps (Fig. 10.6).

Generally, the distribution of bottom sediments in the Antonina bay is strongly influenced by fluvial discharges (mainly rivers Nhundiaquara and Cachoeira), consisting of very heterogeneous sediments and featuring a mix of coarse and fine sediments, hardly sorted, where the percentage of fines is higher than in other areas of the estuary (Soares et al. 1996).

In the beginning of the twentieth century, Antonina was the 4th main Brazilian port, whose activity was relocated in Paranaguá in the 1930s. Many studies show that silting rates are high in the Antonina bay; therefore, dredging is required, with associated problems of finding disposal areas for the dredged materials.

Figure 10.7 shows a panoramic view for the area of the Antonina Bay, where shoals and sand banks can be seen, both a response to a high silting rate typical for the area. Later on, they are covered with grasses and mangroves.

When the evolution in land use in the Antonina bay drainage basins is examined, one can notice an increase of vegetation a result of the reduction of farming and cattle raising. The apparent inconsistency between the raising silting rates in the Antonina bay and the dynamics of land-use change and occupation in the drainage basins can be explained by the human presence in areas more susceptible

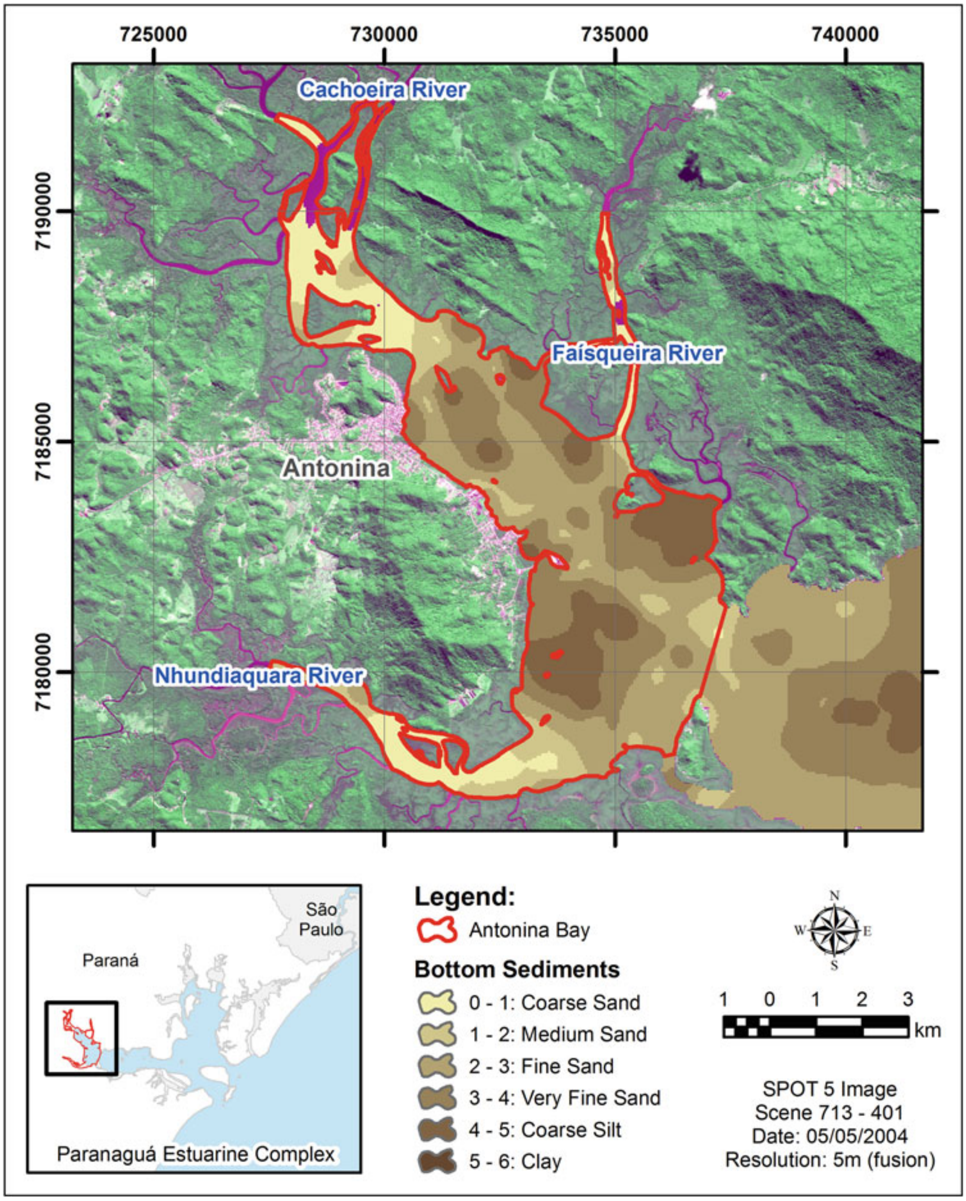

Fig. 10.6 Map of the Antonina bay bottom sediments distribution

to the release of sediments while the reduction of anthropic activities occurs in less susceptible areas (Paula 2010).

10.5 Past and Present in Superagui and Antonina

Despite being located in the same estuarine complex, Superagui Island and the Antonina bay show different situations regarding past and present. Both were important locations, from the historic point of view, in the occupation process of bay of Paranaguá. While in Superagui, with its wide plains and long beaches at the PEC mouth, there was a small but successful Swiss colonization at the end of the ninetieth century, Antonina, located in the estuary innermost point, was an important Brazilian commercial port focused mainly on maté tea and timber (Fig. 10.8) and responding to economic cycles. Along the years, all the region's activity moved to Paranaguá, nowadays the third most important Brazilian port and the main city in terms of population and economy of the Paraná's coast.

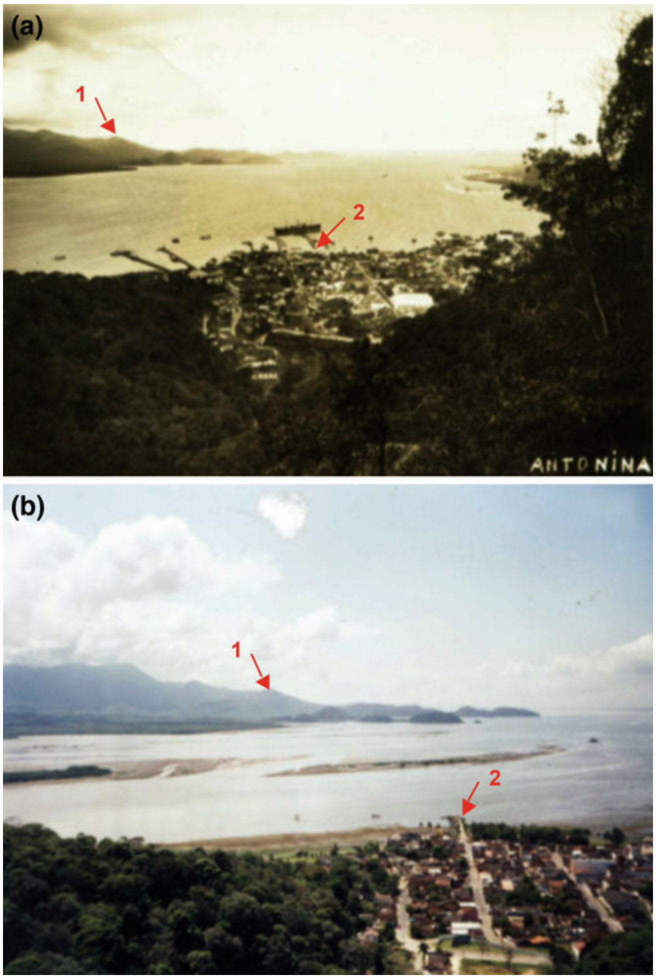

Fig. 10.7 Photographs from 1930 (**a**) and 2002 (**b**) showing silting of the Antonina bay (sediment banks in the middle of the bay). *Mark 1* Crest of Cumeeira ridge; *Mark 2* Pier at the Mar Fair (Town of Antonina)

Centralization of activities in Paranaguá have had visible consequences on Superagui and Antonina. With the creation of the transport modals focused on the port, Superagui ended up as geographically isolated, with the population and economy hardly subject to change in the last few decades. This is the reason why its landscape and natural characteristics have remained well preserved. From the 1970s, it has been considered one of the most pristine areas of the Brazilian Atlantic Forest, and CUs were created with very strict legislation. Dazzling scenery, contrasting the tall green mountains of Serra do Mar with the blue from the sea or the estuary, surrounded by vast mangroves, is common in the region.

The complex interaction between the estuary and the ocean causes significant changes in Superagui coastline, mainly at the mouth of the PEC, without any relevant consequences for the small population living in the area, which, due to its isolation, is poor and needy.

Such as Superagui, but only in the inner part of the estuary, Antonina is also of great scenic beauty due to contrasts created by the proximity of the mountains to the coastal plains, with vast tidal flats covered with mangroves and marshes. The historic town of Antonina, with its colonial manors and old warehouses used to store the goods for trade in the golden era of the port, adds to the value of this landscape. With the shift of activity to Paranaguá, Antonina started declining economically, practically through the whole twentieth century. Consequences are felt to this day, and the town, such as Superagui, is one of the poorest in the State of Paraná, despite the installation of a port terminal in the 1990s.

Adjacent to the Serra do Mar mountains, where landslips are common, the Antonina bay receives a large quantity of sediments brought in by rivers, which, settling there, reduce even further the possibility of access for larger ships. There is a constant need to dredge, but the greatest problem is the

Fig. 10.8 Antonina Bay and Serra do Mar. *Photograph* C.B.V. Paula

disposal of the dredged material, since the bay has CUs everywhere, and its transport to the open sea would make the dredging operation extremely expensive. Sedimentary banks were formed in the last few decades in the Antonina bay and then have become covered by mangroves and marine grassy plants. The resultant landscapes, although meaning a severe silting situation, are an unforgettable experience for nature lovers.

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The Bertioga Coastal Plain: An Example of Morphotectonic Evolution

11

Celia Regina de Gouveia Souza

Abstract

The Bertioga coastal plain, located in the metropolitan region of Baixada Santista (central coast of São Paulo state), contains nearly all of the types of depositional systems that are found on the rest of the Brazilian coast, in spite of its highly restricted area that is less than 6 km wide. Similar to other coastal plains, Bertioga's evolution was associated with variations in climate and the relative sea level (SL) during the Quaternary period. However, the evolution was also influenced by tectonic pulses that produced the following features: (a) a seismic signature indicating a normal fault in the central part of the coastal plain, which depressed block faces the Serra do Mar mountain range, suggesting the presence of a hemigraben ("Bertioga Graben"); (b) a sedimentary column thicker than 100 m in the central part of the coastal plain; (c) the presence of morphotectonic features on the coastal plain (anomalous arrangement and spatial distribution of some Quaternary units (QUs), drainage anomalies, and sets of systemic fractures in marine terraces) and on the Serra do Mar (fluvial capture of the Guaratuba River and triangular facets); (d) the preservation of marine terraces and fluvial deposits that are older than the Cananéia Formation (Marine Isotope Stage—MIS 5e, 100–140 ka); (e) differential control of Holocene marine and alluvial sediments throughout the coastal plain; and (f) the presence of guide layers in Pleistocene and Holocene deposits with throws up to 7.5 m. Thus, the evolutionary model of this coastal plain can in some ways be compared with those proposed for most Brazilian coastal plains, but with the peculiarity that it shows rare features of the transgressive–regressive event that is correlated with MIS 7 (240–260 ka) and has been affected by at least two tectonic pulses at the end of the Pleistocene and one pulse during the Middle to Upper Holocene. The recent creation of the *Restinga* of Bertioga State Park, embracing nearly half of the coastal plain, will enable the conservation of much of the rich plain's biodiversity and protect its important geological–geomorphological heritage, strengthening proposals for future geosites for geoconservation according to the principles set forth by UNESCO.

Keywords

Morphotectonics • Sea level changes • Bertioga coastal plain • Quaternary

11.1 Introduction

The coastal zone of Brazil, which covers approximately 9,200 km, exhibits a wide variety of sedimentary environments or depositional systems from the Quaternary to the present ages. This zone evolved in response to cyclical climate variations and oscillations in relative sea level (SL) that

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interacted with diverse geologic and geomorphological settings, tectonic activities, and a great variability in sediment supply and oceanographic and atmospheric processes particular to each region.

In the context of the evolution of the Brazilian coastal plains, especially in the state of São Paulo, the Bertioga plain is particularly noteworthy because of its exceptional geology and geomorphology. Nearly all sedimentary environments and Quaternary marine formations found throughout the rest of the Brazilian coastline can be found within a small area covering approximately 240 km^2, where the maximum width is less than 6 km (Souza 2007; Souza et al. 2009). This feature and the presence of a sedimentary column more than 100 m thick in the central portion of the plain (Barbosa et al. 2012), with marker layers offset up to 7.5 m, indicate that the evolution of the plains was influenced by tectonic events, in addition to the processes associated with SL fluctuations during the Quaternary.

The municipality of Bertioga is located in the Metropolitan Region of *Baixada Santista* and close to the largest cities on the São Paulo coast—Santos, Cubatão, and Guarujá, ca 120 km from the city of São Paulo (Fig. 11.1).

The lack of good access to the region, at least until the 1980s, and the current environmental legislation have ensured the preservation of extensive remnants of the original coastal plain forests, which cover almost 70 % of the municipality's territory. In some places, these remnants form a continuous corridor from the coastline to the top of the Serra do Mar mountain range.

The coastal plain forests are commonly known as "*Restinga*" vegetation (CONAMA Resolution nº 7/1996), which is one of the ecosystem categories associated with the Atlantic Rainforest biome that was recognized by UNESCO as a Biosphere Reserve in 1992. In Bertioga, they form a set of vegetation mosaics including eight types of phytophysiognomies displayed in a very especial arrangement, unique on the entire Brazilian coastal plain, and which is controlled by the complex spatial distribution of the Quaternary depositional systems (Souza et al. 2008, 2009).

Extraordinary biodiversity and geodiversity in Bertioga (Fig. 11.2), and the constant threat from anthropic pressures to use these resources led to the creation of the *Restinga* of Bertioga State Park in 2010 (*Parque Estadual da Restinga de Bertioga*—PERB; State Decree nº 56,500/2010), which embraces almost a half of the Bertioga coastal plain. At its eastern edge is the *Ribeirão Silveiras Tupi-Guarani* Indigenous Reserve, located in the neighboring municipality of São Sebastião, and whose presence also contributes to the full environmental protection of the park.

11.2 Sea Level Variations in the Quaternary and the Records on Brazilian Coastal Plains

There have been at least five phases of elevated SL (above the current level) over the last 500,000 years. These phases were related to interglacial periods and are correlated with marine isotopic stages (MIS) 1, 5, 7, 9, and 11, with the following respective age windows: 0–20, 100–140, 240–260, 400–420, and 480–500 ka (e.g., Siddall et al. 2010).

The most complete stratigraphic record of these marine oscillations in Brazil is found in the State of Rio Grande do Sul, where the largest coastal plain in the country is located. Four barrier–lagoon systems have been defined on this coastal plain, referred to as Barriers I, II, III (Pleistocene), and IV (Holocene) (Villwock et al. 1986). These barriers are correlated with MIS 9, 7, 5, and 1, respectively (Tomazelli and Villwock 2000). Rare remnants of marine terraces elevated more than 10 m above the current SL and correlated

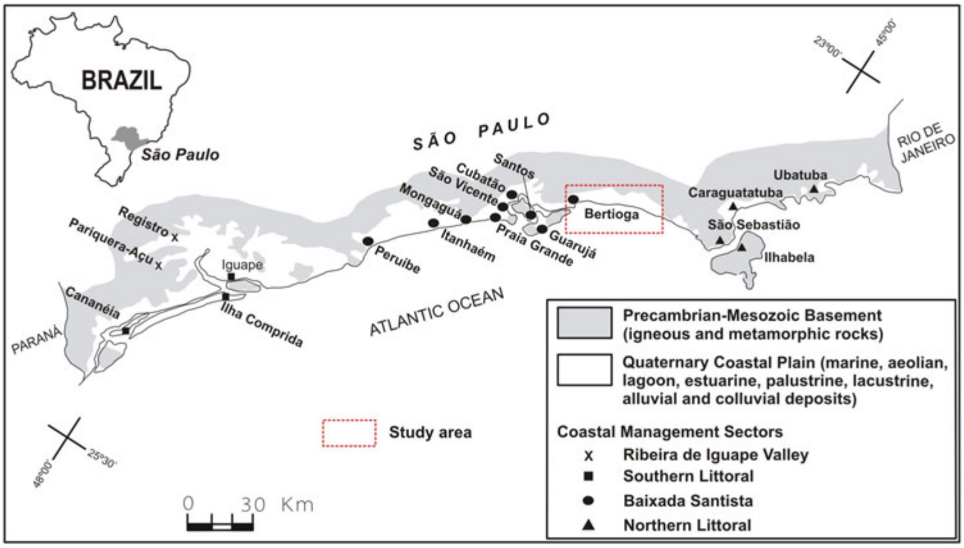


Fig. 11.1 Location of the study area, the municipalities of the São Paulo coastal zone and their related coastal management sectors. *Source* Modified from Souza (2012)

Fig. 11.2 Geodiversity and biodiversity features of Bertioga coastal plain: examples in the river basins of Guaratuba (**A**), Itaguaré (**B**), and Itapanhaú (**C**) (*sources* Celia R. G. Souza, Geological Institute of São Paulo). *A1* Pleistocene fluvial terraces/alluvial forest (*front*) and Pleistocene marine low terraces/*Restinga* High Forest (*back*). *A2* coastal erosion in Holocene beach ridges/shrub at Guaratuba beach. *B1* Itaguaré River mouth/beach—**a** estuarine sandbars, **b** sea cliffs in Pleistocene marine low terraces/*Restinga* High Forest, **c** Holocene beach ridges/*Restinga* Low Forest, **d** structurally controlled hill of basement rocks, and **e** current tidal flats/mangrove. *B2* Detail of B1-b, well-developed spodosol and erosion controlled by tectonic joints systems. *C1* Paleolagoon–estuarine depression—Wet *Restinga* High Forest (*left* of the road) and *Paludosa* forest (*right*); at the back—Pleistocene fluvial terraces/mixed alluvium–colluvium deposits (*Restinga*-Slope Transition Forest) and the Serra do Mar mountain range (Dense Ombrophylous forest). *C2* Remnant of a Pleistocene marine low terrace (with spodic B horizon), with two Pleistocene fluvial sequences at the base and remains of a Holocene shell-mound on the *top* (degraded *Restinga* High Forest)

with Barrier II are also found in the States of Bahia (east–northeastern region of Brazil—Martin et al. 1988), Santa Catarina, Paraná (southern region), and São Paulo (south-eastern region) (Suguio et al. 2005), and in Rio Grande do Norte (northeastern region—Barreto et al. 2002).

The latest Pleistocene transgression maximum, at 120,000 years BP (MIS 5e), left significant records throughout the Brazilian coast that include marine beach deposits sculpted in the form of marine terraces elevated 5–10 m above the current SL. This transgressive–regressive event is known in Brazil as the Penultimate Transgression and as the Cananéia Transgression in São Paulo, where the correlated deposits are called as Cananéia Formation (Suguio and Martin 1978). The most reliable dating of these deposits is attributed to the remnants of a coral reef in southern Bahia, which was ^{14}C dated to 120,000–125,000 years BP (Bernat et al. 1983; Martin et al. 1988).

The Holocene records of SL oscillations predominate in all of the Brazilian coastal plains, and various types of geological–geomorphological markers are commonly found, such as beach ridges and marine terraces elevated from 1 to 4 m above the current SL, barrier–lagoon systems, and remains of beachrocks. The most reliable biological markers are vermetid banks on rocky shores and mollusk banks in paleolagoon–estuarine environments. In Brazil, this MIS 1 event is known as the ultimate transgression; in São Paulo, it is known as the Santos Transgression, and the correlated deposits are called the Ilha Comprida Formation (Suguio and Martin 1978).

Holocene SL variation curves have been obtained for practically the entire Brazilian coast, and they show similar trends (Suguio et al. 1985, 2005; Martin et al. 1987, 2003). The most complete curve is for Salvador (Bahia), which suggests the occurrence of three coastal submergence events (SL elevated above current levels) at 7,800–5,600, 3,700–3,500, and 2,300–2,100 cal years BP alternating with three emergence events (drops in SL) at 5,300–4,200, 3,500–2,800, and after 2,100 cal years BP. The best curves for the state of São Paulo are those from the Cananéia–Iguape (South shore) and Santos (Baixada Santista) regions, where only the initial two uprising and descent phases were detected (maximum elevation of 4.0 ± 0.5 m above current SL).

Angulo and Lessa (1997) and Angulo et al. (2006) reinterpreted various SL paleomarkers used to prepare such curves and dated several vermetid fossils found on the coasts of Paraná and Santa Catarina. The authors concluded that the Holocene SL did not reach levels above 3.5 m and that the SL slowly fell to current levels without oscillations.

Despite discussions regarding the maximum height reached by the Holocene SL and the occurrence of negative oscillations, there is a consensus that in Brazil, the SL crossed "zero" (current level) approximately 7,500 cal years BP (or 7,000–6,500 years BP), what is also supported by geophysical simulations (Peltier 1998; Milne et al. 2005). Besides, there is an agreement that the marine transgression maximum occurred around 5,700–5,100 cal years BP (or 5,600–4,900 years BP) (Martin et al. 2003; Bezerra et al. 2003; Suguio et al. 2005; Angulo et al. 2006). On the other hand, the high frequency of positive and negative oscillations identified and/or interpreted by some authors, between 4,000 and 2,500 cal years BP could correspond to SL changes resulting from low-magnitude climate changes and/or local and/or regional neotectonic events.

Thus, it should be stressed that in relation to the possible role of neotectonics in studies of the evolution of the Brazilian coastal plains, discussions on the topic have been rare (e.g., Dillenburg and Hesp 2009). This lack of discussion is because, geotectonically, the Brazilian coast is considered a highly stable, passive margin. The same pattern emerges in other countries on the Atlantic coast in the Southern Hemisphere, where there are still few citations of neotectonic events in the coastal plains. In Australia and South Africa, for example, the marine levels that do not fit glacio-eustatic models have been recently attributed to neotectonic control (Bezerra et al. 2003).

In this sense, the most important references on neotectonics in the Brazilian coastal zone are on the Rio Grande do Norte (northeastern Brazil), where normal faults that cut across Pleistocene and Holocene alluvial and marine deposits apparently controlled the sedimentation of the coastal plain and/or resulted in rapid SL oscillations or even altimetric anomalies in the deposits (Silva 1991; Bezerra et al. 2001, 2003; Barreto et al. 2002). Similarly, height anomalies in marine terraces and biological markers of marine paleolevels have been associated with uplift in the last 6,600 years BP in the São Pedro and São Paulo Archipelago (equatorial Atlantic Ocean) (Campos et al. 2010). In the northern region, Souza-Filho et al. (2009) reported tectonic influences on the formation of barrier islands associated with two episodes of minor subsidence on the coast of Pará in the last 3,000 years.

11.3 Synthesis of the Geological–Geomorphological Evolution of the São Paulo Coast

The coast of São Paulo features two large geological–geomorphological compartments (see Fig. 11.1): the coastal mountain range (*Serrania Costeira*) and the coastal plain ("*Baixada Litorânea*") (Almeida 1964).

The coastal mountain range consists of the Serra do Mar and some isolated hills on the coastal plains. The Serra do Mar is a structural escarpment formed at the edge of the Atlantic Plateau in southeastern Brazil, and its maximum elevations in São Paulo range from 800 to 1,000 m (see also Chap. 22). It is mainly composed of Precambrian high-grade metamorphic rocks (gneisses, granulites, migmatites, and quartzites) and granite/granitoids bodies, which were cut by Jurassic basic dikes and sills, and Cretaceous alkaline bodies (Almeida and Carneiro 1998; Almeida et al. 2000; Zalan and Oliveira 2005).

The coastal plain, that also includes the current beaches, consists of marine beach deposits intercalated and interdigitated by alluvial, eolian, estuarine, lagoon, and palustrine sediments with ages ranging from the Quaternary to the present (Suguio and Martin 1978; Souza et al. 2008). They are bordered by beaches with distinct morphodynamic signatures (Souza 2012).

The current physiography of the coast results from a sequence of events and geological, geomorphological, climatic, and oceanographic processes that determined the evolution of its basement (Serra do Mar), the genesis and development of the watershed basins and coastal plains, and the consolidation of the current coastline and beaches.

In summary, the São Paulo coast went through six major evolutionary stages from the Proterozoic to the Quaternary and present day, as follows:

(a) Various orogenic cycles between the Neoproterozoic and the older Paleozoic that resulted in the collision and merging of cratons.

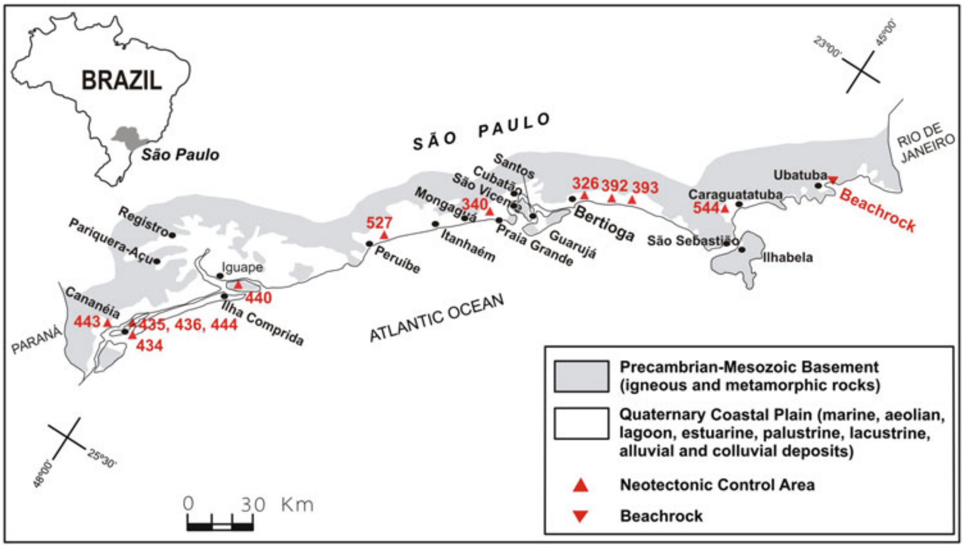
(b) Consolidation of the basement of the South American Platform (end of the Proterozoic to the Cambrian), with the formation of mobile tracks (current geological framework), such as the orogenic belt in southeastern Brazil.
(c) Effects of the implantation and evolution of the intracratonic Basin of Paraná (which forms the eastern border of the Atlantic Plateau) between the Paleozoic and the Mesozoic.
(d) Breakup of the Gondwana supercontinent, triggering continental drift, the opening of the Southern Atlantic Ocean, the formation and development of the Marginal Santos Basin (Jurassic–Paleogene), the intrusion of dikes and diabase sills in rocks of the continental edge, continual uplifting of the continental margin, and reactivation of the old basement structures.
(e) Significant late tectonic activity (isostatic compensation) between the end of the Cretaceous and the Quaternary that led to progressive and pulsed uplift of the Serra do Mar (end of the Cretaceous–Paleocene), the intrusion of alkaline bodies in the coastal region, the sloping of old leveling surfaces and driving of much of the drainage network toward the interior of the continent (see also Serra do Mar: The most "tormented" relief in Brazil), as well as the development and evolution of the continental rift of southeastern Brazil—CRSB (Riccomini 1989) (Paleogene–Early Pleistocene). The evolution of the CRSB, in turn, was responsible for the installation of taphrogenic basins on the Atlantic Plateau and grabens/hemigrabens in the coastal zone. One example is the Cananéia Graben, a hemigraben that falls toward the interior and caused sedimentary stacking of more than 400 m in the largest coastal plain of the state of São Paulo located at its Southern Littoral (Souza et al. 1996). The Serra do Mar escarpment was originally located in the middle of the current continental platform, approximately 40 km from the current coastline (Zalan and Oliveira 2005). Its recent position results from various tectonic reactivations, strong denudation, and intense erosive retreat that occurred since the Early Miocene, which is the maximum age given for the alluvial fans of the Pariquera-Açu formation. This formation outcrops along the Serra do Mar foot only in the southern littoral of São Paulo and experiences tectonically controlled sedimentation (Melo 1990). Evidence of neotectonic reactivations can be observed in many areas along the Serra do Mar escarpment in São Paulo, for example, as sets of triangular facets (e.g., Ribeiro et al. 2005) and river captures (e.g., Oliveira 2003).
(f) Finally, between the Middle Pleistocene and the Holocene, climatic changes and SL oscillations (such as the transgressive–regressive Cananéia and Santos events) acted to fill the coastal plains in a landscape initially dotted with numerous coastal embayments and islands and bordered on the continent by the Serra do Mar escarpment. According to Zalan and Oliveira (2005), neotectonic pulses acted locally to control the development of the largest bays and estuaries along the coast, which represented the rifts/grabens that were submerged during the transgressive SL events. Examples of such tectonic structures are the Cananéia (Souza et al. 1996) and Bertioga (later in this chapter) grabens/hemigrabens. The latter might be associated with a larger structure, possibly another hemigraben linked to the Cubatão Fault, which was responsible for the development of the Santos–São Vicente bays, the Santista Estuary complex, the Guarujá–Cubatão–Santos–São Vicente–Praia Grande coastal plain, and the Bertioga Channel that connects it to the Bertioga coastal plain. Further evidence of tectonic activity on the coastal plains of São Paulo includes drainage network anomalies, sets of systematic joints and microfaults in Pleistocene marine terraces with hardened spodic B horizons (Souza and Souza 2001), as well as altimetric anomalies in marine terraces.

The general NE–SW alignment of the São Paulo coastline is controlled by the largest structures of the Precambrian basement, which were reactivated during the Mesozoic and the Paleogene–Quaternary, such as the Cubatão, Bertioga, and Caraguatatuba fault zones, all parallel to the current coastline. The NW–SE structures, which are generally associated with Mesozoic basic dikes and sills, are responsible for local interruptions of the general orientation pattern of this coastline.

Although studies on neotectonics in the São Paulo coastal zone are rare, the Quaternary evolution of the CRSB provides some important clues as to how and when the reactivations may have occurred. They include a deformational event that took place in the Late Pleistocene–Holocene and generated NW–SE compression, giving rise to structural highs, another deformational event that occurred in the Holocene and was characterized by an E–W to NW–SE extension, while a younger, E–W compressive stress field seems to be active up to the present (Riccomini et al. 2004).

Various indicators of Quaternary tectonic activity can be observed along the São Paulo coast, including at Bertioga (Souza and Souza 2001) (Fig. 11.3; Table 11.1). Although still preliminary and little studied, this dataset suggests that this coast experienced predominantly vertical tectonic forces but also some horizontal stress (dextral and compressive strike slip), mainly in the WNW–ESE and E–W directions, which supports the CRSB evolutionary model. The vertical stress appears to be responsible for regional and local control of the formation and evolution of the coastal plains, while the horizontal stress controlled the macrodrainage network, which was periodically modified by tectonic pulses and reactivation of previous structures (Souza and Souza 2001).

Fig. 11.3 Areas where morphotectonic features have been found on the São Paulo coastal plain



These tectonic structures can also influence the current morphology of the shoreline, even in areas with Pleistocene marine terraces hardened by orstein horizons (spodosols), as appears to be the case at the mouth of the Itaguaré River in Bertioga (Bertioga Graben area of influence), in the south of Ilha Comprida, and on all of Ilha de Cananéia (both in the Cananéia Graben area of influence). In such areas, orthogonal subvertical fracture systems, or possible tectonic joints, reshaped sharp sea cliffs by erosive dismantling of structured "blocks" (Fig. 11.4). The very presence of such cliffs at these sites could be the result of structurally controlled accelerated erosion.

In the subsurface, other evidence of Quaternary tectonic activity has been interpreted by some authors as the seismic signatures of normal faults, such as in Ilha Comprida (Souza et al. 1996), São Sebastião Channel (Alves 2012), and Bertioga (Barbosa et al. 2012).

The normal fault located in the central portion of the Bertioga coastal plain separates two blocks with different maximum depths to the basement. The higher block is turned toward the sea, and its basement is reached at the depth of 60 m; the lower block is tilted toward the interior of the coastal plain, and the basement is at a depth greater than 100 m (Fig. 11.5). This tectonic structure, which should be associated with the Bertioga Fault zone (N50E) and most likely evolved in response to the CRSB evolution, can be interpreted as a hemigraben, which is formally named here as "Bertioga Graben." It is possible that the Bertioga Graben's formation was genetically related to the development of the tectonic-structural framework (most likely also a hemigraben) that now sustains the Santista estuary complex, connected to each other by a structure that gave rise to the Bertioga Channel (align with N50E). Additionally, the framework could be contemporary to the event that originated the "Cananéia Graben."

Determining when these neotectonic events occurred on the coast of São Paulo is not an easy task. For example, a beachrock found in Ubatuba (see location in Fig. 11.3) may provide some hints. Judging from the ^{14}C dating of two different micrite cements that fill both the body and a system of joints (most likely tectonic) of that beachrock (Souza 2013), it can be assumed that some tectonic activity occurred in the region between 4,400 and 3,950 cal years BP (or 4,370 and 3,860 years BP).

11.4 The "Puzzle" of the Quaternary Geology–Geomorphology of the Bertioga Coastal Plain

The Bertioga coastal plain covers 240 km^2, with a length of approximately 45 km and a maximum width slightly under 6 km. It is bordered by the Serra do Mar mountain range, which rises to elevations up to 900 m and forms a nearly rectilinear, imposing escarpment. This physiographic arrangement seems to control local climate, leading the Itapanhaú watershed to be the second most rainy area (around 4,000 mm/year) in Brazil.

Although only a brief summary of geological and geomorphological evolution of this coastal plain is presented here, it was based on a systemic and comprehensive analysis of various environmental attributes, including the following:

(a) the spatial arrangement of the Quaternary units[1] (QUs) (Souza 2007; Fig. 11.6);
(b) their main geologic features (Fig. 11.6 and Table 11.2)—lithology (Souza 2007), hydrogeology (Moreira

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[1] Spatially homogenous units include similar geological, geomorphological, pedological, and hydrogeological behaviors (Souza and Luna 2008).

Table 11.1 Structures and features suggesting Quaternary tectonic activity on the coastal plains of São Paulo and the likely associated tectonic stress regimes (for locations, see Fig. 11.3)

Area	Systematic joints (vertical/subvertical) in marine deposits	AD	JO	JC	Tectonic stress regime orientation	Tectonic stress regime (probable)	Morphotectonic features (drainage and relief anomalies, major tectonic structures and seismicity records)
Cananéia							
435	N15E (4/m), N65W (3/m)	80	X		EP1 V, EP2 = EP3	Uplift	Superimposed drainages. Drainage lineament (Itapitangui River): N36E, 12 km length. Cananéia Graben. Guapiara Lineament. SZ of Cananéia
436	N53E (5/m), N36W (5/m)	89	X				
443	N24E (1/m), N73W (2/m)	83	X				
	N18E (1/m), N70W (1/m)	88	X				
	N40E (1/m), N55W (1/m)	85	X				
444	N28E (1/m), N70W (1/m)	82	X				
	N05E (1/m), N75W (1/m)	80	X				
	N45E (1/m), N50W (1/m)	85	X				
I. Comprida 434	N40E (1/m), N60W (1/m)	80	X		EP1 V, EP2 = EP3	Uplift	Cananéia Graben. Guapiara Lineament. SZ of Cananéia
Iguape 440	N70E (3/m), N10 W (2/m)	80	X		EP1 V, EP2 = EP3	Uplift	Drainage lineaments (Ribeira de Iguape and Comprido rivers): N50E, 15 km length. Seismicity in Iguape. Guapiara Lineament: NW–SE. ZS of Cananéia
Peruibe 527	N33E (2/m), N60W (2/m)	87	X		EP1 V, EP2 = EP3	Uplift	Superimposed drainages. Seismicity in Iguape. ZS of Cananéia
	N43E (3/m), N45W (2/m)	88	X				
S. Vicente/PR. Grande 340	N73E (4/m), N34W (3/m) Falha Sinistral: N06W deslocando N64E	83	X	X	EP1 V or EP1 N70 W/H, EP3 N20E/H	Uplift or Dextral strike slip: N60E Sinistral strike slip	Superimposed drainages. Drainage lineaments: N30E and N60E, 3 and 2 km length. Cubatão (N65E) and Jurubatuba Faults (N55E). GL of Além Paraíba (N45E)
Bertioga							
326	EW (10/m), NS (10/m)	90	X				Superimposed drainages. Fluvial capture of the Guaratuba River. Drainage lineaments (Itapanhaú and João Pereira rivers): N60E, 12 km length. Micro-faults in Pleistocene marine terraces. Set of anomalies at the Itaguaré River mouth area: channel controlled by a EW structure, relief anomaly in a basement hill (millonites parallel to the shoreline), and cliffs in marine terraces controlled by two system of orthogonal subvertical joints. Remnants of the Morro do Icapara and Cananéia formations. Bertioga fault (N50E)
	N18E (10/m), N70W (8/m)	88	X		EP1 V, EP2 = EP3	Uplift	
	N05E (9/m), N80W (10/m)	85	X				
392	EW (10/m), N07W (8/m)	83	X		EP1 V, EP2 = EP3	Uplift	
393	N55E (10/m), EW (10/m)	35		X	EP2 V, EP1 N73E/H, EP3 N17 W/H	Horizontal compression: N73E/H	

(continued)

Table 11.1 (continued)

Area	Systematic joints (vertical/ subvertical) in marine deposits	AD	JO	JC	Tectonic stress regime orientation	Tectonic stress regime (probable)	Morphotectonic features (drainage and relief anomalies, major tectonic structures and seismicity records)
Caraguatatuba 544	N80E (7/m), N83W (7/m)	17		X	EP1 N88E/H	Horizontal compression: EW/H	Superimposed drainages. Drainage lineaments (Camburú River): N80E and N20W, 8 and 5 km length. Camburú fault (N80E). SZ of Caraguatatuba. Remnants of the Cananéia formation
	EW (5/m), N75W (6/m)	15		X	EP1 N84 W/H		
	N70E (2/m), N85W (4/m)	25		X	EP1 N82E/H		
Ubatuba Beachrock	EW (1,5/m), N06W (1/m)	84	X		EP1 V, EP2 = EP3	Uplift	Remnants of the Cananéia formation. GL of Ubatuba (N55E)

DA dihedral angle, *OJ* orthogonal joints, *SJ* shear joints, *SZ* seismogenic zone, *GL* Gravimetric Lineament, *EP1* Axis of maximum deformation, *EP2* Axis of intermediate deformation, *EP3* Axis of minimal deformation

Fig. 11.4 Possible structural control of the erosive reshaping of sharp cliffs lines in Pleistocene marine terraces with orstein horizons (spodosols). **a** Itaguaré River mouth in Bertioga—orthogonal joints in the EW and N55E directions. **b** Southern Ilha Comprida at the Cananéia lagoon outflow—N40E and N60W directions

2007; Souza et al. 2009; Pereira 2012), granulometry (Moreira 2007; Martins 2009), mineralogy (Martins 2009), stratigraphy (Fig. 11.7), geochronology (Martins 2009; Coelho et al. 2010 and unpublished data), and tectonics (Souza and Souza 2001; Barbosa et al. 2012—Fig. 11.5, and unpublished data—Fig. 11.7);

(c) their geomorphological attributes (Table 11.2)—morphometry, morphology, and involved morphodynamic processes (Souza 2007; Moreira 2007; Souza et al. 2009; Martins 2009; Badel-Mogollón 2012);

(d) their associated sets of soils (Table 11.2)—types, chemistry, and pedological evolution (Rossi 1999; Moreira 2007; Martins 2009; Badel-Mogollón 2012; Coelho et al. 2010); and

(e) their associated phytophysiognomies (Table 11.2)—types of vegetation, phytosociology, floristics, and sub-biomes (Souza et al. 2008, 2009; Badel-Mogollón 2012; Pinto Sobrinho 2012).

The Bertioga coastal plain features a unique arrangement of spatial distribution of QUs (see Fig. 11.6) along the entire Brazilian coast, which is also distinct between the Itapanhaú and the Itaguaré-Guaratuba rivers drainage basins.

Three major groups of depositional systems or sedimentary environments fill in and outcrop on this coastal plain, some of them inactive and others still evolving:

(a) marine beach: current beaches (Pr), Holocene beach ridges (*LHTb*) and marine terraces (*LHTa*), and Pleistocene marine high (*LPTa*) and low (*LPTb*) terraces;

(b) estuarine–lagoon and lacustrine–palustrine: current tidal flats (*LOL*) and Holocene paleoestuarine–lagoon depressions that evolved into lacustrine and palustrine environments (*LCD*);

(c) fluvial: Pleistocene (*LPF*) and Holocene to current (*LHF*) terraces, floodplains, bars and riverbed deposits, and Holocene to current (*LMP*) plains of mixed deposits (alluvial sediments and colluvial deposits formed by debris and mudflows during extreme flash-floods).

11.4.1 Pleistocene and Holocene Marine Beach Depositional Systems

11.4.1.1 Pleistocene Marine High (LPTa) and Low (LPTb) Terraces

The oldest marine deposits in Bertioga are the Pleistocene marine high terraces (LPTa) that occur mostly in the central portion of the coastal plain. In the Itaguaré and Guaratuba rivers basins, these deposits stand out as remnants of recessed/depressed (4.5–8.0 m) and highly carved (CxLPTa) terraces, interspersed by small depressions (Cx-LCD). Where both units are difficult to be individualized even on aerial photographs at detailed scales, they form a complex unit named as Cx-LPTa/LCD. In the Itapanhaú River basin, the LPTa are associated with old fluvial deposits (Cx-LPF), generally at low elevation levels, and form another complex unit. However, remnants of LPTa can still occur at elevations up to 13 m close to the Serra do Mar foothills, where there is no evidence of eolian activity.

OSL datings from the top of LPTa yielded ages of 168,000 ± 15,000 (Itapanhaú basin) and 162,000 ± 13,000 (Itaguaré basin) years BP (Martins 2009; Coelho et al. 2010). However, because OSL ages are commonly rejuvenated in old and highly pedogenized sediments[2], it may be

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[2] Samples with high levels of radioactive material (organic material, heavy minerals, and/or iron oxide) embedded after sediment burial have OSL/TL ages lower than the actual age, or rejuvenated, which is one of the intrinsic constraints of this dating method (Sallun et al. 2007). Likewise, samples subject to many fluctuations in the groundwater level also have rejuvenated ages.

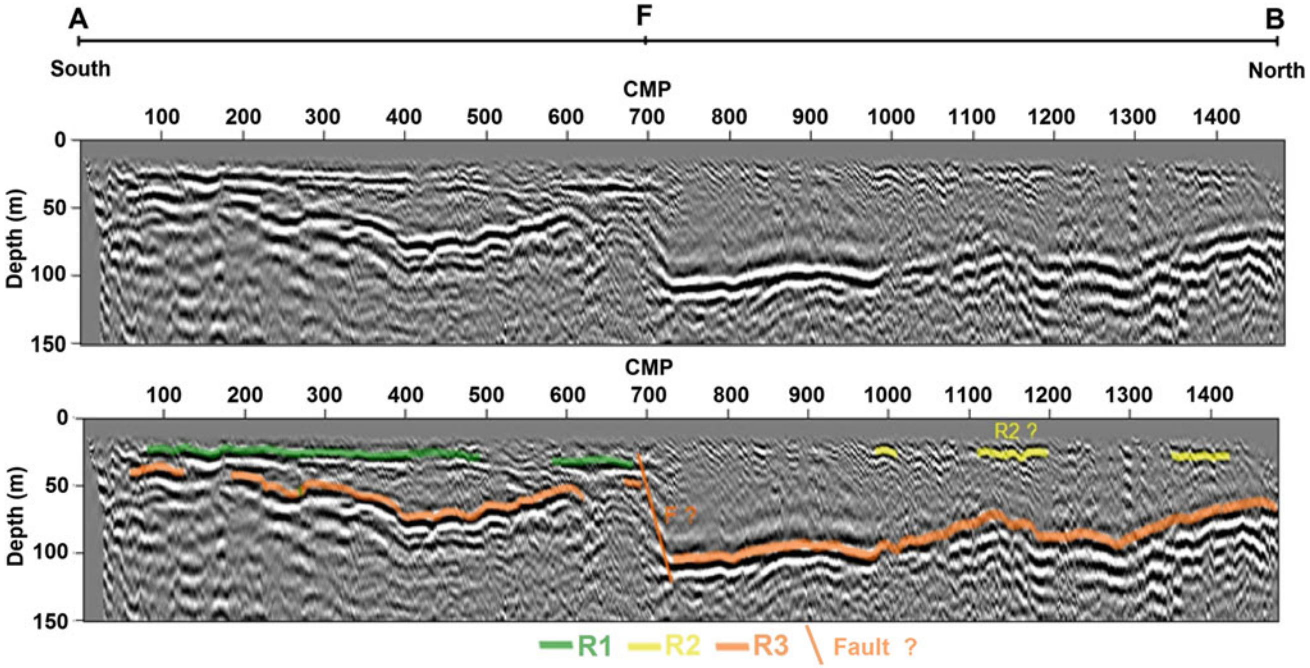

Fig. 11.5 Seismic signature of a normal fault (here, formally defined as the "Bertioga Graben") and various seismic reflectors (*R*) obtained on the central portion of the Bertioga coastal plain. The oceanic coastline is to the south, and the Serra do Mar is to the north. R3 surface of the basement; R1 and R2 borders of sedimentary units (Pleistocene and Holocene) with significant differences in terms of compactness, density, and consequently acoustic impedance. *Source* Barbosa et al. (2012)

expected that these deposits are even older. Thus, LPTa is interpreted as correlated with the Morro do Icapara Formation, defined by Suguio and Martin (1994); in other words, it would be associated with MIS 7.

The second and younger generation of Pleistocene marine terraces (LPTb) has a very different spatial distribution than LPTa, outcropping as a continuous strip along the entire coastal plain and separating the central and frontal portions of that plain. The elevations range from 4.5 to 6.0 m in the Itaguaré and Guaratuba river basins (low/depressed levels), but can reach 7.0–9.0 m in the Itapanhaú River basin (see Fig. 11.2 C2). An important morphological feature of this unit is the geometry of its boundaries, exhibiting very irregular and sinuous contours (see Fig. 11.6). These deposits (OSL age 125,600 ± 14,500 years BP—Martins 2009; Coelho et al. 2010) are correlated with the Cananéia Formation (Suguio and Martin 1978; Souza 2007) and therefore are associated with MIS 5e.

A particularity of both generations of Pleistocene marine deposits is the presence of well-developed, deep spodosols that sometimes feature structures from the dismantling of the Bh horizons and even their complete disappearance. These characteristics indicate that these soils have a polygenic origin, with several cycles of pedogenesis controlled by oscillations in the groundwater level, thus evolving for many thousands of years (Coelho et al. 2010). Moreover, it is expected that their evolution is directly related to fluctuations in the SL, especially those of a glacio-eustatic nature.

Deep spodosols were found in the cores Madal-03 (5 m thickness in subsided LPTa, at Guaratuba River basin) and the Itag-02 (11 m thickness in LPTb, at the Itaguaré River mouth) (Fig. 11.7). Samples of orstein horizons collected in Madal-03 (2.15 m deep) and Itag-02 (6.60 m deep) revealed ^{14}C ages, respectively, of 32,720–31,680 cal years BP (or 28,020 ± 140 years BP) and 2,740–2,580 cal years BP (or 2,860 ± 30 years BP). These results may suggest at least two major podzolization phases in this region, in the Late Pleistocene and in the upper Holocene.

Schwartz (1988) found a main phase of podzolization and formation of orstein horizons in sandy deposits in the Congo that revealed ages between 30,000 and 40,000 years BP. This time interval coincides with MIS 3 (30,000–40,000 years BP), when the SL was a few meters below the current level. On the southeast coast of Brazil, for example, there are records suggesting that at that time the SL was approximately 7–8 m below the current level (Klein 2005; Alves 2012).

Thus, also considering the several OSL and ^{14}C ages in the range between 45 and 24 ka, obtained for spodic horizons of LPTa and LPTb (Martins 2009; Coelho et al. 2010, and this chapter), it is likely that these terraces have been under the effects of that phase of pedogenesis during the MIS 3.

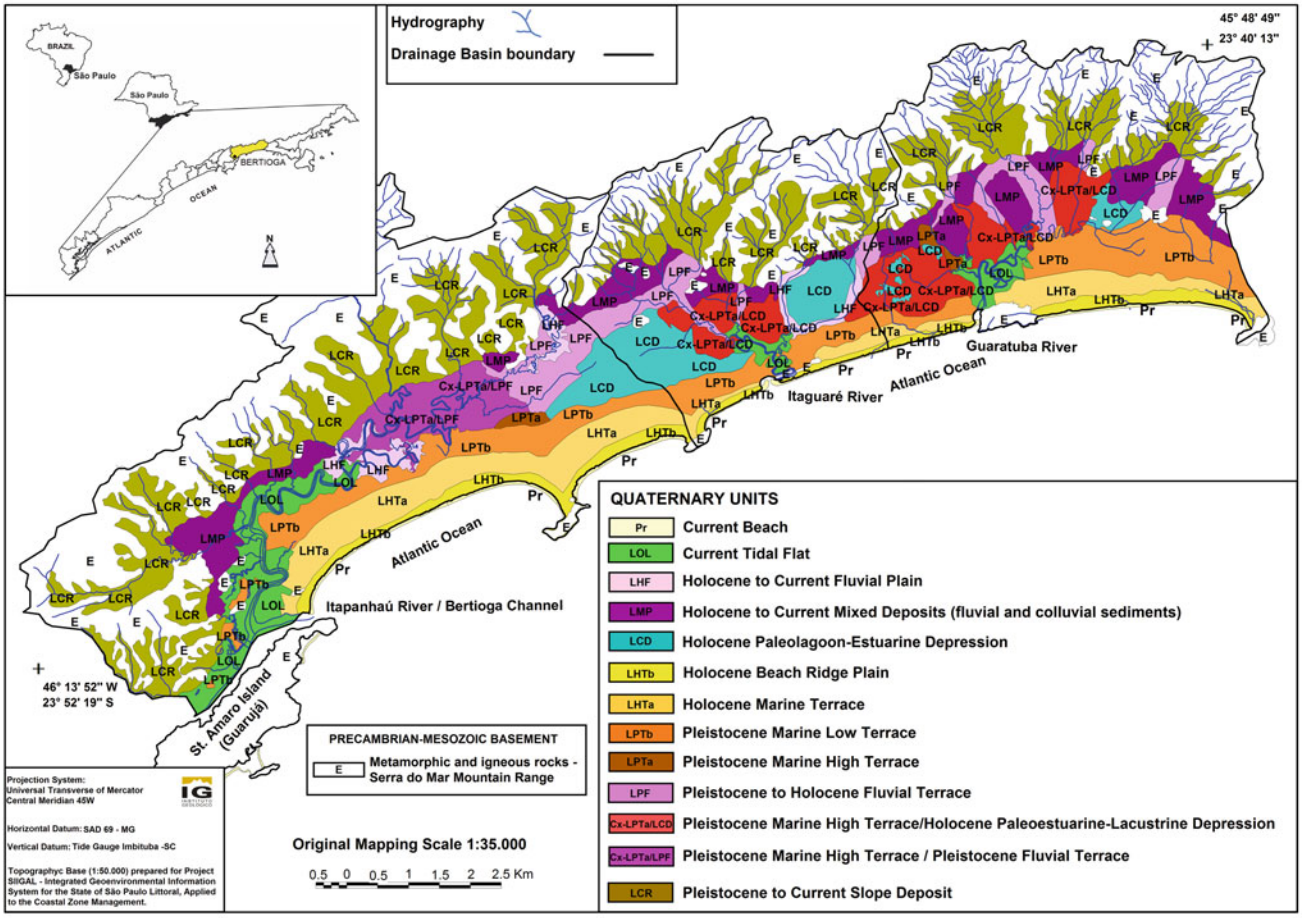

Fig. 11.6 Map of Quaternary units on the Bertioga coastal plain. *Source* Modified from Souza (2007)

11.4.1.2 Holocene Marine Terraces (LHTa) and Beach Ridges (LHTb)

The Holocene marine deposits also consist of two generations. The oldest is formed by marine terraces (LHTa) with elevations between 3.0 and 4.0 m that still retain the wavy morphology of beach ridges; the youngest forms a plain of beach ridges (LHTb) with elevations between 1.5 and 2.5 m. The geologic and geomorphological characteristics and the chronostratigraphic relationships (Figs. 11.6 and 11.7) indicate that these deposits are related to the Ilha Comprida Formation and were therefore constructed during the Santos transgressive–regressive event (Suguio and Martin 1978; Souza 2007), associated with MIS 1.

Both generations of deposits occupy the entire coastal plain front, outcropping continuously in the three drainage basins, albeit with distinct spatial distributions. In the central part of the coastal plain between the Itaguaré River basin and the mouth of the Guaratuba River, the strip of outcropping LHTa and LHTb is quite limited in width, rarely exceeding 300 m. Beyond this stretch, the widths increase considerably in both directions, reaching 700–800 m. These differences are responses to the processes that controlled the marine sediments along the coastline during the Holocene. At the maximum of the Santos Transgression, the shoreline was close to the foot of the Pleistocene marine low terraces (LPTb) that appeared as a barrier of sharp sea cliffs, supported by hard orstein horizons of deep spodosols (that provided resistance to coastal erosion). Thus, when the SL fell down, the shoreline started to prograde (LHTb deposits) from this barrier line and was prone to a number of different processes that may have included tectonic-structural control of the barrier, differential erosion along the barrier controlled by spodosols, and coastal dynamics regime linked to coastal cells (second model described in Souza 1997). It is very likely that these processes were mutually dependent.

Based on a ^{14}C age obtained for estuarine–lagoon sediments at the base of the Itag-01 core (Fig. 11.7), located in LHTb deposits near the Itaguaré River mouth, it is clear that the marine influence was already strong in the current shoreline by the beginning of the Holocene (9,010–8,720 cal years BP, or 8,000 ± 50 years BP), when the SL was approximately 19–20 m below the current level along

Table 11.2 Geological, geomorphological, pedological, and phytophysiognomic characteristics of Quaternary Units (QUs) on the Bertioga coastal plain (modified from Souza et al. (2008, 2009) (for QU location and legend, see Fig. 11.6)

QU	Geological domain	Geomorphological domain	Pedological domain	Phytophysiognomic domain
Marine beach deposits				
Pr	Current beach deposits (medium, fine, and very fine sands) with local eolian reworking. Water table (WT): shallow and dependent on the tidal cycle	Intermediate with dissipative trends beaches; elevation: 0–2 m above the current mean sea level (CMSL = +0.78 m at the Port of Santos tide gauge in 2013)	Arenosols (only on backshore zones with no coastal erosion)	Pioneer plants (beaches with no coastal erosion)
LHTb	Marine beach deposits of Early Holocene age (fine to very coarse sands and biodetritic gravels), locally overlayed by aeolian deposits. WT: 0.40–1.20 m (dry season)	Regressive beach ridges (wavy morphology); elevation: 1.5–2.5 m above the CMSL	Arenosols, spodosols (locally)	*Restinga* Low Forest and *Restinga* High Forest (locally)
LHTa	Marine beach deposits of Late Holocene age (very fine and medium sands), locally overlayed by aeolian deposits. WT: 0.50–1.50 m (dry season)	Lower marine terraces closer to the shoeline (gently wavy morphology); elevation: 3.0–4.0 m above the CMSL	Spodosols (Humiluvic)	*Restinga* High Forest
LPTb	Marine beach deposits of younger Pleistocene age (very fine and fine sands), with local aeolian reworking. WT: 1.0–2.7 m (dry season)	Marine terraces forming a continuos strip along the coastal plain (narrow, or wavy morphology locally); elevation: 4.5–9.0 m above the CMSL	Spodosols (Humiluvic and Ferrihumiluvic, with orstein horizons and polygenic evolution), Arenosols (locally)	*Restinga* High Forest
LPTa	Marine beach deposits of older Pleistocene age (very fine sands), with undifferentiated aeolian deposits locally. WT: 1.0 to >3.0 m (dty season)	Marine terraces remnants, higher and more internalized than the others, forming irregular and small elevations 4.5–13.0 m above the CMSL	Spodosols (Humiluvic and Ferrihumiluvic with orstein horizon, polygenic evolution), Arenosols (paleospodosols with dismantling structures)	*Restinga* High Forest
Cx-LPTa	Marine beach deposits of older Pleistocene age (very fine sands), with undifferentiated aeolian deposits locally. WT: 1.0 to >3.0 m (dty season)	Isolated and irregular remnants of marine terraces bordered/interspersed by either small and shallow paleolagoonal–estuarine–lacustrine depressions (Cx-LPTa/LCD), or fluvial terraces remnants (LPTa/LPF), forming lithological complexes very little or no individualized in aerial photos; marine terraces elevation: 4.5–8.0 m above the CMSL		
Estuarine, Lagoon, Lacustrine, and Palustrine deposits				
LOL	Estuarine deposits of Late Holocene to the present ages (sandy pelitic sediments). WT: <0.10 m	Current tidal flats and paleolagoon terraces bordering Histosols (the estuarine zone of the main three rivers); elevation: −0.5 to +1.5 m above the current MSL	Histosols	Mangrove (tidal flats) and *Apicum* (paleolagoon terraces)

(continued)

Table 11.2 (continued)

QU	Geological domain	Geomorphological domain	Pedological domain	Phytophysiognomic domain
LCD	Estuarine–lagoon deposits of Holocene age overlayed by lacustrine–palustrine sediments of Holocene to the present ages (silty–clayey–sandy and organic-colloidal sediments); current alluvial and colluvial deposits (locally). WT: 0–Palustrine-lacustrine–estuarine sediments of Holocene to the present ages (pelitic and organic-colloidal sediments that can deep more than 6 m); alluvial and colluvial deposits (locally). WT: 0,0–0.20 m	Paleolagoon–estuarine–lacustrine depressions (broad and deep); elevation: 1.0–1.5 m above the CMSL	Organosols (Sapric and Fibric) and Gleysols (Melanic and Haplic locally)	*Paludosa* (Paludal) forest (deeper paleolagoons)
Cx-LCD		Paleoestuarine-lacustrine depressions (small, shallow and filled) bordered/interspersed by remains of marine high terraces, forming a lithological complex (Cx-LPTa/LCD) very little or no individualized in aerial photos; depression elevation: 1.5–2.0 m above the CMSL		Wet *Restinga* High Forest (shallower estuarine–lacustrine depressions)
Fluvial and slope deposits				
LHF	Fluvial deposits of Holocene to the present ages (sands, silty sands, and gravels). WT: 0.50–1.20 m (dry season)	Floodplains, low terraces, bars and bed depositional environments (meandering systems); follows the current rivers valleys at the central and the back portions of the coastal plain; elevation: 2.0–5.0 m above the CMSL	Gleysols (Haplic and Melanic)	*Restinga* High Forest, *Restinga* -Slope Transition Forest, Wet *Restinga* High Forest and *Paludosa* forest
LPF	Fluvial deposits of Pleistocene to Holocene ages (sands, silty sands, and gravels). WT: 0.50–1.50 m (dry season)	Fluvial terraces (high, narrow and broad) formed into floodplains, beds and bars environments (meandering system) and anchored at the foothills in the back of the coastal plain; elevation: 7.5–10.0 m above the CMSL. They do not following the valleys of the current rivers and are in association with LMP, LPTa and Cx-LPTa units	Gleysols (Haplic), Cambisols (Fluvic), and Fluvisols	Alluvial forest
Cx-LPF	Fluvial deposits of Pleistocene to Holocene ages (sands, silty sands, and gravels). WT: 0.50–1.50 m (dry season)	Remnants of fluvial terraces (very dissected) and fluvial paleovalleys interspersed by remains of LPTa, forming a lithological complex (CxLPTa/LPF) very little or no individualized in aerial photos; aluvial terraces elevation: 5.0–8.0 m above the CMSL		
LMP	Undifferentiated mixed deposits, formed by Holocene alluvial sediments reworked and buried by Late Holocene to current colluvial sediments originated from debris and mudflows (extreme flash-floods). WT: 0.20–1.10 m (dry)	Dissected plains located at the back of the coastal plain in association with LPF terraces; plain elevation: 5.0-7.0 m above the CMSL	Fluvisols , Gleysols (Haplic and Melanic locally), Cambisols	*Restinga*-Slope Transition Forest and Paludosa Forest (locally)
LCR	Slope deposits formed since the Pleistocene up to the present, represented by colluvial, talus, and alluvial fans deposits (the all granulometric classes). WT: ≥2.0 m (dry season)	Low slopes of the Serra do Mar foothills; elevation: >10 m above the CMSL	Regosols, Cambisols (Haplic), Ferralsols	*Restinga* -Slope Transition Forest

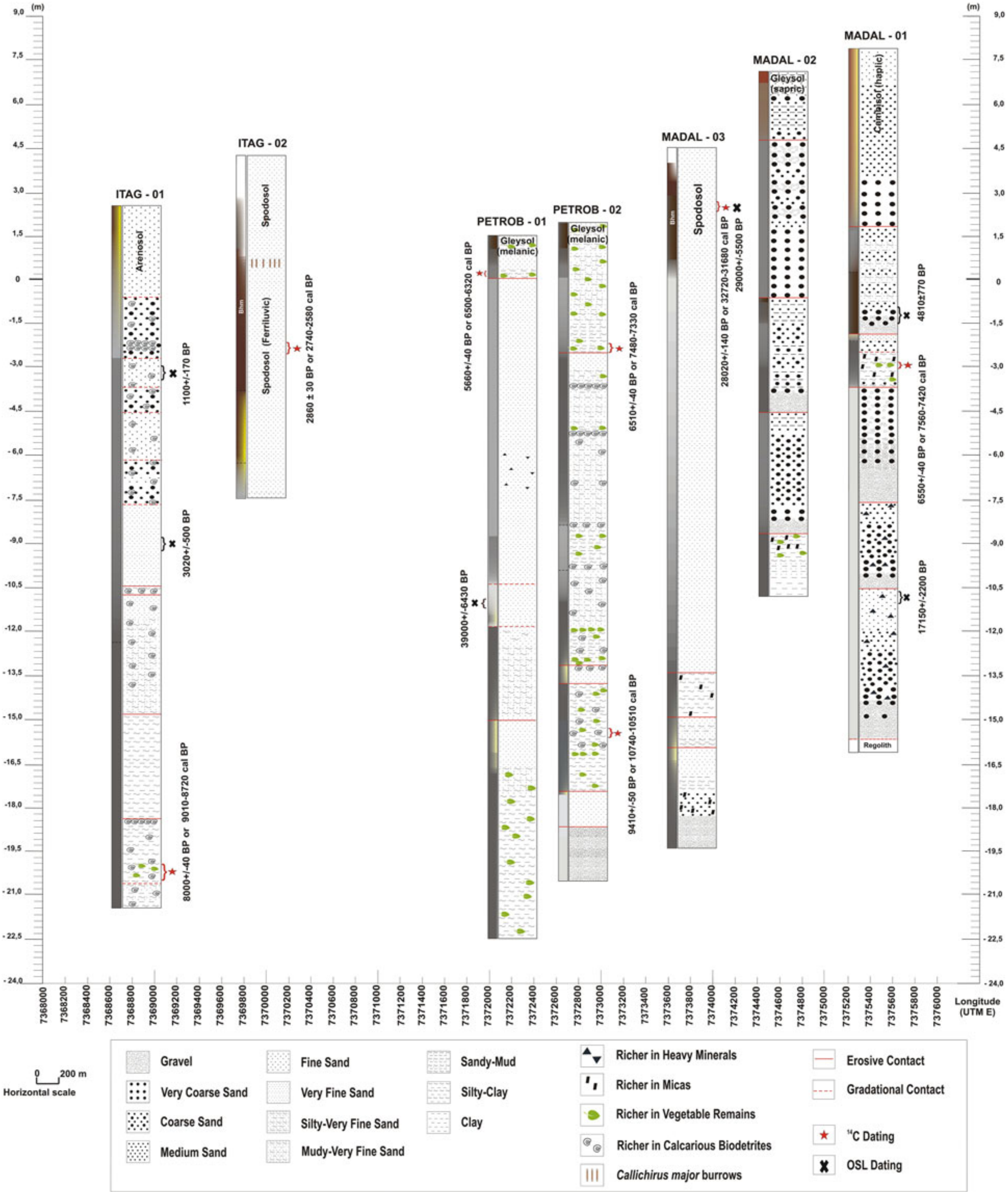

Fig. 11.7 Stratigraphic profiles located in different depositional systems. Marine beach: Holocene (LHTb: Itag-01) and Pleistocene (LPTb: Itag-02; Cx-LPTa: Madal-03). Paleolagoon–estuarine–lacustrine–palustrine depression: Pleistocene to the present (LCD: Petrob-01 and Petrob-02). Fluvial and mixed: Pleistocene to the present (LPF: Madal-01; LMP: Madal-02)

the São Paulo state. A continuous and well-demarcated topographical level around the 20-m isobaths on the São Paulo continental shelf seems to be the evidence of eustatic stabilization in this period (Conti and Furtado 2006).

In the same core (Itag-01), a pelitic lithofacies (3.5 m thick of bay deposits) resting in erosive contact above the estuarine–lagoon deposits marks a rapid phase of coastal submergence. In this sense, the presence of beachrocks at

13 m deep on the continental shelf of São Sebastião, dated to ^{14}C 8,000 cal years BP (Klein 2005), also demonstrates that the marine transgression was rapid during this period.

Judging by these results and the age (top) of a very inland LHTa deposit (OSL 5,100 ± 1,000 years BP—Martins 2009; Fig. 11.7), the SL must have crossed "zero" (present coastline) for the first time in the Holocene at approximately 7,000–6,500 (7,500 cal) years BP, corroborating what has been suggested in the literature (e.g., Martin et al. 2003; Dillenburg and Hesp 2009).

In the top of the Itag-01 core, the sequence formed by two regressive marine beach lithofacies (quite distinct sedimentologically from each other), separated by a thin layer of pelitic sediments in erosive contact, suggests that after the first transgressive phase, the SL slowly descended to just below the current level (regressive beach ridges—LHTa), then it rose again very quickly (strong erosion of LHTa and pelitic deposition), and then slowly fell again (regressive beach ridges—LHTb) since OSL 3,020 ± 500 years BP. On the other hand, in the LHTb sequence, the intercalation of 7 m thickness of storm deposits (OSL 1,100 ± 170 years BP) may indicate climate oscillation during most of the final progradation of the shoreline, surely with a greater influence of extratropical cyclones.

This evolution seems to agree with the interpretations of Suguio and Martin (1978, 1994), who suggested two transgressive phases with maximums of 4.0 m at 5,100 years BP (or 6,070–5,600 cal years BP) and 3 m at approximately 3,600 years BP (3,512–3,162 cal years BP), and two regressive pulses with the SL falling to a few meters below the current one.

11.4.2 Pleistocene to Holocene Estuarine–Lagoon and Holocene to Current Lacustrine–Palustrine Depositional Systems

Along the central area of the coastal plain in the Itaguaré and Guaratuba River basins (Fig. 11.6), there are irregular and filled depressions, where the maximum elevation ranges from 1.0 to 2.3 m. The sedimentary column reaches more than 100 m thickness in the center of the coastal plain (northern block of the hemigraben) and approximately 70 m thickness at the edge of the depression (southern block of the hemigraben) (Barbosa et al. 2012) (see Fig. 11.5).

The stratigraphy provided by Petrob-01 and Petrob-02 cores (Fig. 11.7) suggest complex geologic evolution, exhibiting Pleistocene marine beach sequences and/or Pleistocene fluvial deposits buried by Holocene lagoon–estuarine sequences, all of them buried by Holocene lacustrine sediments, and finally by the current palustrine deposits. However, both cores have a particular stratigraphic arrangement that includes abrupt lithological gaps and throws of approximately 3.0 m in Pleistocene marine deposits (normal fault). Moreover, in Petrob-02, the sedimentary column reaches 19 m thickness of lagoon–estuarine deposits burying the remains of a decapitated Pleistocene marine deposit (Morro do Icapara Formation).

The beginning of the Holocene marine influences within the paleolagoon occurred at the Pleistocene/Holocene boundary, just before ^{14}C 10,740 cal years BP (or 9,410 ± 50 years BP), when the SL was 18–20 m below the present level. The maximum of the Santos Transgression into the coastal plain occurred ca ^{14}C 6,500–6,320 cal years BP (or 5,660 ± 40 years BP), based on the age of a sandy–pelitic deposit resting above the subsided terrace of Cananéia Formation (LPTb), in Petrob-01. This result corroborates the literature consensus.

Considering that the original paleolagoon–estuarine depression was very restricted in area, all these features suggest that its origin may only be interpreted as linked to tectonic reactivations of the Bertioga Graben that controlled fluvial sedimentation and marine ingressions into the coastal plain, most likely since the Pleistocene, but surely throughout the Holocene.

11.4.3 Pleistocene and Holocene to Current Fluvial Depositional Systems

The fluvial environments consist of Pleistocene to Holocene river terraces (LPF), Holocene to current alluvial deposits (LHF), and alluvial–colluvial mixed deposits (LMP). The LPF outcrops are found predominantly at the back of the entire coastal plain close to the Serra do Mar foothills, figuring a spatial distribution of irregular polygons with unusual shapes and generally truncated by other units, such as LMP and Cx-LPTa/LCD (Fig. 11.6). They are cut by superimposed drainages to form structured arrangements and drainage anomalies. In the Itaguaré and Guaratuba river basins, LPF is formed by almost 24 m thick coarse to very coarse alluvial sediments (Madal-01 core, Fig. 11.7) and occurs in basal and lateral association with the LMP unit.

LMP (Madal-02 core, Fig. 11.7) unit is constituted by undifferentiated mixed deposits formed by Holocene alluvial sediments that were reworked and buried by Late Holocene to current colluvial deposits, which were originated from debris and mudflows during extreme flashflood events. Currently, LMP areas are very jagged and intersected by a tangle of fine, rambling channels that are inundated only during intense rainfalls. This behavior seems to be related to another more recent morphotectonic anomaly.

In the Itapanhaú River basin, LPF forms a complex association with remnants of LPTa (Cx-LPTa/LPF). In a river bank approximately 7 m high (elevation 9.95 m) (see Fig. 11.2-C2), there appears a sequence formed by Pleistocene marine beach sands (LPTb—rejuvenated OSL 28,800 ± 6,200 years BP—Martins 2009 and Coelho et al. 2010) resting on two sequences of Pleistocene fluvial deposits (LPF—OSL ages of 162,100 ± 27,500 years BP for the inferior and 119,600 ± 17,700 years BP for the superior—Martins 2009; Coelho et al. 2010). These results suggest significant correlations between these fluvial deposits and the Morro do Icapara and Cananéia Formations.

The set of characteristics described above provides evidence of an origin strongly controlled by tectonic events for both LPF and LMP units, since ordinary continental erosion and fluvial deposition processes alone could not explain such sedimentary anomalies.

According to Oliveira (2003), the Guaratuba River basin results from an evolution of a fluvial capture developed on top of the Serra do Mar, which was interpreted as a response to the last phase of CRSB tectonic reactivation in the Late Pleistocene–Early Holocene (Riccomini et al. 2004; Ribeiro et al. 2006). OSL datings on two alluvial deposits with spodosols, both located close to the capture site, revealed maximum and minimum ages of 29,000 ± 5,000 years BP and 10,000 ± 1,000 years BP (Neves 2012). Despite the likely rejuvenating of these ages, it is noteworthy that the older one coincides with the Pleistocene podzolization phase proposed above (SL rising).

In the Madal-01 core (elevation at 7.9 m) over 12 m thickness of gravels, arranged in erosive contact over the regolith, may be correlated with the phase of river capture. The OSL age obtained for the middle of this sequence is 17,150 ± 2,200 years BP, but it is most likely quite rejuvenated. Above this sequence lies a pelitic lithofacies (sedimentary anomaly) of lacustrine origin, whose age at the top is ^{14}C 7,560–7,420 cal years BP (or 6,550 ± 40 years BP). It seems to be deposited in a large lake formed as a result of the huge volume of water now flowing into the coastal plain after the river capture, concomitantly with the rising of SL at the time when the Santos Transgression crossed “zero” and inundated the tectonic depression. In Madal-02 (elevation at 7.2 m), this lacustrine sequence occurs approximately 6 m below the level at which it occurs in Madal-01, suggesting a normal fault with the depressed block facing inland.

Therefore, a new tectonic pulse occurred between the Mid-to-Late Holocene, probable shortly after 4,040 years BP (OSL 4,810 ± 770 years BP for the gravels above the lacustrine deposits in Madal-01). Beyond the response to this tectonic event, the gravel sequence also indicates the beginning of the adjustment of the drainage network in the Guaratuba River basin and indirectly the phase of marine regression after the maximum of the Santos Transgression (shortly before 5,580 years BP). The tilting of blocks in LPF led to the formation of a subsided paleosurface on it, upon which LMP deposits were later laid down.

The younger fluvial deposits (LHF) occupy mainly the bottom of the current valleys and have evolved since the first regressive phase of the Santos Transgression. In the Itaguaré River basin, the spatial distribution of LHF features a remarkable drainage anomaly (interpreted as a morphotectonic feature), because it follows two tributaries of lower hierarchical order that outline the LCD unit forming an arc (see Fig. 11.6).

11.5 Summary of the Evolution of the Bertioga Coastal Plain

Like all Brazilian coastal plains, climate changes and relative SL fluctuations controlled the Quaternary evolution of the Bertioga coastal plain. However, neotectonics also seem to have contributed dramatically by controlling the lithological and structural framework of this coastal plain (Bertioga Graben), the reactivations of which played a key role in the sedimentary packaging, spatial arrangement, and reformation of the outcropping QUs.

11.5.1 Pleistocene

Tectonic events associated with reflections of the evolution of the CRSB and the reactivation of the Bertioga Fault (N50E), probable between the Late Paleogene and Early Pleistocene, led to the establishment of the Bertioga Graben, a hemigraben sloped inland on the central part of the coastal plain. At the end of the Middle Pleistocene, a transgressive–regressive event associated with MIS 7 gave rise to different depositional systems related to the Morro do Icapara Formation, such as transgressive and regressive barrier islands (LPTa), estuarine–lagoon, fluvial (LPF), and slope (part of LCR). In the upper Pleistocene, approximately 120,000–125,000 years BP, another transgressive–regressive event associated with MIS 5e (Cananéia Transgression) eroded a part of the Morro do Icapara Formation deposits and constructed new depositional systems related to the Cananéia Formation, such as transgressive and regressive barrier islands (LPTb), estuarine–lagoon, fluvial (LPF), and slope (LCR).

It is possible that during the entire Late Pleistocene, other reactivations of the Bertioga Graben have promoted subsidence and uplift in the central part of the coastal plain, as well as strong carving and erosion in the sedimentary environments. A significant phase of pedogenesis and podzolization occurred between 45 and 24 ka BP, during the transgressive event MIS 3, when the SL was a few meters below the current level. Still in the Late Pleistocene, probably before 29,000 ± 5,000 years BP, a major tectonic pulse reactivated the Bertioga Graben and triggered the fluvial capture of the

Guaratuba River. Accordingly, Riccomini et al. (2004) noted the occurrence of tectonic reactivations of CRSB in the Late Pleistocene–Early Holocene, and Alves (2012) suggested possible seismic activity in the São Sebastião region in the Late Pleistocene.

In the central portion of the coastal plain, this tectonic reactivation caused the following phenomena: subsidence, deep carving, and intense erosion on the Morro of Icapara Formation and at least on the inland boundary of the Cananéia Formation, as well as faults and throws in both deposits; development of large depressions and deep valleys upon which the Holocene lagoons and estuaries were established; acceleration of the marine ingression on the current shoreline and within the coastal plain since the Pleistocene/Holocene transition, when the SL was ca 18–20 m below the current level; and the establishment of systematic sets of fractures in Pleistocene marine terraces hardened by orstein horizons.

11.5.2 Holocene

At the Pleistocene/Holocene transition, with the SL still well below the current level, an extensive lagoon–estuarine system incorporating at least the three watershed basins of the Bertioga covered a vast area from the current inner continental shelf to the outer limit of the LPTb unit at least. In the central depression of the coastal plain, the newly carved deep channels began receiving brackish water, so restricted lagoons were established well before ^{14}C 10,740–10,510 cal years BP (or 9,410 ± 50 years BP).

The SL rose rapidly and crossed “zero” (current coastline) ca 7,500 cal (or 7,000–6,500) years BP. The maximum of the Santos Transgression occurred approximately 6,500–6,320 cal (or 5,660 ± 40) years BP, when the SL was at around 3.5–4 m above the current level and much of the coastal plain was submerged (Fig. 11.8). At this time, two tectonically controlled large lagoons (Itaguaré-Guaratuba

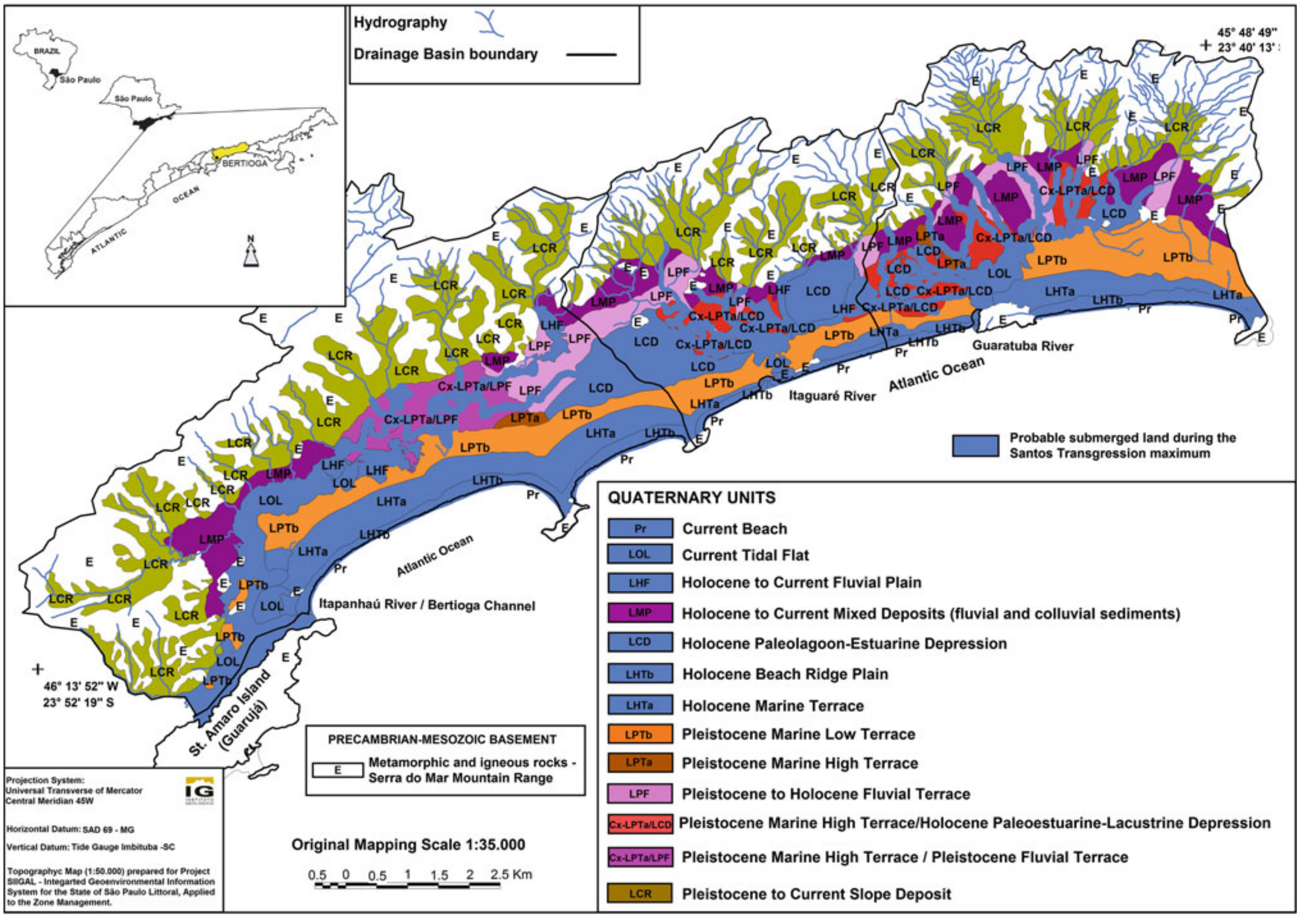

Fig. 11.8 The Bertioga coastal plain during the Santos Transgression maximum

and Itapanhaú) were barred by the sharp sea cliffs formed on Pleistocene marine low terraces (LPTb) supported by orstein horizons and segmented in areas where the river mouths are today.

At the back of the Guaratuba coastal plain, a lake dammed the huge volume of fresh water that flowed into the coastal plain as a consequence of the fluvial capture in the Late Pleistocene, and due to the rapid marine transgression (Santos Transgression) underway at that time. The completion of this lacustrine sedimentation occurred shortly after 7,420 cal (or 6,550 ± 40) years BP.

After the maximum of the Santos Transgression, the SL fell down to a few meters below the current level. The coast quickly prograded from the line of LPTb cliffs, resulting in the development of a regressive beach ridges plain (LHTa), on a regime of low wave energy and large sediment supply at least since 5,100 years BP. Simultaneously, the first realignment of the drainage network in the Holocene occurred, which began shortly before 5,580 years BP.

Subsequently, a new fast transgressive pulse in which the SL peaked at 2.5–3.0 m above the current level caused erosion and the drowning of part of the LHTa deposits. This pulse may have been driven by a new tectonic event that also caused erosion and faulting in LPF fluvial terraces (throws in lacustrine deposits) and gave rise to a subsided paleosurface upon which firstly alluvial sediments and latterly alluvial–colluvial sediments (LMP) were deposited. Other consequences were differential subsidence in the central portion of the coastal plain, causing the formation of small lakes (paleocourses of dammed rivers) in the areas of CxLPTa/LCD and CxLPTa/LPF; and the establishment of fracture systems in LPTa and LPTb spodosols. This Holocene tectonic reactivation must have occurred shortly after 4,040 and before 3,520 years BP, what corroborates the suggested range for the tectonic event that likely affected the Ubatuba beachrock between 4,370 and 3,860 years BP.

In the subsequent phase of falling SL (since 3,020 ± 500 years BP), the negative oscillation of the base level and groundwater level led to a new phase of pedogenesis ca 2,740–2,580 cal (2,860 ± 30) years BP, and consequently the rejuvenation and dismantling of the old spodosols in Pleistocene marine terraces (LPTa and LPTb), as well the formation of Arenosols on the newly sedimented beach ridges (LHTa). Obviously, these processes were possible because at that time forests, likely similar to the contemporary ones, have already covered the Pleistocene marine terraces and spread out toward the LHTa deposits very fast, suggesting climate quite similar to the current one.

Meanwhile, a new generation of regressive beach ridges (LHTb) carried to the last shoreline progradation in the Holocene, governed by a large sediment yield, narrow accommodation space for sediments, and wave regimes of initially low energy and then high energy. A likely short climate oscillation, with a greater influence of extratropical cyclones (probably), lasted for 700 years until shortly before the current SL "stabilization." At the back of the coastal plain, this climate oscillation phase would have been marked by the occurrence of extreme flashflood events responsible for the deposition of the younger deposits of LMP.

With the end of the marine regression, the end of the adjustment of the drainage network, and the return to climatic conditions similar to the current ones, the lakes in the central depression of the coastal plain began to become clogged and turned into confined palustrine environments, where organic Histosols started to develop. The current beaches were established when the SL has "stabilized" at a level similar to the current one, at least before the stage of historic SL rise (Souza 2012).

In a short time, the forests spread over the coastal plain, covering the newly sedimented deposits and specializing according to the characteristics of the depositional environment, then evolving into the different current phytophysiognomies and their mosaics (Souza et al. 2009).

11.6 Final Considerations

The Quaternary evolution of the Bertioga coastal plain is only partly comparable with the most existing work in Brazil (Suguio and Martin 1978; Suguio et al. 1985, 2005; Villwock et al. 1986, 2005; Martin et al. 1987, 1988, 2003; Silva 1991; Angulo and Lessa 1997; Bezzera et al. 2001; Tomazelli and Villwock 2000; Barreto et al. 2002; Bezerra et al. 2003; Angulo et al. 2006; Dillenburg and Hesp 2009; Souza-Filho et al. 2009).

Generally, macroscale events such as the marine transgressions and regressions in the Late Pleistocene and the Holocene were well identified in Bertioga. The most striking differences between the model presented here and those existing for the Brazilian coast elsewhere are the identification and prioritization of tectonic events, contemporary or not with SL fluctuations during the Pleistocene and Holocene periods, and their consequences in the landscape arrangement and the current modeling of the coastal plain. Moreover, the establishment of relationships between marine, coastal, and continental processes that are jointly responsible for the different stages of landscape evolution is a significant advance.

The evolution of the Holocene marine deposits proposed here agrees with the interpretations of Suguio and Martin (1978, 1994) for the São Paulo coast, which considered two phases of submergence and emergence of the coast during periods similar to those observed here. However, in the case of Bertioga, it was clear that the second transgressive pulse was quite influenced by tectonic activity. Therefore, the criticism offered by Angulo and Lessa (1997) and Angulo et al. (2006) against those interpretations and the SL curves for the state of São Paulo seems to lose their basis, at least for the Bertioga coastal plain.

Finally, there is an evident need to better understand the role of Quaternary tectonics in the evolution of Brazilian coastal plains, especially those located in orogenic regions such as the southeast coast, as well as the importance into establish curves of SL changes specific for each area.

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Brazilian Pantanal: A Large Pristine Tropical Wetland

12

Mario Luis Assine

Abstract

The Pantanal is a Quaternary sedimentary basin located in the central-west region of Brazil. Its origin has been linked to stresses transmitted from the western margin of the South American continent into the interior of the craton. Therefore, the Pantanal is part of the Andean foreland system. It presents alluvial plain morphology with altitudes between 80 and 200 m surrounded by desiccated plateaus. Northeast-southwest-aligned faults, many associated with the Transbrasiliano Lineament, control part of the drainage network within the Pantanal Basin. The Paraguay River meanders through an extensive fluvial plain, bordering Precambrian terrains at the western edge of the basin. The Paraguay River is the main river of a depositional system characterized by fluvial megafans, among which the Taquari River megafan stands out. Since the Late Pleistocene, the Pantanal landscape has been changing in response to a climate shift from colder and drier to wetter and warmer conditions. These climate changes are recorded in the Pantanal landscape, which is marked by relict depositional landforms of varying ages formed in environmental and climatic conditions differing from the present. The thousands of Nhecolândia lakes located in the southern sector of the Taquari megafan are examples of relict landforms. These lakes are mostly freshwater lakes connected through rainwater runoff, forming wide and shallow channels (locally called "vazantes") that drain the fluvial plain during and after the wet season. In contrast, some saline lakes (locally called "salinas") remain isolated from the surface drainage and are relict landforms of a degrading landscape. The Pantanal is a large tropical wetland exhibiting mostly native vegetation, where wildlife is preserved in its natural habitats. The rivers building the fluvial megafans are prone to frequent avulsions, shifting their channels according to sediment infilling dynamics in the fluvial plain. These shifts in river courses result in considerable changes in the hydrography and geography of the flood plain.

Keywords

Brazilian Pantanal • Wetlands • Fluvial landscape • Changing rivers

12.1 Introduction

The Pantanal is located between latitudes 16 and 21° S; 90 % of its area is situated within the central-west region of Brazil, with the remaining area extending into Paraguay and Bolivia. The Pantanal is an inland depression within the hydrographic basin of the Upper Paraguay River, with altitudes between 80 and 190 m above sea level, and it is surrounded by plateaus carved in Paleozoic sedimentary rocks and Precambrian crystalline rocks. The Pantanal is an alluvial plain dominated by rivers showing a seasonal hydrological cycle, with extensive floods occurring between December and May. Extending over 135,000 km^2, the Pantanal is one of the most important wetlands in the world (Por 1995; Fraser and Keddy 2005; Junk et al. 2006). It is

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almost unspoiled and is internationally recognized for its rich biodiversity and extraordinary natural beauty (Fig. 12.1).

According to monthly temperatures and precipitation, the local climate is classified as Aw (savanna climate) according to the Köppen climate classification (Alho 2005). Mean temperatures range between 20 °C in July and 27 °C in December. Precipitation decreases from east to west and from north to south, displaying mean values between 1,200 and 1,300 mm in the eastern and northern plateaus and 800 mm at the border with Bolivia. In the plain, precipitation ranges from 800 to 1,200 mm, and the potential evaporation varies from 1,300 to 1,600 mm, resulting in a negative water balance. Therefore, the wetland exists due to water inflow from the adjacent plateaus that is then retained in the fluvial plain, a process that is facilitated by slow surface runoff (due to the low gradient) and infiltration and retention in the sandy sediments that form most of the alluvial plain.

Due to its geographical location, the Pantanal exhibits elements of the three different biomes that dominate its surroundings: semi-deciduous Amazon forest (northwest), tropical savanna (east), and "Chaco" steppe-like savanna (southwest). However, endemic flora species in the Pantanal are few in comparison with the variety found in those biomes (Prance and Schaller 1982). The fauna in the Pantanal is very rich, however, composed of species from the surrounding biomes, with especially large numbers of fish (263), amphibian (35), reptile (85), bird (444), and mammal (195) species (Alho 2008).

The Pantanal is a large pristine tropical wetland because human settlement is of low density, and economic activities are limited to extensive livestock farming. Deforestation is low; that is, in 2008, only 12 % of the Pantanal plain area was cleared (Silva et al. 2011). However, concerns about the future of the area are growing as a consequence of the major ventures that are being implemented due to the construction of the Paraguay–Paraná waterway, designed to facilitate export of the region's economic production (Bucher and Huszar 1995; Hamilton 2002). Additionally, private properties cover more than 95 % of the Pantanal plain area (Seidl et al. 2001), and only a few nature conservation areas exist. The Pantanal National Park in Mato Grosso consists of four protected areas, totaling only 1,356 km^2 or approximately 1 % of Pantanal total area.

12.2 Geological and Geomorphological Evolution

The Pantanal is located within a sedimentary basin structurally controlled by faults, with a north–south elongated depocenter and maximum sedimentary thickness of over

Fig. 12.1 The Pantanal is a vast low-gradient alluvial plain and is seasonally flooded. It is a rich natural and unspoiled ecosystem, showing high flora and fauna biodiversity. The flooded areas are dominated by aquatic macrophytes, including a species of giant water lily (*Victoria amazonica*). (*Photographs* by ECOA—Ecologia and Ação)

500 m (Fig. 12.2a). Since the work of Almeida (1959), the origin of the Pantanal Basin has been associated with the stresses being transmitted from the western margin of the South American continent into the interior of the craton; therefore, the Pantanal is part of the Andean foreland system (Horton and DeCelles 1997; Ussami et al. 1999). However, the origin and evolution of the basin cannot be explained solely by the Andean dynamics. The origin and evolution of the basin are linked to a regional epeirogenic uplift during the Cenozoic, after the generation of the extensive Sul-americana planation surface (King 1956) at the end of the Cretaceous (Almeida and Carneiro 1998).

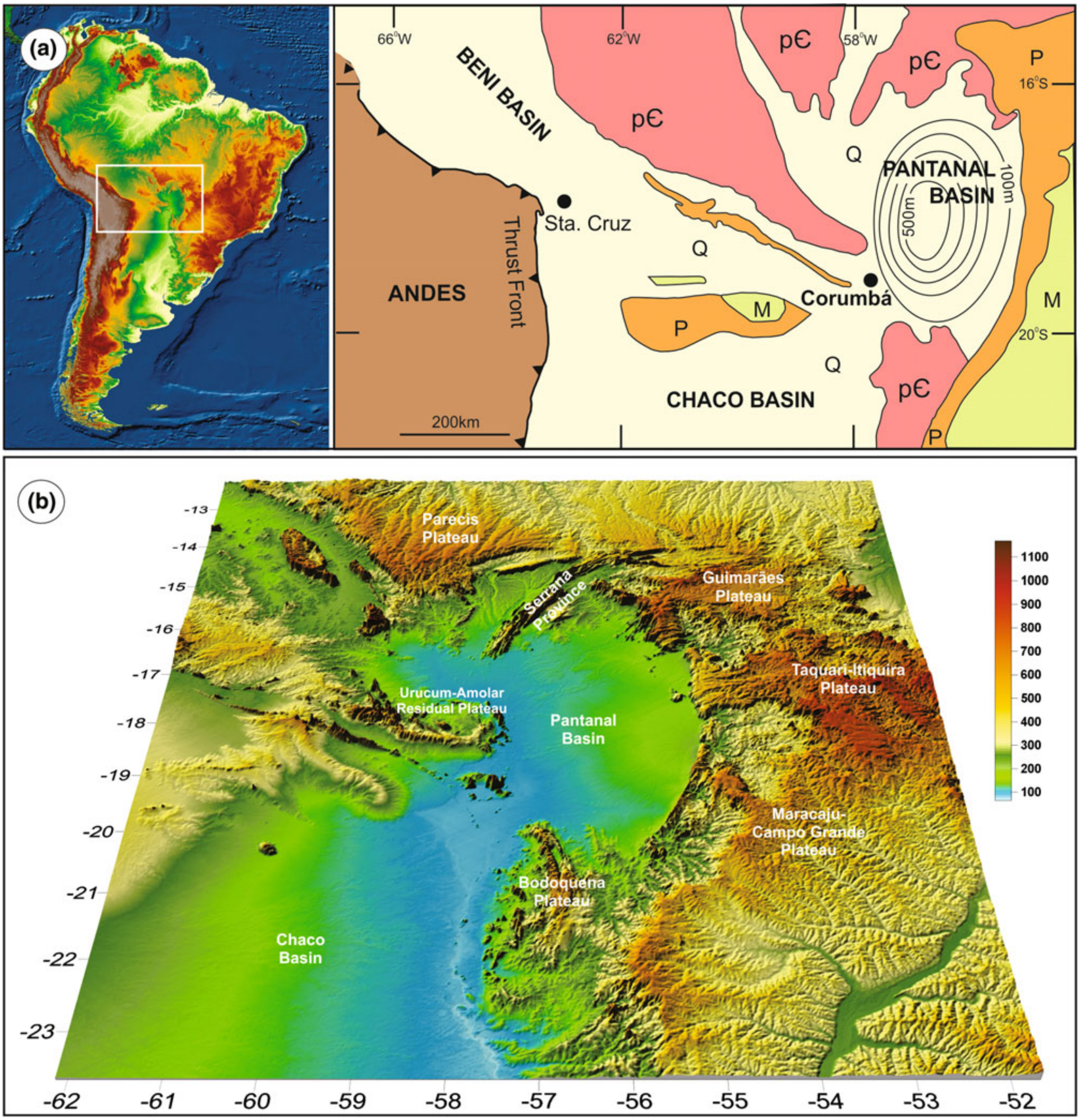

Fig. 12.2 Pantanal Basin. **a** Geotectonic position of the basin in relation to the Andean orogen and the foreland basins of Beni and Chaco; sediment thickness curves in meters (geological units: *Pє* Precambrian; *P* Paleozoic; *M* Mesozoic; *Q* Quaternary). **b** Diagram showing the Upper Paraguay depression, where the Pantanal Basin is situated; the surrounding plateaus sloping toward different directions, defining an exhumed central plateau; and the narrow passage between the Bodoquena plateau and the residual Urucum-Amolar plateau, which makes the connection with the Chaco plain (digital elevation model built from SRTM and NASA data)

The epeirogenic uplift is associated with important episodes of tectonic reactivation occurring in central-southern Brazil in the Cenozoic, which are responsible for the uplift of the Serra do Mar and the formation of the rift system in southeastern Brazil (Melo et al. 1985). In the central-west region of Brazil, the epeirogenic uplift resulted in the formation of a basement uplift (*boutonnière* in Ab'Sáber 1988), separating the Paraná and Chaco basins. The *boutonnière* acted as a sediment source and water divide of the continental paleodrainage (Almeida 1965).

During the basement uplift, major faults caused the subsidence of its central part, creating the Pantanal Basin. The origin of the basin dates from the Paleogene, but it is still uncertain when sedimentation started, as the bottom sediments are yet to be dated. The dome configuration is still evident in the morphology of the radial drainage on the plateaus surrounding the Pantanal Basin. In these areas, the detritic–lateritic deposits found at the surface are remnants of the South American plain. Iron and manganese concentrations are found at the Urucum massif, in the western margin of the basin, in the supergene deposits associated with the surface (Fig. 12.2b). The Pantanal resulted from this geological and geomorphological evolution, which caused the subsidence of the basin and formation of large erosion amphitheaters in the surrounding plateaus, thus favouring sedimentation in the plain mainly due to alluvial processes. All these processes contributed to the emergence and maintenance of the extensive flood plains (Fig. 12.3).

The Pantanal Basin is an inland plain with altitudes between 80 and 200 m and is surrounded by desiccated plateaus. In the western margin of the basin, the Paraguay River fluvial plain borders exposed Precambrian rocks (Fig. 12.3). These Precambrian rocks occur as elevated outcrops controlled by NE-SW- and WNW-ESE-aligned faults. Many of the NE-SW faults are associated with the Transbrasiliano Lineament and control many alluvial channels within the Pantanal plain (Assine 2003). The Transbrasiliano Lineament was first recognized as an important geotectonic element in this area by Soares et al. (1998). The structurally controlled channels within the alluvial system provide clear evidence of neotectonic activation in the basin, which is seismically active with recent records of earthquakes.

12.3 Wetlands and Alluvial Landforms

The Pantanal plain is formed by different sectors, whose delimitation is based on their varying characteristics regarding the nature and timing of flooding (Hamilton et al. 1996). The different flooding patterns are strongly controlled by the geomorphology of the plain, notably large alluvial fans, interfan systems, and the Paraguay plain (Assine and Soares 2004).

The Paraguay is the main river of the depositional system, characterized by the presence of the alluvial megafans built by the Taquari (Braun 1977; Souza et al. 2002; Assine and Soares 2004; Assine 2005; Zani 2008), Aquidauana (Facincani and Assine 2010), and São Lourenço Rivers (Corradini 2011; Corradini and Assine 2012). All these rivers are characterized by distributary drainage network, but they show distinctive flooding and sedimentation patterns. The Taquari River is the most remarkable, comprising approximately 50,000 km^2 or ca. 37 % of the area of the Pantanal plain, placing it among the largest alluvial fans in the world (Fig. 12.4). The Paraguay River shows a distributary pattern in some sectors, such as in the northwestern Pantanal around Cáceres, where the Paraguay alluvial megafan has been built by the river (Assine and Silva 2009; Silva 2010). The peak flooding in this area occurs between February and March, soon after precipitation peak that occurs from January to February. At the fringe of the fan, which is defined by the course of the Corixo Grande River, there are several lakes, among which the Uberaba is most prominent.

Between the Uberaba Lake and the city of Corumbá, the Paraguay River meanders along a long and wide fluvial plain and is characterized by the presence of an active meander belt (Fig. 12.5), various secondary channels, and small lakes. During the flooding season, the waters overflow the channel and spread into the plain, creating an extensive inundated area, and even reaching the lakes on the left margin of the river (McGlue et al. 2011). South of the city of Corumbá, the Paraguay River receives waters from the tributaries draining the southern part of the wetland and flows into the Nabileque area (Fig. 12.4). Located in the southernmost end of the Pantanal, the Nabileque area subsides less and acts as the base level of the wetland. In this area, the Paraguay River forms a meander belt embedded in the plain, where paleochannels forming an intricate paleonetwork of distributary drainage are preserved (Kuerten 2010; Kuerten and Assine 2011). The flooding peak in this area occurs between May and June, three to four months later than in the northernmost areas of the Pantanal. This delay is due to the slow propagation of the flooding wave through the plain of the Paraguay River.

12.4 Changing Rivers

Rivers building alluvial megafans change their courses constantly, in response to the sediment infilling dynamics of the plain. The process of fluvial avulsion leads to frequent changes in the Pantanal's hydrography, considerably altering the geography of the wetland.

Fig. 12.3 The Paraguay River flows from north to south in the western edge of the basin bordering the Precambrian terrains of the Amolar mountain range. The fluvial plain is annually flooded during summer and is characterized by many secondary channels and small lakes. (*Photographs* by ECOA—Ecologia and Ação)

Changes in river courses are frequent in the active distributary fan lobe of the lower Taquari River, reflecting the ever-changing nature of the river (Assine 2005; Assine et al. 2005). Here, where the channel and its sandy levees are topographically higher than the adjacent flood plain, levee crevassing (locally known as “arrombados”) and the formation of distributary channels occur frequently, favouring avulsion processes. One well-documented avulsion event in the 1990s altered the course of the lower Taquari River, which shifted westward at the “Arrombado Zé da Costa” and began discharging into the Paraguay River, approximately 30 km upstream of the old river mouth.

Large-scale avulsion is ongoing near the Caronal farm in the vicinity of the Taquari distributary lobe apex, as described in previous studies (Assine 2005; Assine et al. 2005; Zani 2008; Buehler et al. 2011; Makaske et al. 2012; Zani et al. 2012). The channel in this area has been subjected to rapid aggradation, resulting in the reduction of channel depth, emergence of sand bars, and triggering of avulsion processes with levee crevassing and formation of distributary channels (Fig. 12.6).

The waters flowing out of the main channel through the levee breaches in the channel-margin embankments formed anastomosed channels on the right margin of the Taquari

Fig. 12.4 Main rivers forming the Pantanal depositional system. The wetland area is identified by the *yellow line*. The Taquari megafan is the most prominent geomorphological feature. Its surface is characterized by the presence of well-defined paleochannels, which represent past river channels. A large part of the Pantanal plain is covered by seasonally flooded open fields (*pink*). The areas of the Paraguay River plain remain flooded for longer periods (NASA GeoCover TM Landsat 5 mosaic images, 1987/1993, composition 7R4G2B)

River. These anastomosed channels carry water to lower lying areas, as the main channel is topographically higher than the flood basin. This area in the right margin of the Taquari River is the natural path for the establishment of a new river course.

12.5 Paleoclimatic Fluctuations and Relict Landforms

Optically stimulated luminescence dating has indicated Upper Pleistocene ages for the megafan deposits (Assine 2003; Kuerten 2010; Silva 2010; Corradini 2011). The landscape in the Pantanal area has changed considerably since the Late Pleistocene, when fluvial megafans formed in semiarid environments under colder climate conditions (Clapperton 1993). The formation of the wetlands occurred in response to wetter and warmer conditions prevailing during the Holocene (Assine and Soares 2004), but the exact timing of these environmental changes is yet to be defined.

Based on the analyses of sediment cores obtained from the bottom of the Gaiva Lake, located in the right margin of the Paraguay River, Whitney et al. (2011) concluded that the climate was distinctly dry in the Pantanal area between 45.0 and 12.2 ka BP (the last glacial period). The sharp shift to wetter conditions was determined to have occurred between

Fig. 12.5 Point bars in meandering rivers. **a** Paraguay River near the city of Corumbá, in the flooding season. **b** Negro River exhibiting lateral bars

12.8 and 12.2 ka BP. The expansion of wetlands in the Pantanal started from the Paraguay River plain, where water flowing from the surrounding plateaus accumulates due to the lower topographic elevation. However, the sedimentological, palynological, and geochronological data obtained by Bezerra (1999) indicate a spatially uneven response within the plain, suggesting the individualization of the Negra and Castelo lakes around 10.2 and 5.19 ka BP, respectively. According to McGlue et al. (2012), the period between 11.0 and 5.3 ka BP was marked by climate fluctuations that caused changes in the levels of the marginal lakes and discontinuous sedimentation, characterized by erosive events caused by intermittent flows. A regional drought event between 5.3 and 2.6 ka BP, identified from the hiatus observed in the sedimentary record of the Gaíva Lake (McGlue et al. 2012), resulted in changes in the base level of the Paraguay River and the formation of sets of meanders of various ages (Assine and Soares 2004). In the Late Holocene, starting from 3.0 ka BP (Whitney et al. 2011) or 2.6 ka BP (McGlue et al. 2012), the climate became wetter, similar to the present climate, giving rise to the modern Pantanal wetland.

Fig. 12.6 Crevassing of river levees and formation of distributary channels in the *right* margin of the Taquari River; the avulsion processes are changing the river course (oblique aerial photographs taken in February 2000)

These climate changes are recorded in the Pantanal landscape, which shows relict depositional landforms of varying ages, reflecting environmental and climate conditions different from the ones currently observed. An example of such landforms would be thousands of small freshwater and salt lakes in the Nhecolândia area (southern sector of the Taquari megafan), forming a *sui generis* and beautiful landscape that is different from the rest of the Pantanal (Fig. 12.7). The Nhecolândia lakes are dominantly elliptic, generally northeast-aligned, although circular, pyriform, crescent, and irregular forms are also observed (Soares et al. 2003; Evans and Costa 2013). The origin of these lakes has been linked to eolian processes since the pioneering works of Almeida (1959). According to Tricart (1982), the lakes are relict landforms created through deflation processes. Interpreting old dune fields, Klammer

Fig. 12.7 Nhecolândia lakes, southern section of the Taquari megafan. **a** Typical landscape of northeast-aligned lakes. The lakes are surrounded by sand ridges with tree vegetation, display aquatic macrophytes, and are interconnected during flood periods by surface water flows. **b** Salt pans have alkaline waters and no floating vegetation, and they are not connected to surface drainage

(1982) identified the lakes as salt pans, although the author suggested they were formed in interdune areas. Approximately 10 % of the lakes are saline and have alkaline waters (Barbiéro et al. 2002, 2008; Furquim et al. 2010), leading Goudie (1991) and Goudie and Wells (1995) to include the Nhecolândia lakes as examples of salt pans. However, some researchers believe the evidence is insufficient to infer the contribution of eolian processes in the formation of these lakes (Colinvaux et al. 2000; Barbiéro et al. 2008).

The landscape of the Nhecolândia lakes has been continually changing under the influence of surface water flows. Many freshwater lakes are interconnected through rainwater runoff, forming wide and shallow channels (locally called "vazantes"), which drain the fluvial plain during and after the wet season (Fig. 12.8). Therefore, the lakes progressively lose their morphological identity inherited from past environmental conditions. In contrast, some saline lakes (locally called "salinas") remain isolated from the surface drainage and are relict landforms of a degrading landscape.

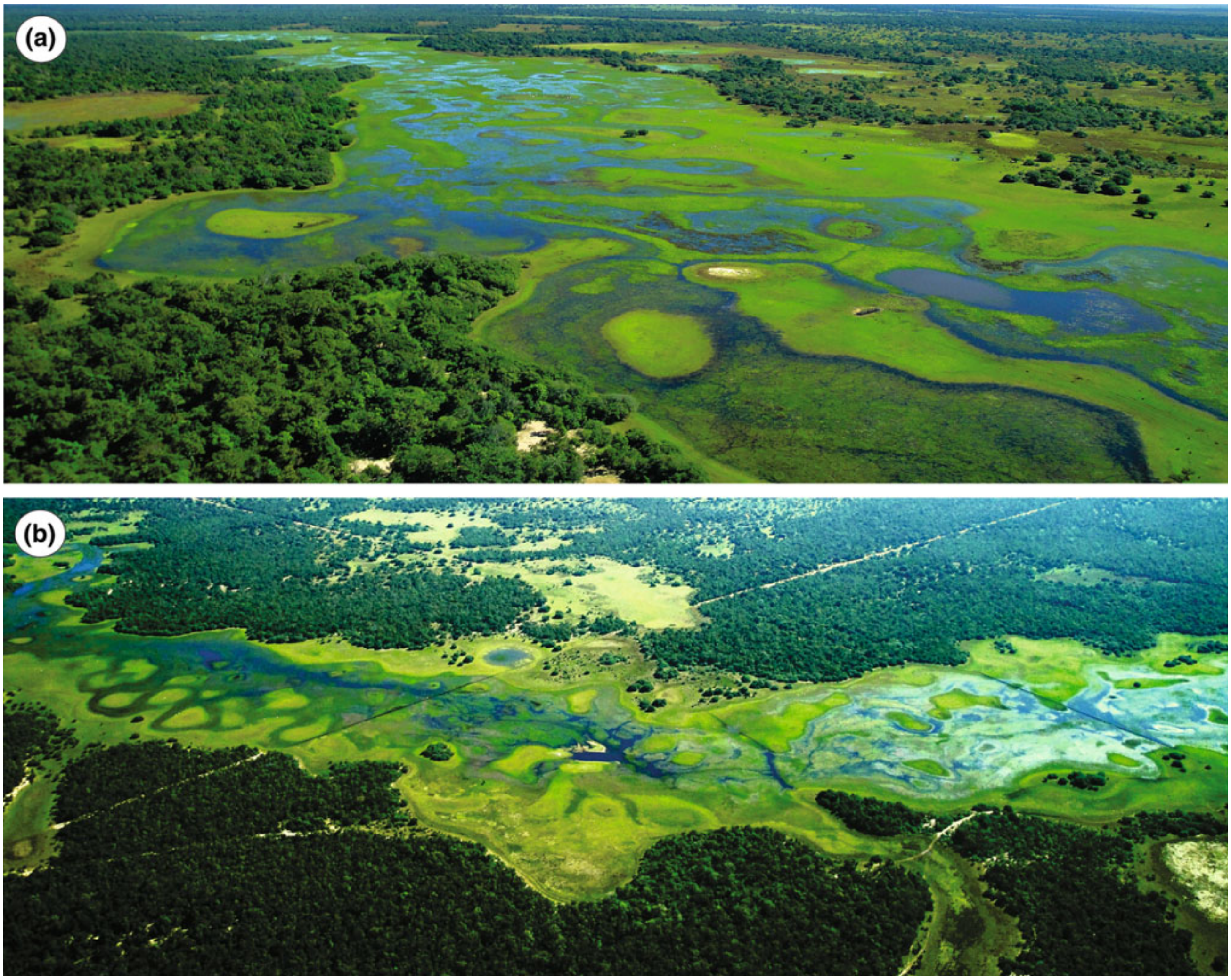

Fig. 12.8 Shallow and wide channels (locally called “vazantes”) connect the lakes and progressively alter the original landscape, forming the surface drainage system of Nhecolândia. (*Photographs* by ECOA—Ecologia and Ação)

12.6 Conclusion

The Pantanal is a Quaternary sedimentary basin situated inland in South America. The basin exhibits depositional landforms registering the paleoclimatic changes that have occurred in the area since the Late Pleistocene. The geomorphological evolution of the area has resulted in a large alluvial plain, where the landscape is continuously changing in response to fluvial avulsion processes (i.e., shifts in river channels). The Pantanal is a large tropical wetland where native vegetation still dominates in most of the area, and wildlife is preserved in its natural habitats.

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Potiguar Basin: Diversity of Landscapes in the Brazilian Equatorial Margin

13

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Abstract

The Potiguar Basin is located in the equatorial margin of northeastern Brazil and presents several landform types related to a passive margin. These include features related to alluvial, eolian, coastal, and karst processes. In this context, compression that has affected the basin since the Paleogene has caused uplift, which is mainly observed in the central part of the basin and where a tectonic dome forms the highest elevated landform. Tectonic uplift has controlled the origin of several landforms, such as the karst landforms, fault-controlled valleys, the shoreline geometry, elevated sea cliffs, and alluvial-marine plains. The whole basin area now evolves under the influence of climate, eustasy, and neotectonics.

Keywords

Potiguar Basin • Neotectonics • Coastal cliffs • Karst • Alluvial plain

13.1 Introduction

The Potiguar Basin in northeastern Brazil exhibits a vast collection of landforms, which are the result of the joint action of tectonic, climatic, and eustatic processes. These landforms include sea cliffs, dune fields, alluvial valleys colonized by riparian forest and mangrove vegetation, and carbonate karst ledges and caves (Fig. 13.1), which reveal the morphogenetic phases and formative events along the equatorial margin of Brazil during the Cenozoic.

The topography of northeastern Brazil, and mainly the area along the Atlantic seaboard, exhibits a series of morphostructural compartments. These compartments encompass several landforms, genetically linked with the reactivation of ductile and brittle structures that control the present-day morphology. These structures consist of NE-trending Precambrian basement shear zones, which were generated during the Brasiliano orogeny at 740–570 Ma (Brito Neves et al. 2000), and NE- and NW-trending Cretaceous faults, which originated during the Pangea breakup in the Jurassic-Cretaceous at 150–120 Ma (Matos 2000; De Castro et al. 2012). Subsequent reactivation of these Precambrian and Cenozoic structures occurred in the Cenozoic (Bezerra and Vita-Finzi 2000). In the crystalline basement, these structures include structural massifs and incised valleys, which form high- and low-topographic areas, respectively, oriented along the structural trends (Fig. 13.2). In the sedimentary basins, these structures include cliffs, valleys, and canyons that exhibit outstanding scenic beauty.

Despite these tectonic features, the evolution of the study area is still explained on the basis of the classical studies of erosion surfaces in South America (e.g., King 1962; Bigarella and Andrade 1965). However, recent studies have reinterpreted northeastern Brazil in the context of plate tectonics and intraplate deformation. These studies have added new concepts to the evolution of the present-day landforms, as well as included results of numerical dating and modeling (Bezerra et al. 2001, 2008; Nóbrega et al. 2005; Gurgel et al. 2013).

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Fig. 13.1 General features of landforms in the Potiguar Basin, northeastern Brazil: **a** sea cliff, **b** coastal dune field, **c** speleothems in a cave, located a few meters below the plateau surface in the Jandaíra Formation

This chapter describes the most important landforms in the Potiguar Basin and discusses their origin and relationship to endogenous factors such as tectonics or exogenous factors such as eustasy, as well as alluvial and aeolian action. These landforms include dune fields, alluvial valleys, mangrove coasts, cliffs, and erosional scarps. This complex landform system also comprises a structural dome in the center of the Basin, which has been dissected by adjacent fluvial valleys.

13.2 Tectonic, Stratigraphic, Eustatic, and Climate Setting

The Potiguar sedimentary basin started to be formed during the breakup between South America and Africa (Matos 2000) and evolved until the Cenozoic (Bezerra and Vita-Finzi 2000). The tectonic framework of this basin consists of

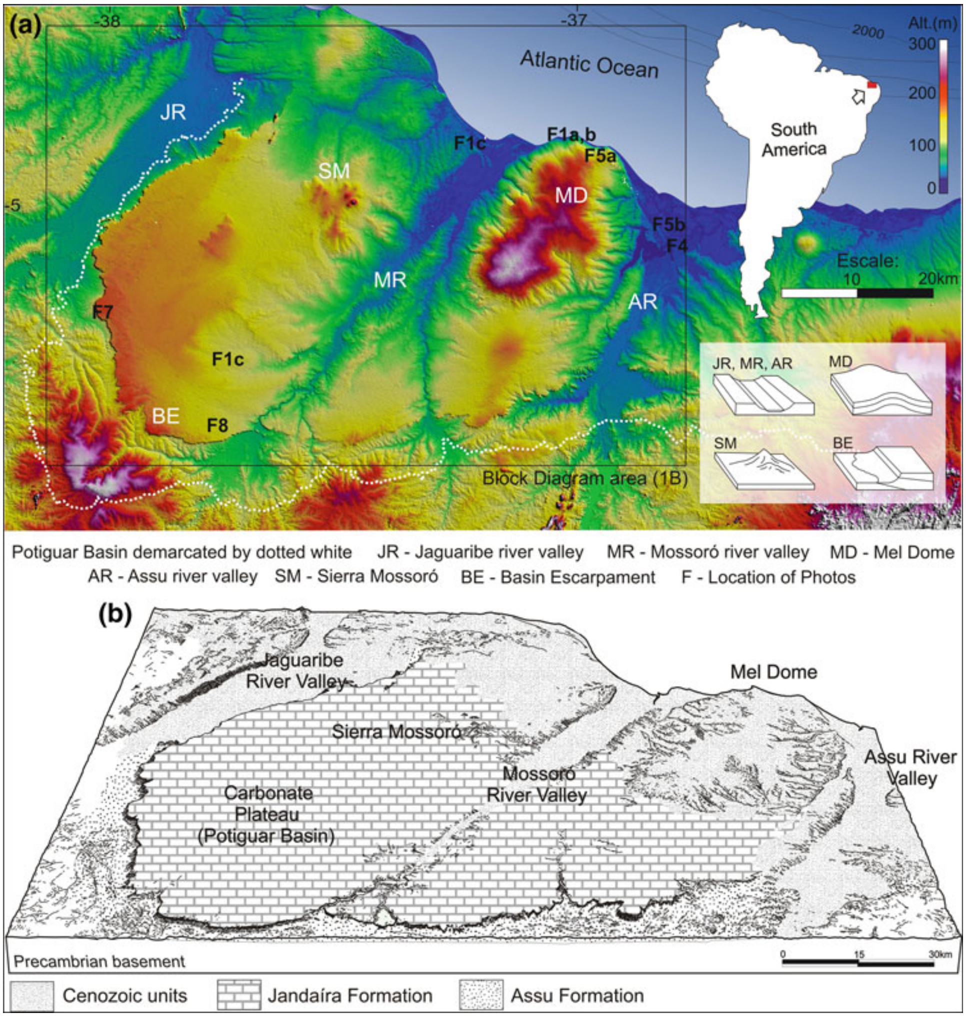

Fig. 13.2 **a** Shuttle radar topography and location of main study area and **b** block diagram of the central part of the Potiguar Basin

a central rift, which is mainly composed of NE-trending normal faults and NW-trending transfer faults (Matos 1992). Rift formation commenced in the Neocomian (~140 Ma) (Nóbrega et al. 2005) along reactivated basement shear zones (De Castro et al. 2012). The rift phase was followed by thermal subsidence and post-rift marine transgression and regression in the Cretaceous (Matos 1992). The sedimentary infill of the rift is mainly composed of a siliciclastic sequence, and the post-rift units comprise Cretaceous sandstones and limestones (Souto Filho et al. 2000). These Cretaceous units are capped by Miocene sandstones and conglomerates (Lima 2008), and Quaternary alluvial and marine sediments (Moura-Lima et al. 2011) (Fig. 13.3).

Eustatic influence on the Potiguar Basin is mainly recognized in the late Quaternary. The littoral zone of the basin is characterized by interglacial marine deposits dated for 220 and 120 ka (Barreto et al. 2002). Holocene marine deposits occur along the coast in estuaries and are mainly composed of tidal flat and channel sediments, mangrove swamp deposits, and beachrocks related to sea level changes from 7,000 to 1,000 cal yr BP (Bezerra et al. 2003).

The present-day climate is semiarid and annual rainfall ranges from 600 to 800 mm, with rains concentrated within the first months of the year (Peterson and Haug 2006). Drought episodes are common in this area. These conditions have not favored hillslope failures or gravity flows, and erosion has been most characterized by gullying and unchanneled overland flows (Corrêa 2001). Several studies pointed to a similarity between the present-day climate of the area and that of the late glacial and the penultimate interglacial times (Bezerra et al. 2008; Gurgel et al. 2013).

13.3 Main Geomorphological Features of the Potiguar Basin

The numerous landforms of the Potiguar Basin are related to the post-rift phase, i.e., the passive margin stage of the continental margin. The compressive stress field that affected the basin after the Cretaceous induced topographic inversion and uplift, mainly observed in the central part of the basin.

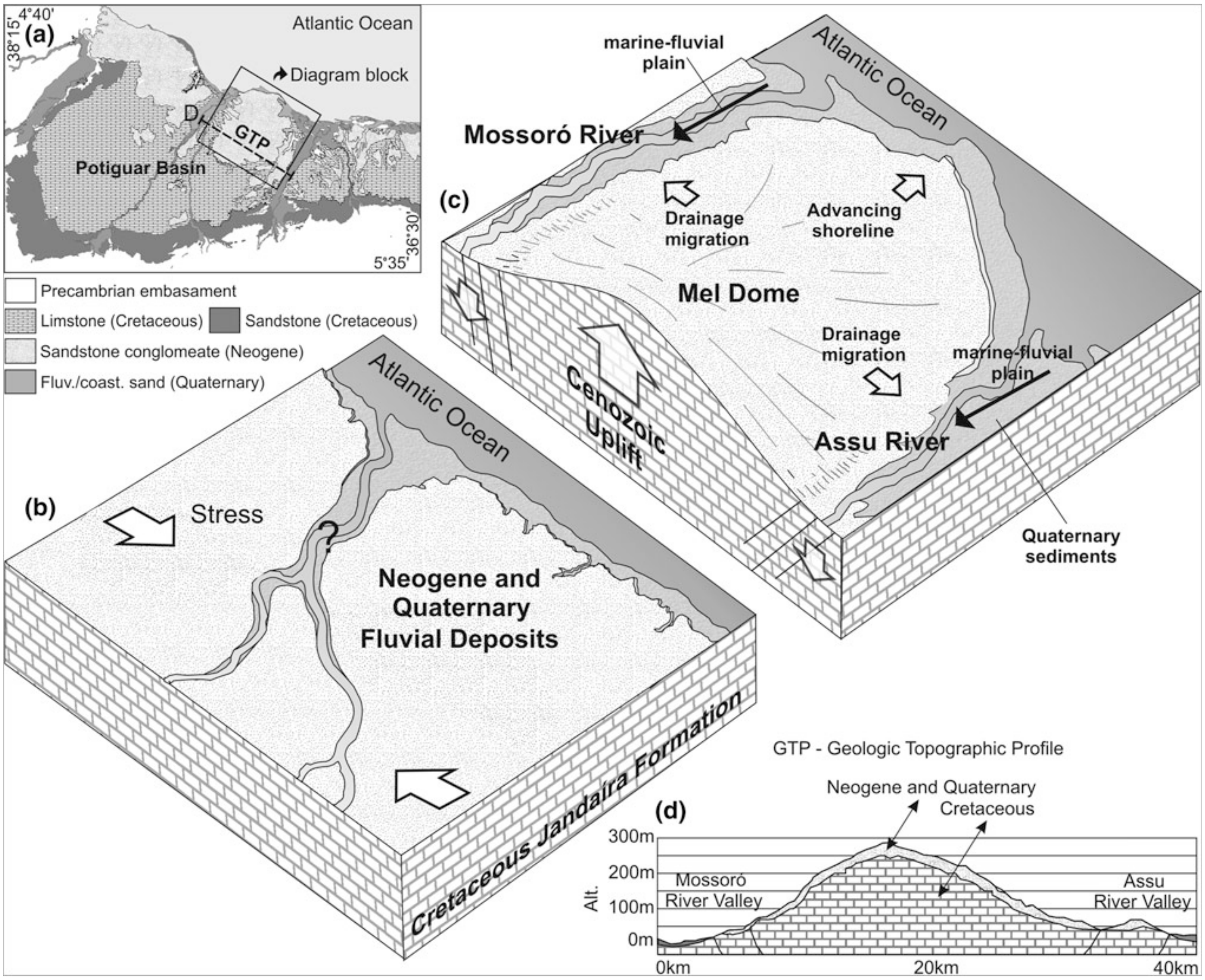

Fig. 13.3 Evolution of alluvial channels during the uplift of the Mel dome in the central part of the Potiguar Basin: **a** map of the central and western part of the Potiguar Basin; **b** block diagram of the central part of the basin before uplift; **c** present-day morphology of the Mel dome; and **d** NW-trending cross section of the central part of the dome

This uplift has influenced landform evolution in different ways, such as lateral migration of alluvial valleys and generation of fault and joint systems.

13.3.1 Structural Dome

The central part of the Potiguar Basin is characterized by the presence of the structural Mel dome, which has influenced the topography and sediment deposition from the Neogene to the Quaternary. The Mel dome reaches 270 m in height at 12 km from sea cliffs. This steep transition contrasts with the usual altitudes inland, which reach 30–60 m. The main evidences for the association of the Mel dome with basin inversion are its large elliptical shape and altitude, centrifuge drainage pattern, reverse faults that affect post-rift units observed in seismic sections and resistivity surveys, and the evidence of uplift of marine Miocene and alluvial Quaternary sediments (Maia 2012). The Cretaceous–Miocene boundary was uplifted and now stands at 200 m asl in the central part of the dome, whereas Miocene marine and Quaternary alluvial sediments occur in altitudes as high as 270 m. These boundaries occur below the sea level height in the area surrounding the dome.

The uplift of the dome influenced river pattern in the central part of the basin, causing lateral migration of alluvial channels away from the dome (Fig. 13.3). This emergence of the dome has also influenced the shape and sediment pattern in the valleys that occur at both sides of the structural high (Maia 2012). The Mel dome has been described as the result of differential erosion. However, the evidence presented above indicates that the dome has been formed by the EW- to NW-oriented compression that has affected the area in the Cenozoic (Bezerra and Vita-Finzi 2000).

The Mel dome is the most important evidence of Cenozoic tectonics, and it contributed to the origin of high sea cliffs and alluvial valleys. Soils in the dome area are developed over Quaternary sediments and favor agriculture that mainly focuses on tropical fruits. There is no evidence of strong erosion in the dome area due to the high permeability of the soils and Quaternary sediments, as well as the low-topographic gradient.

13.3.2 Alluvial Plain

Two main river valleys occur in the central part and a third valley occurs at the western limit of the Potiguar Basin (Fig. 13.4). In the central part of the basin, the Mossoró valley forms the western limit of the Mel dome, whereas the Assu valley forms the eastern limit of the dome (Figs. 13.2 and 13.3). The western limit of the Potiguar Basin is marked by the Jaguaribe valley. These valleys follow NE-oriented Cretaceous faults, which have been reactivated in the Miocene–Quaternary. The most important topographic features of these landforms are flat topography at the river mouths related to low-elevated plains in the central part of the valleys. The central part of these valleys is composed of alluvial and marine sediments (Fig. 13.4), which occur close to sea level height and as far as 25 km inland in the Mossoró valley, 10 km inland in the Assu valley, and 3 km inland in the Jaguaribe valley. Bezerra et al. (2003) concluded that the marine deposits were generated during the past Holocene transgression, which took place in the area at about 4,500–5,000 cal yr BP.

The generation of these large fluvial-marine plains is related to tectonic inversion that has affected the Potiguar Basin (Fig. 13.3), as well as sea level changes that affected the coastal area in the late Quaternary (Barreto et al. 2002; Bezerra et al. 2003). Pleistocene alluvial deposits occur at the eastern margin of the Mossoró River and the western margin of the Assu River. This pattern is related to the lateral migration of alluvial channels away from the dome in two opposite directions: toward NW in the Mossoró valley and toward SE in the Assu valley. The late Quaternary deposition is concentrated in low lands that surround the Mel dome.

The large alluvial and coastal plains contributed to the natural salinization of valley floors, which makes the area the most important salt producer in Brazil (Rocha et al. 2012). However, the area has been subjected to high environmental impacts of saline facilities, shrimp tanks, and deforestation of natural vegetation.

13.3.3 Coastal Plain

The littoral zone of the Potiguar Basin is 280 km long (Fig. 13.2) and exhibits a great diversity of landforms, which results in considerable scenic beauty (Figs. 13.5 and 13.6). Its most important landforms are coastal tablelands, sand beaches, sea cliffs, coastal sand dunes, and beachrocks. Sea cliffs are formed where the coastal tablelands reach the littoral zone, and these cliffs rise to altitudes up to 100 m above the sea level and are usually capped by sand dunes. The costal tablelands are typically composed of Miocene sediments, overlain by Quaternary alluvial and eolian sediments. The tablelands are dissected by NE-oriented fault-controlled river valleys (Barreto et al. 2004).

Fig. 13.4 Alluvial-marine plain of the channel in the central part of the Potiguar Basin. The saline evaporation tanks form rectangular areas alongside of the river channels

Sand beaches are composed of white quartz sands and marine organic fragments, with grain size that ranges from fine to coarse and poor sorting, where the sediments are characterized by intense and constant reworking by alluvial, eolian, and marine transport. The strip of sand beaches along the Potiguar Basin is interrupted at river estuaries, and they are limited by sand dunes and sea cliffs. In certain locations, these beaches exhibit beachrock units that prevent coastal erosion (Bezerra et al. 2005).

Vegetated and non-vegetated sand dunes occur along the littoral zone of the Potiguar Basin. These dunes mainly comprise barchan and longitudinal types (Fig. 13.5), where grain size ranges from fine to medium sand. Dunes are usually white, reddish, and yellow, with rounded to sub-rounded grains, and they are usually composed of quartz and fragments of marine shells (Barreto et al. 2004). Large dune fields occur between the Assu and Mossoró valleys, where dunes migrate inland when wind direction is oblique to the coast and where dunes cap sea cliffs as high as 30 m and reach the coastal tablelands. The semiarid climate, flow of sediments from the beaches, the coastal morphology, and the solid discharge of alluvial sediments contribute to the high availability of sediments and the large dune field observed in the area. In addition, the erosion of coastal tablelands also provides material that gives the dune fields a reddish color (Fig. 13.5).

In the Assu and Mossoró estuaries, the evolution of alluvial and coastal systems allowed for the formation of large tidal plains that were colonized by mangroves (Fig. 13.5), which characterize endemic ecosystems in the equatorial littoral zone of Brazil. These areas are characterized by low-lying relief, periodically flooded by tides. The vegetation is composed of grass and small bushes adapted to hypersaline conditions. More recently, mangroves have been destroyed and have been replaced by shrimp farms, which have caused significant environmental damage to the coastal area of northeastern Brazil.

Sea cliffs are another common landform along the coastline. They mark the limit between the coastal tablelands and the beaches, and they are usually the result of abrasion caused by sea level changes (Bezerra et al. 2003). They form steep topographic steps developed on Miocene and Quaternary sandstones and conglomerates (Fig. 13.6). The cliffs composed of Miocene units are usually capped by a reddish lateritic crust and are typically reddish, yellow, and white, which corresponds to the variation of weathering process (Balsamo et al. 2013). These cliffs reach 100 m in altitude in uplifted areas such as the Mel dome, where the land protrudes more than 10 km into the sea (Maia 2012). There is no other similar sea cliff height in the littoral zone of northeastern Brazil. The cliffs are up to 5 km long and are interrupted in a few places by river mouths or fault-related incisions. Some cliffs are oriented along faults, such as the one in the littoral zone in the northeastern part of the Mel dome, which trends NW and is controlled by the Afonso Bezerra fault system (Moura-Lima et al. 2011).

Another feature observed on these sea cliffs is the seasonal change of vegetation, which transforms the coastal landscape frequently. The semiarid area reaches the EW-trending littoral zone at the Potiguar Basin due the E and SE-trending trade winds that reach the coast (Amarante et al. 2003). Therefore, there is no increase in rain in the area and grasses, bushes and xerophytes that occur in the littoral zone and on the top and at the toes of sea cliffs are adapted to the seasonal changes.

The existence of large dune fields and salines has made this area to be known as a “white coast,” where an incredible contrast among the deciduous and xerophytes vegetation, white dune fields, sea cliffs, long beaches, and the sea occurs. These landforms bear no traces of human interference for many kilometers, despite an increasing touristic activity and human occupation. Therefore, sand dunes and coastal cliffs represent the best-preserved landforms in the Potiguar Basin due to limited human occupation and low touristic activity in these areas.

13.3.4 Carbonate Plateau and Karst Landform

The southern part of the Potiguar Basin encompasses a carbonate plateau (Fig. 13.7), which is related to the outcrop of the Jandaíra Formation, the largest Cretaceous carbonate ramp to outcrop along the continental margin of Brazil (Fig. 13.7). The most common landforms on the plateau are karstified fault-related canyons and caves. Most landforms are related to epigenetic karst, i.e., karst developed from circulation of meteoric waters. The plateau is usually capped by caliche soil, which is typical of weathering of carbonate rocks in dry and hot weather.

The plateau dips ~2° toward to the north and forms dissected tablelands that characterize most of the onshore part of the Potiguar Basin. This carbonate platform is in conformable contact, at its base, with the siliciclastic rocks of the Açu Formation. The carbonate rocks of the Jandaíra Formation include bioclastic (green and red algae, miliolids, and mollusks) and oolitic calcarenites, calcilutites with planktonic and benthonic foraminifers, and calcilutites (Bezerra et al. 2009).

Most of the present-day epigenic karst system of the Jandaíra Formation is now dry and lies above the nearby river level in the vadose zone. This zone makes up a roughly stratiform horizon more than 100 km long, where water

Fig. 13.5 **a** Barchan dune and tidal channel at the mouth of Conchas River. The area is located in the littoral zone between the Assu River and Mossoró River. **b** Coastal mangroves in the Potiguar Basin

inflow occurs through rainfall and flooding from the nearby rivers. We estimate the minimum thickness of this karstified–fracture zone to be ~30–40 m. The karst system was developed along faults, fractures, and bedding planes. Caves consist of vertical passages up to 20–30 m deep and horizontal passages up to 300 m long (Fig. 13.8). At the surface, both faults and joints are opened by solution. However, the frequency of enlarged fractures and faults diminishes rapidly with depth. As a result, preserved fault breccias are relatively uncommon at the surface and more common below 40 m deep.

Caves formed along faults are mostly oriented in three directions, which coincide with fault directions in outcrops: N–S, E–W, and NW–SE. In the Jandaíra Formation, the architecture of faults and joints allowed us to rule out any hypothesis of randomly distributed karst conduits. Little folding and nearly

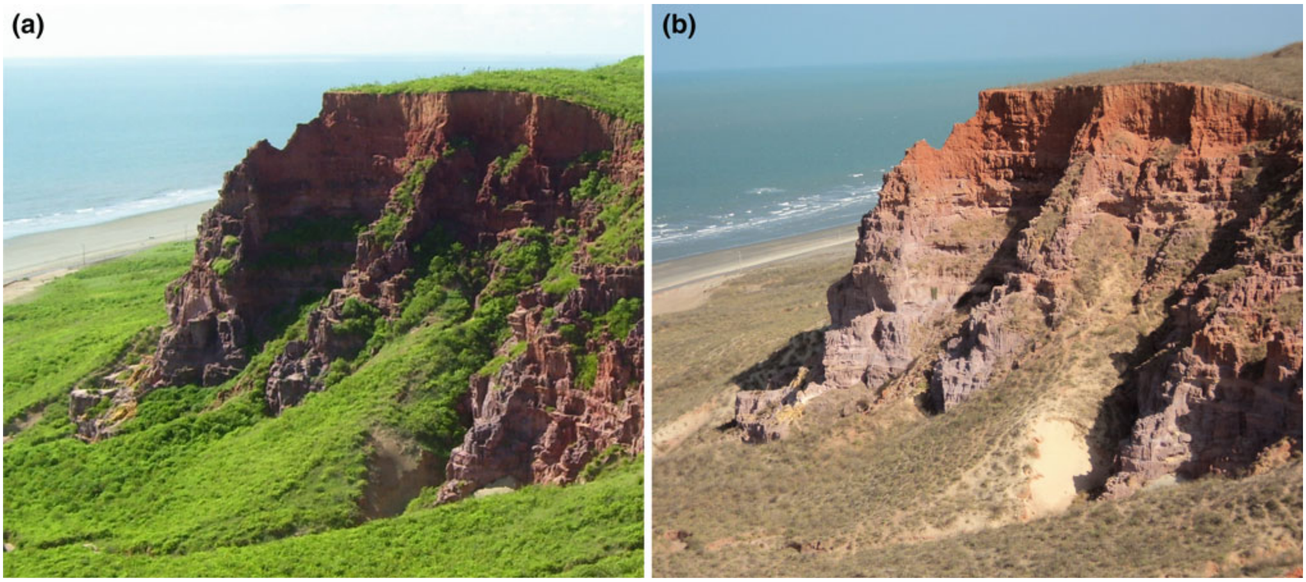

Fig. 13.6 Cliff in the northern part of the Mel dome in the rainy (**a**) and dry season (**b**)

Fig. 13.7 Carbonate plateau in the Jandaíra Formation

flat-lying layers characterize the study area. In these circumstances, faults and joints act as pathways of high permeability. Leaching mainly advanced through structural channels and through bedding planes. This occurs through dozens of meters to a hundred of meters according to our structural mapping. The Jandaíra Formation is a mixed case where both tectonic and sedimentary features play an important role.

The Soledade ledge, which is located in the western part of the Potiguar Basin, is one of the most spectacular sites in region due to its prehistorical paintings and Quaternary fossils used to decipher paleoclimate evolution. Nowadays, this site is protected by Federal law, and it has become a major touristic attraction, visited daily by tourists from overseas, local schools, and universities.

Fig. 13.8 **a** Dry drainage channel in Jandaíra Formation—Soledade Ledje. **b** Speleothems in a cave, located a few meters below the plateau surface in the Jandaíra Formation. **c** Carbonate ledge and karst relief

13.4 Conclusions

The Potiguar Basin contains post-rift sedimentary units from the late Cretaceous to the Quaternary. These units are cut across by a system of NE- and NW-trending faults, which are reactivated older structures from the rift phase and the basement. These structures control the course of river valleys and the presence of a dome related to tectonic basin inversion. Deposition of Miocene marine sediments and Quaternary alluvial and marine sediments occured in fault-controlled troughs. The effect of sea level changes is observed in the late Quaternary. This record is composed of marine terraces from the last Pleistocene glacial/interglacial cycles and marine deposits of the last Holocene transgression. The latter fill flat, low-lying valleys. Wind action has deposited several dune fields along the coast. The semiarid weather has favored dune deposition, which cap the coastal tablelands. A carbonate plateau occurs in the southern part of the basin. The plateau is capped by a tropical soil developed in dry climates, and it is affected by karst processes, which are mainly developed along faults.

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14

The Anavilhanas and Mariuá Archipelagos: Fluvial Wonders from the Negro River, Amazon Basin

Edgardo M. Latrubesse and José Cândido Stevaux

Abstract

With a mean annual discharge of $\sim 29{,}000\ \mathrm{m}^3\ \mathrm{s}^{-1}$, the Negro River ranks as the sixth in the world in terms of water discharge and is the second largest tributary of the Amazon. The Mariua and Anavilhanas are two huge, fascinating archipelagoes of the Negro River that sustain the largest flooded “igapó” forest systems in the world and rich fish diversity. This chapter presents how hydro-geomorphology and changes in environmental conditions controlled the formation and functioning of these two anabranching reaches in the Negro River. The present hydro-sedimentary dynamics is not compatible with the existing morphology, which is product of a Middle-Late Holocene history. The very low amount of suspended sediment transported by the Negro is not sufficient to construct the intricate islands and floodplain. This condition produces a permanent non-equilibrium stage that controls not only river geomorphology but also vegetation distribution. As a product of long history, the Negro River basin with its wonderful pristine fluvial archipelagos and the “igapó” forests faces their most dangerous enemy: The irrecoverable destruction of the Amazon Rivers by the environmentally irresponsible dam construction planned by the Brazilian government.

Keywords

Negro River • Fluvial geomorphology • Amazonian floodplain forests • Igapó • Holocene

14.1 Introduction

The Amazon fluvial system, with a huge drainage area of 6,200,000 km^2, covered for the most part by the Amazon rainforest, discharges nearly 18 % of the total world freshwater to the ocean and functions as a major collector to water and sediments from a large variety of tributaries. The most opulent and fascinating mosaic of wetlands and floodplain lakes on the planet, which sustain huge biodiversity and have a primary role in atmospheric emissions of carbon dioxide and methane, is supported by this mega fluvial system (Latrubesse 2012). Recently, Latrubesse (2008) included the Amazon, Congo, Orinoco, Yangtze, Madeira, Negro, Brahmaputra, Japura, and Parana rivers in a new category of very large rivers—“the mega-rivers,” those with a Q_{mean} of more than $\sim 17{,}000\ \mathrm{m}^3/\mathrm{s}$. Among the mega-rivers, six are located in South America. In this context, the Amazon is a world of superlatives because four of the ten largest rivers on Earth are located in the basin. In addition to the largest rivers listed above, other Amazon tributaries are among the largest rivers in the world (Ucayali, Marañon, Tapajos, Purus, and Xingú). Moreover, twenty-four of the thirty-four largest tropical rivers in the world are also located in South America (eighteen of them in the Amazon basin) (Latrubesse et al. 2005).

Currently, a critical topic in fluvial geomorphology concerns an understanding of why the largest rivers differ from the smaller ones, and how this response is observed in the channel planform geometry (Latrubesse 2008; Ashworth and Lewin 2012). It is interesting to emphasize that the largest

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rivers in the world (in terms of water discharge) are anabranching alluvial systems. Anabranching rivers are defined as multichannel systems where flow is separated by vegetated and stable islands. In this way, anabranching rivers differ totally from braided rivers, which commonly present abundant bedload transport and have the flow separated by mobile sand or gravel bars inundated at moderate to high water levels.

The Congo River in Africa and the Negro in Brazil (Fig. 14.1) are the two large rivers that have the most complex alluvial archipelagos in the planet. Both rivers drain predominantly Precambrian rock basins in tropical rainforest, with the Brazilian river presenting the most diversity in island morphology. Other complex, non-alluvial, multichannel systems, such as the *Si Phan Don* (Four Thousand Islands) in the Mekong River and the Xingu rapids in Brazil, have developed on bedrock, and for that reason, they are not included in this category. Another impressive characteristic is the channel depth of the Negro, which in its lower course reaches 90–100 m, being probably the deepest alluvial channel in the world (the deep channels of the Congo River are excavated in basement rock in a non-alluvial reach).

The Mariua and Anavilhanas are the two huge and fascinating archipelagoes of the Negro River that sustain the largest flooded "igapó" forest systems in the world and rich fish diversity of over 1,000 species (Chao 2001) (Fig. 14.2). For all the above reasons, we consider that the gigantic archipelagos of the Negro River are unique and deserve to be included among the geomorphologic wonders of the planet.

14.2 The Negro River: General Framework

With a mean discharge of ~29,000 $m^3\ s^{-1}$, a drainage basin of 696,000 km^2 and a specific discharge of 0.041 $m^3\ s^{-1}\ km^2$, the Negro is the second largest tributary of the Amazon (Fig. 14.1) after the Madeira River, whose mean discharge is 32,000 $m^3\ s^{-1}$ (Filizola 1999), basin size is 1,360,000 km^2, and the specific discharge amounts to 0.024 $m^3\ s^{-1}\ km^2$.

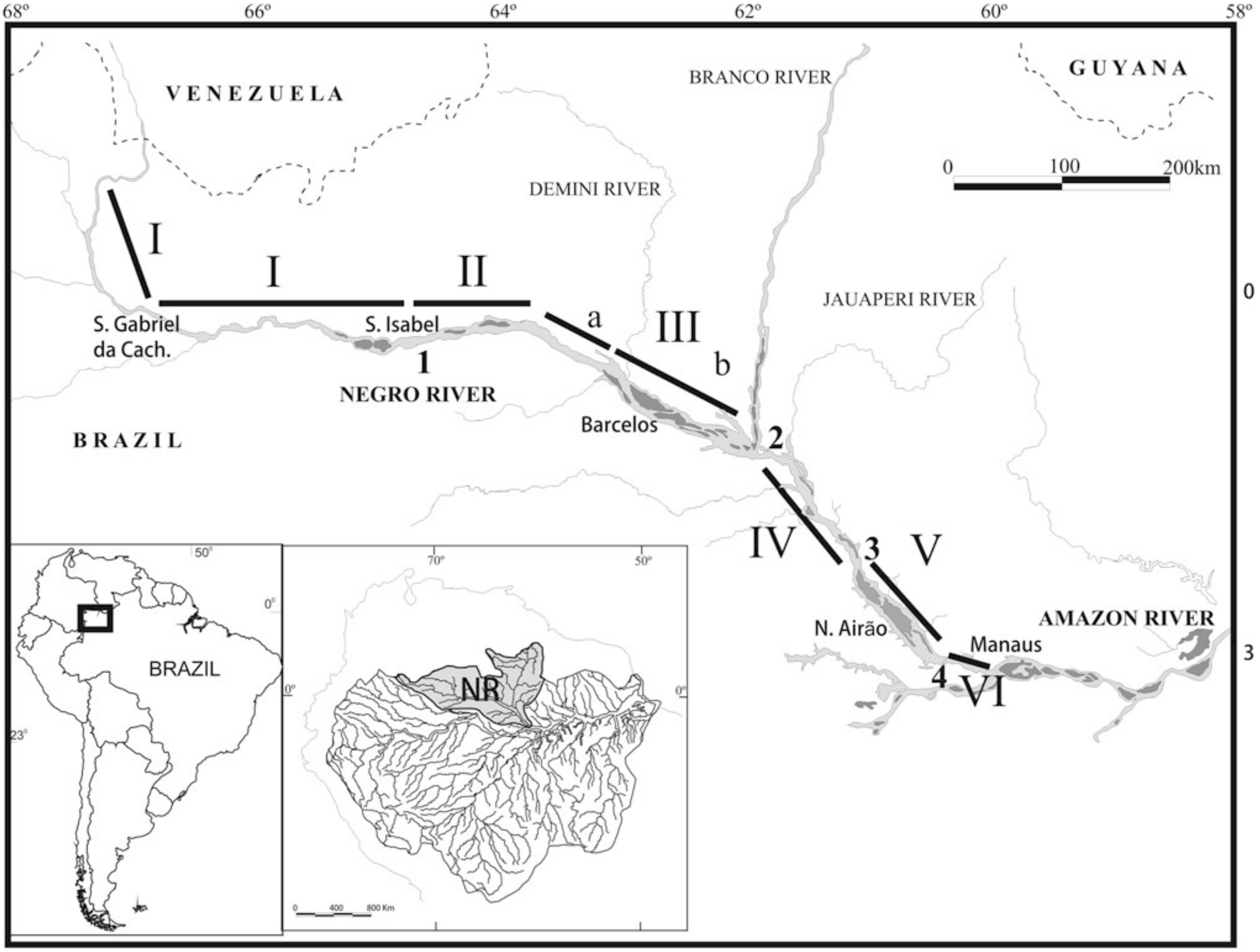

Fig. 14.1 The Negro River. Geomorphologic reaches (I, II, III, IV, V, and VI), nodal points (1–4), and major cities (adapted from Latrubesse and Franzinelli 2005)

Fig. 14.2 Aerial views of the **a** Anavilhanas archipelago; **b** Mariuá archipelago

The Negro River ranks sixth in the world in water discharge and runs approximately 2,250 km from its headwater in Colombia until its mouth in the Solimões-Amazon River at the city of Manaus (Fig. 14.1). Regarding the geomorphologic style of the channel and floodplain, and the structural control of the valley and following Latrubesse and Franzinelli (2005), the river can be divided into six major geomorphologic reaches (I–VI, Table 14.1).

More than 90 % of the Negro basin is in Brazil, with the remaining parts in Colombia and Venezuela (Goulding et al. 2003). The basin of the Negro River, with one of the highest annual rainfalls across the Brazilian Amazon, has annual average rainfall of 2,000–2,200 mm, reaching over 3,000 mm in the upper sections near the Equator, and the mean monthly temperatures vary little over the year, ranging between 25 and 28 °C (Sombroek 2001). Among more than 500 small tributaries in the Brazilian territory, the only remarkable one is the Branco River in the lower basin (Fig. 14.1). The Branco River has its source in northern Roraima and is the main yielder of fine sand to the Negro (Sioli 1984; Goulding et al. 2003; Latrubesse and Franzinelli 2005).

The Negro is a typical black-water river of the Amazon basin because of the high content of humic substance. In spite of the olive-brown to coffee-brown colors, the Negro's water has transparency of 1.3–1.5 m due to its very low concentration of suspended sediment of $\sim$7.9 mg L^{-1} (Sioli 1984). For this reason, this giant river discharges only 8 Mt/year annually in the Solimões-Amazon (Filizola 1999), an insignificant amount relative to the huge water discharge. Bedload is composed of white supermature quartz sand (Franzinelli and Potter 1983; Latrubesse and Franzinelli 2005). Fine sediments are formed by iron-rich kaolinitic clay and sand derived from weathered rocks of the Precambrian crystalline basement or Paleozoic and Mesozoic sedimentary rocks. The more conspicuous present-day active landforms along the Negro are sand bars.

The Negro basin is covered by a complex vegetation mosaic that includes equatorial rainforest, savanna (lavrado), *campina* (herbaceous vegetation), *campinarana* (mixed herbaceous-arboreal vegetation), and flooded forest (igapó). Vegetation is very well preserved and the local economy is mainly restricted to the extraction of non-timber forest resources and fishery (Emperarie 2000; German 2004). Non-forest economic activities are also conducted in the region, including gold mining, gravel extraction, and sandstone outcropping for construction (Goulding et al. 1996). Furthermore, sport fishery and ecotourism are important activities in the region, especially along the lower Negro section near the city of Manaus. More than 100 small-flooded forest fish support a regional thriving and socioeconomic valuable ornamental fishery in the Rio Negro (Chao 2001; Cooke et al. 2009).

Excluding Manaus at the mouth and Boa Vista on the Upper Branco River (its main tributary), approximately 90,000 inhabitants live in the Rio Negro Basin, concentrated mainly in four major cities: São Gabriel da Cachoeira, Santa Isabel, Barcelos, and Novo Airão (IBGE 2008) (Fig. 14.1).

The lower Negro River is protected by national and state parks, areas of environmental protection (APA), an "extractive reserve" with sustainable development, and one indigenous area. In total, more than 11 million hectares of the basin are protected, which represents one of the largest protected areas in the world. This area is a part of the Amazon Ecologic Corridor and the Core Zone of the Biosphere Reserve.

The complex hydrology of the Negro River responds not only to spatial differentiation in rainfall, but also to the backwater effects at its mouth, caused by the oscillation in the water level of the Solimões-Amazon. The hydrographic curve at the Manaus gauge station indicates that water level fluctuations in the lower Negro are in phase by the impoundment of the Solimões–Amazon River (Sternberg 1987; Richey et al. 1989). The backwater effect extends as far as Moura, 300 km upstream from the mouth of the Negro (Meade et al. 1991).

In Manaus, the river oscillates up to 15–16 m with an average of $\sim$11 m, whereas 470 km upstream from the confluence at Barcelos (reach III), the average oscillation is $\sim$7 m, (Latrubesse and Franzinelli 2005; Montero and Latrubesse 2013) (Fig. 14.3). The lowest stage in reach III occurs in October–November, while downstream it occurs in February–March. In opposition to this falling period in reach III, water level begins to rise in the downstream reaches V and VI (Meade et al. 1991). The Rio Negro hydrograph is also affected by the geomorphic features of the floodplain. For instance, there is a delay in stage oscillation in Barcelos compared with downstream reaches. It is caused by the reservoir effect produced by the Mariuá Archipelago and by the large uprised tectonic block of reach III.

14.3 The Mariuá Archipelago

The Mariuá archipelago is an anabranching section of the Negro made up of vegetated and stable islands in reach III (Figs. 14.1, 14.2b, and 14.4; Table 14.1). The archipelago is divided into two sub-reaches, "a" and "b," related to two sunken tectonic blocks elongated in NW–SE direction and limited, at the Demini River, by a general NW-trending lineament. Reach III spreads for 4,143 km^2, with 1,827 km^2 for sub-reach "a" and 2,316 km^2 for sub-reach "b" (Fig. 14.4) (Latrubesse and Franzinelli 2005).

In some parts, the floodplain is almost filled up with recent alluvial sediments and huge areas show an impeded drainage system with paleochannels features. The floodplain and islands are flooded for several months each year and covered

Table 14.1 Reaches of the Negro River

Reach	Delimitation	General description
I	Upper basin from the source to Nodal point 1	River course controlled by E–W fractures in crystalline rocks of the Precambrian Shield. The area is the source of large part of the water runoff. The channel is characterized by rapids and rocky islands
II	The river runs for nearly 300 km, downstream Nodal point 1	The river follows in E–W direction exhibiting an alluvial anabranching pattern and a broad Holocene floodplain
III	It begins where the river turns to a nearly NW–SE direction for 275 km up to Nodal point 2	The river develops an anabranching alluvial reach (Mariuá Archipelago). A huge asymmetrical terrace on the left side is present. The alluvial plain width reaches 16–18 km
IV	From Nodal point 2–3 along 140 km	The alluvial plain narrows to about 5–10 km, although the river presents an anabranching pattern with smaller and elongated islands and channels in alluvium and/or bedrock
V	120 km reach between Nodal points 3 and 4	This reach is characterized by a wide channel belt 15–20 km in width, incising the Cretaceous Alter do Chão Formation. The anabranching pattern forms the Anavilhanas Archipelago which is composed by large muddy island
VI	From Nodal point 4 to the confluence with the Solimões-Amazon River	Single-channel reach, without islands, following a strong tectonic control. River width ranges from 3 to 10 km

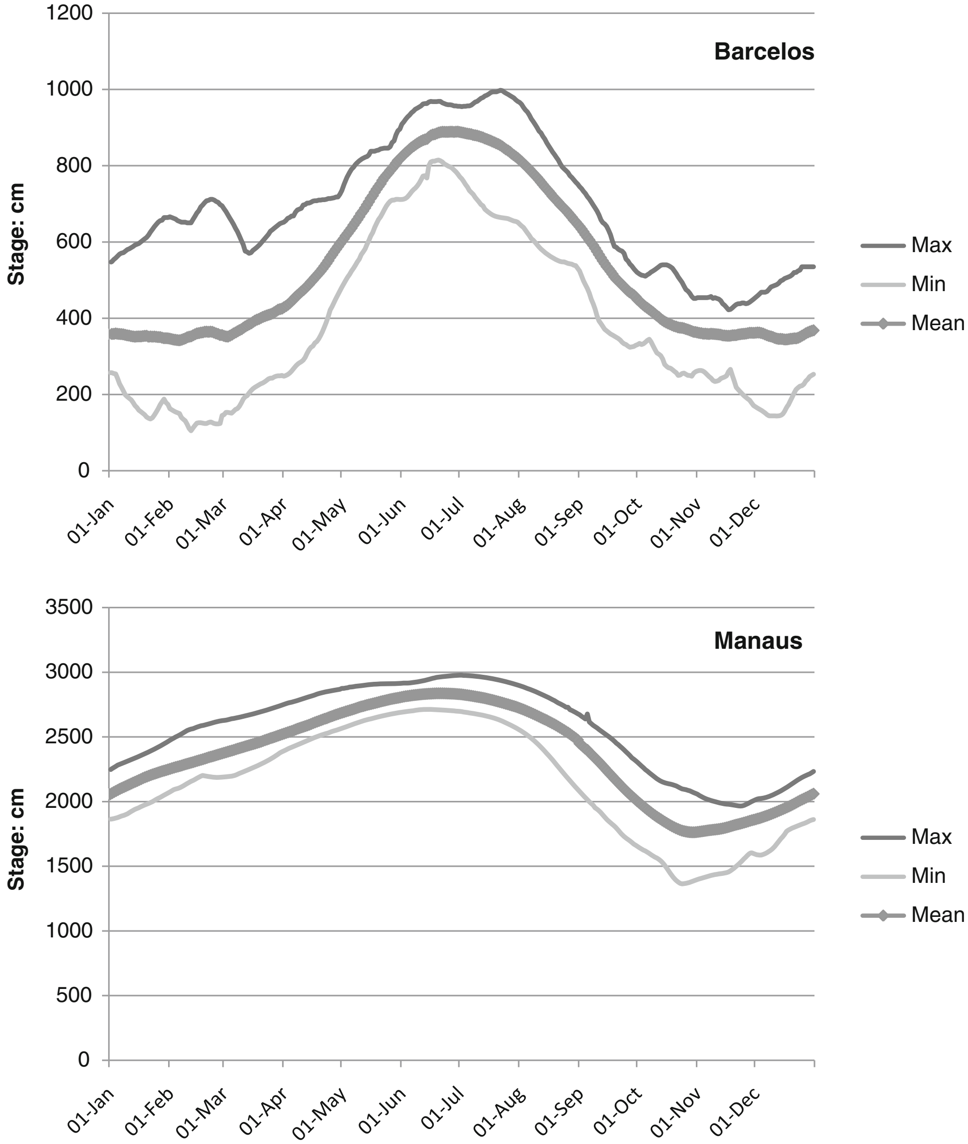

Fig. 14.3 Mean, maximum, and minimum daily stage hydrographs at Barcelos and Manaus (2000–2011)

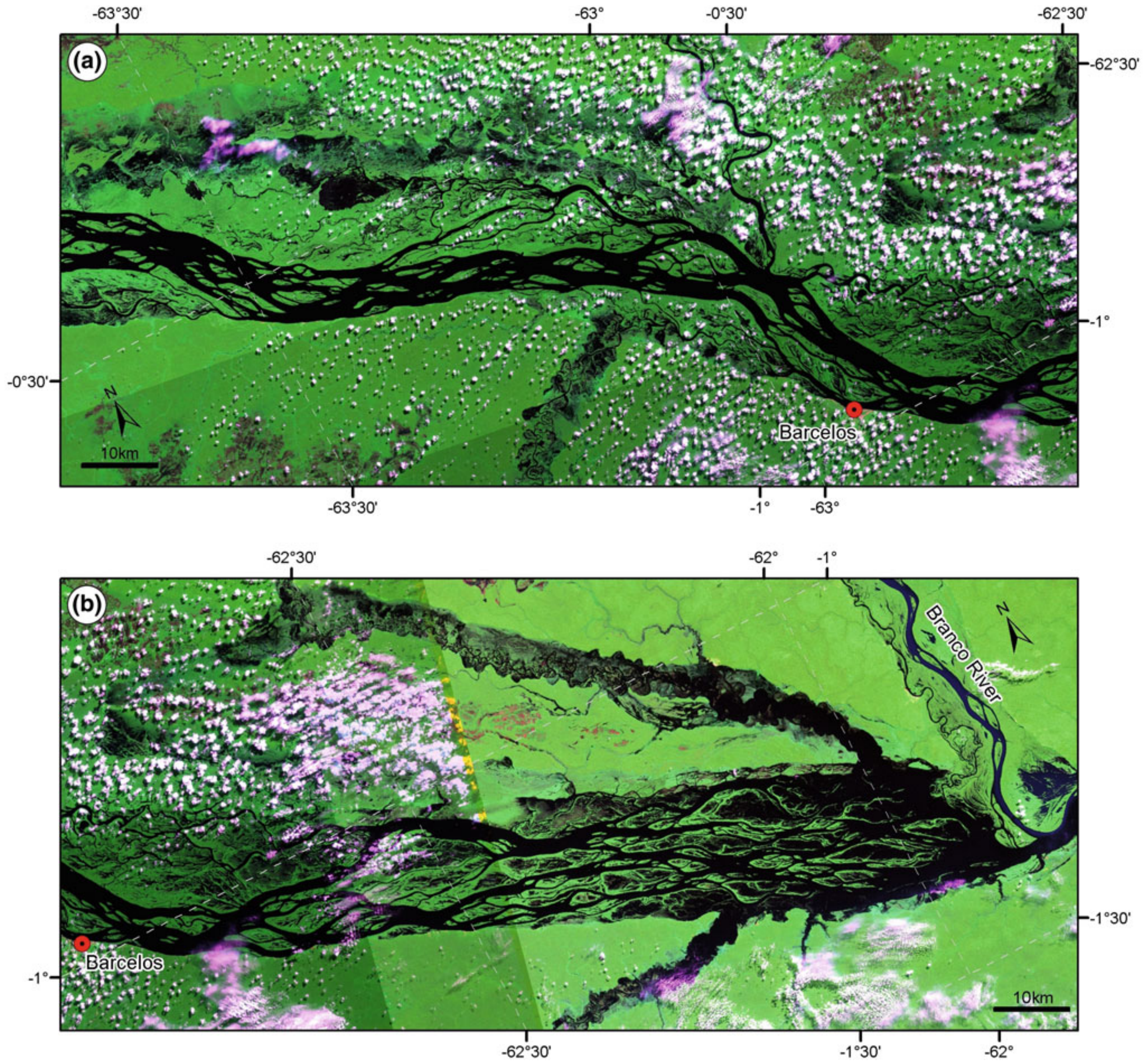

Fig. 14.4 The Mariuá Archipelago (reach III; **a** and **b**). See Fig. 14.1 for location

by more than four meters of water. Narrow floodplain channels partially drain into the impeded floodplain water. These kinds of areas are more frequent on the left side of the river but can be also identified in some reaches on the right side. In downstream areas of the archipelago, the islands spread across the width of alluvial plain, dividing the channel in several minor branches. In this case, it is impossible, at a first glance, to identify which one is the main channel.

An evident downstream fining trend in grain size is observed in island sediments of reach III. In both sub-reaches "a" and "b," the upper sectors feature typical sandy-core islands topped by muddy sediments that become more and more muddy downstream. Local floodplain channels can be present in this reach, running mainly along depressed paleochannels. An intricate, anastomosed pattern of small channels crosses the floodplain, forming—by erosive processes—hundreds of large islands (Fig. 14.4). In the downstream portion of reach III, the Branco River forms an internal delta that fills up this portion of Negro River floodplain.

Other conspicuous features in reach III are sand bars that occur at the downstream end of the islands or as middle-channel bars (Figs. 14.2b and 14.5). They consist of medium to coarse supermature quartz, white sand (Franzinelli and Potter 1983; Latrubesse and Franzinelli 2005). In the dry

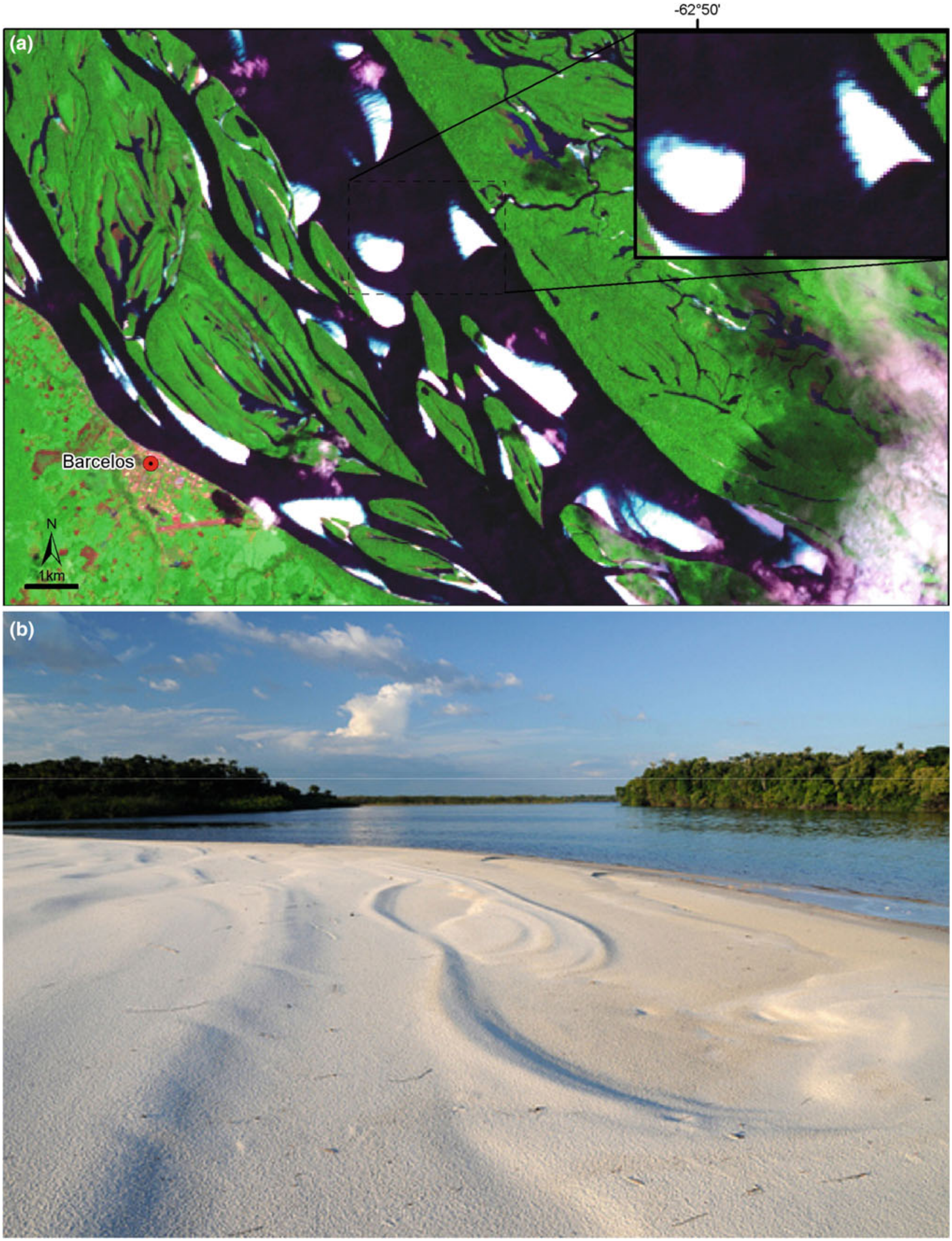

Fig. 14.5 **a** Sand bars emerging during the low stage season along reach III. **b** Large sand bar in reach III at low water stage. Many channels of this reach are very shallow because aggradation continues to be active because the area acts as an efficient trap for sandy sediments

season, wide sandy sheets can extend between higher banks, showing large fluvial dune structures and ripple marks on their surfaces.

14.4 The Anavilhanas Islands

The Anavilhanas islands are a very complex archipelago formed by fine sediments, covered by vegetation (Figs. 14.2a, 14.6, and 14.7). The islands were formed in reach IV, but spread into reach V where the width of the valley favors their expansion. The area of the Anavilhanas sedimentary basin controlled by tectonic lineaments is ~2,050 km^2. Channels occupy ~33.5 % of the total area, the islands (levees) make for 40.6, and 25.9 % are covered by lakes and pools. The islands are totally flooded during the high water stages with only the igapó vegetation emerging from the water surface. However, the tectonic block containing the river valley is not totally filled with sediment and considerable space is still available. Currently, the floodplain cannot be filled by sediments because of the low content of suspended sediment in the Negro's water.

The anabranching pattern is intricate and, although a dominant straight channel pattern is observed along the steep rocky right bank, secondary slightly sinuous channels contour the islands. Two main types of islands can be identified in the Anavilhanas Archipelago. In the more upstream-proximal part, the islands are shorter and compact with a large rounded lake in the head and short tails, while from the middle to downstream reach, the islands are larger and characterized by a typical "phantom" morphology with very long tails (Figs. 14.6 and 14.7).

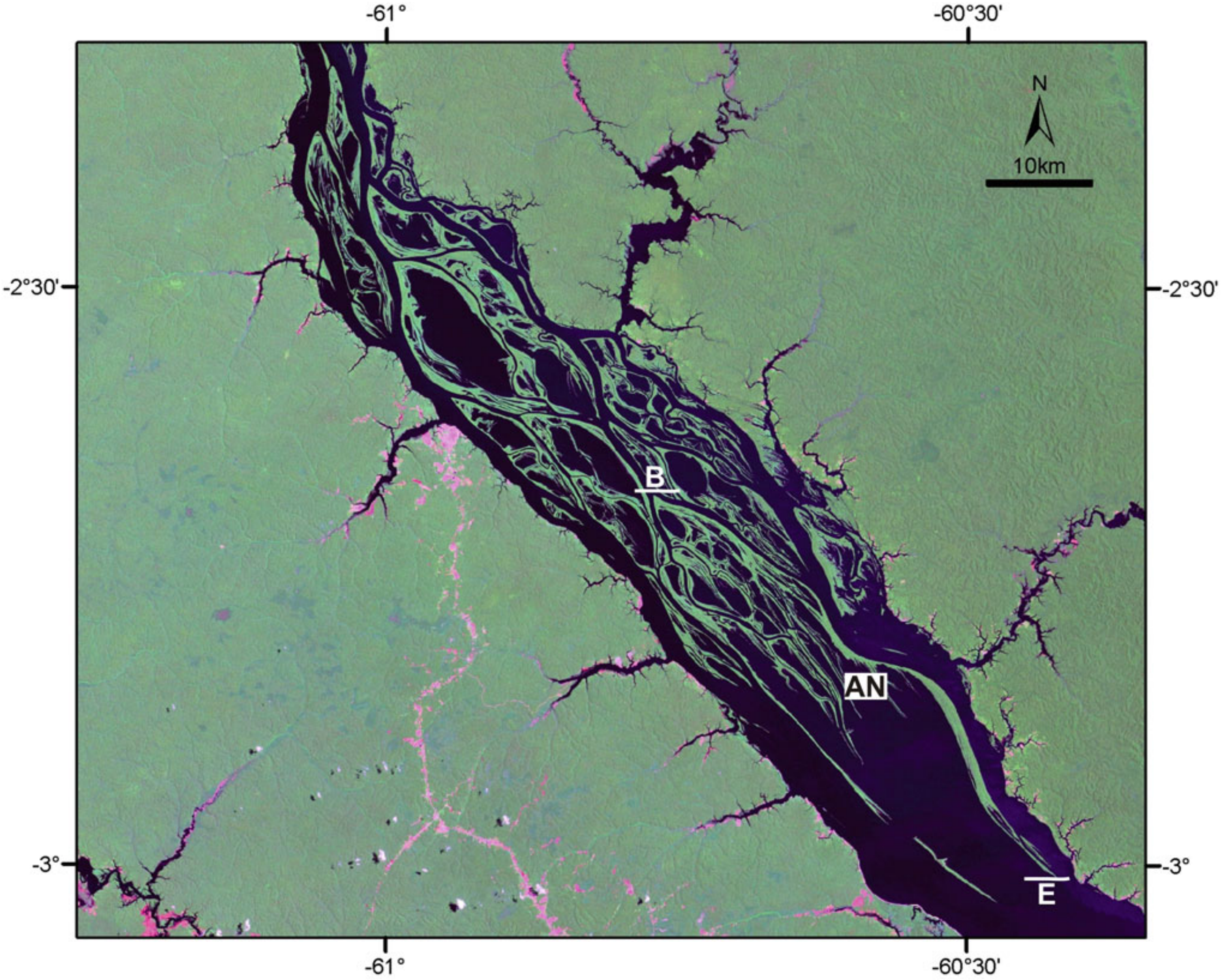

Fig. 14.6 Anavilhanas Archipelago (Reach V). The long Anavilhanas Island, ca. 50 km in length, from B (*beginning*) to E (*end*). See Fig. 14.1 for location and details in Fig. 14.7

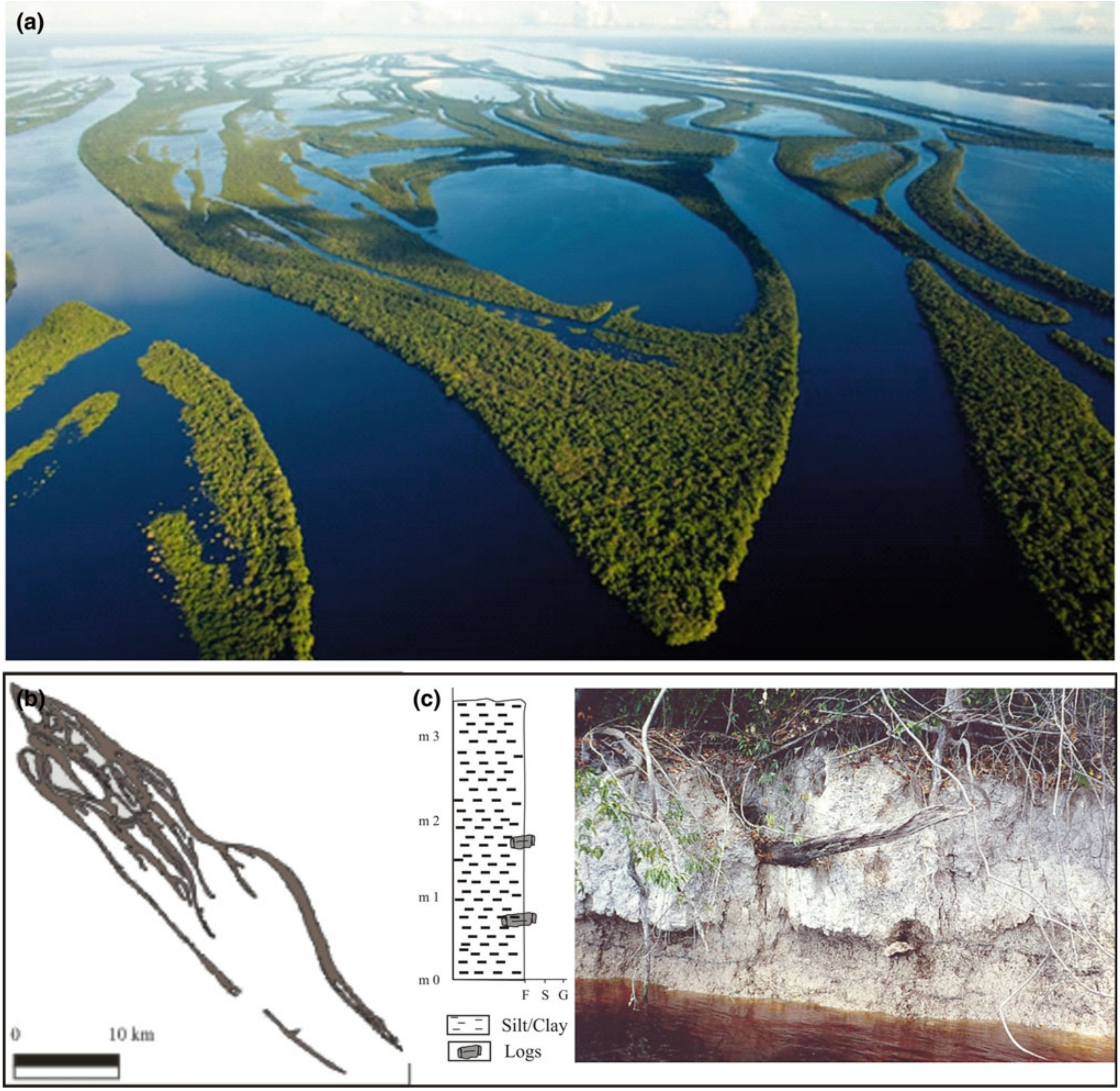

Fig. 14.7 **a** Aerial view of the Anavilhanas Archipelago. **b** The phantom morphology of the Anavilhanas Island, the longest island of the Anavilhanas Archipelago. **c** Partial exposure of typical fine-sediment banks in the Anavilhanas islands, reaches IV and V. During the dry season, island banks can be over 7 m in height

The more spectacular example is the Anavilhanas Island which is ~50 km long but the tails are approximately 140 m in width (Figs. 14.6 and 14.7). In general, the islands have lightly elliptical plan morphology surrounded by narrow natural levees formed by fine sediments that protect wide lakes inside the islands during the flood stage. During the low water stage, these water bodies can disappear completely or may remain depending on water volume and morphology.

The islands consist of a sequence of thin horizontal beds of clayey silt, affected by root bioturbation (Fig. 14.7). Charcoal fragments and layers produced by fire or associated with archeological artifacts (some pieces of ceramics, for example), as well as some logs are present in this sediment. The banks are steep and reach 7 m high during the low season, but in general, its height decreases gradually downstream. The internal lake banks are smoother than the outside banks. The Anavilhanas lithology is not compatible with the present hydrosedimentary dynamics of the river, which, as mentioned above, transports an insignificant amount of suspended sediments.

The upstream area shows a large density of levee morphologies on the islands and a multi-channel pattern formed by narrow channels (Figs. 14.2a, 14.6, and 14.7). The channels are not more than 12 m in depth, ~1,500 m in width and have a width/depth ratio ranging from 20 to 60 (values corrected to higher stages). In contrast, at the end of the archipelago, a large area of "dead water," ~6 km wide × 40 km long, occurs between the two main tails of the Anavilhanas Island. The width/depth ratios oscillate between ~80 and >400 (values corrected to higher stages).

Concerning the origin and evolution of Anavilhanas, Tricart (1977) suggested a delta model for the Anavilhanas formation as a consequence of the Flandrian transgression of the middle Holocene. On the other hand, Sioli (1991) maintained that the islands are forming at present as a consequence of the sedimentary input of the Rio Branco to the Negro. However, some problems exist with both interpretations regarding timing and processes involved in the formation of the archipelago. Radiocarbon dating recorded in the islands oscillates between ~3.7 and ~1 ka BP, indicating more recent formation than the Flandrian transgression. In this case, Anavilhanas cannot be a delta formed as a response to the transgression effect. On the other hand, the Branco River is a sandy river with insufficient suspended load to explain the deposition of these giant islands and given the temporal point of view, the islands are not being formed at present. The vegetated islands are relict forms since the river today does not transport sufficient suspended load to form new levees-islands (a type of island where only the levees keep emerged).

Four main components are essential for the development of the Anavilhanas: (a) sufficient amount of suspended sediments, (b) low energy environment, (c) linear space accommodation in the valley; (d) "rising" base level (Latrubesse and Franzinelli 2005). Apparently, these conditions were reached at the Middle-Late Holocene transition. The Anavilhanas evolved through vertical accretion in a low energy system, where the levees were limiting a complex of anabranching channel systems and generating successive channels by avulsion.

14.5 Igapó Forest

In central Amazonia, the prevailing floodplain forest is differentiated into nutrient-rich white-water "várzea" forest and nutrient-poor black water or clear water "igapó" forest (Prance 1979) (Fig. 14.8). These forests are mostly affected by long flood pulses subjecting trees to extended inundation periods of up to 8 months and to flooding amplitudes of up to 10 m or more (Junk 1989). The Mariua and Anavilhanas islands in the Negro River are typically flooded for ~4–5 months per year (Montero and Latrubesse 2013). This dynamics imposes a strong restriction on plant assemblages whose species composition and structural patterns are continuously changing along the river channel (Rosales et al. 2001; Wittmann et al. 2004; Albernaz et al. 2012; Monteiro 2011; Montero et al. 2014).

Black water and clear water rivers carry low loads of suspended matter and solutes, resulting in the scarcity of nutrients. These rivers have brown- or tea-colored waters, the color being the result of high concentrations of suspended humic substances and organic acids (Sioli 1984). The igapó forests mostly occur along black and clear water rivers that drain the Paleozoic and/or Precambrian Shields of Guyana and central Brazil. The largest clear water rivers are the Xingu, Tapajós, and Trombetas whose floodplains cover approximately 67,000 km^2, while the main example of a black water river is the Negro River, whose floodplains cover ~118,000 km^2 (Melack and Hess 2010), supporting the largest black water inundation forest in the world (Montero 2011).

The physiognomy and floristics of the igapó forest differ substantially from the "várzea" forest (Prance 1979). Trees have lower heights and the forest is less stratified than its white-water counterpart (Figs. 14.7a and 14.8). The canopy height averages about 15–20 m, with a few emergent trees up to 30 m, but woody lianas are almost absent. An analysis of growth behavior indicates that tree ages in species of more or less the same diameter are more than twofold higher in the igapó (maximum age >500 years) than in várzea (maximum age <200 years) (Schöngart et al. 2005; Fonseca Junior et al. 2009). Species diversity is also very different in both types of fluvial forests. The Negro River igapó, with an average of 63 sp ha^{-1}, is one of the poorest forest types in the Amazon and in comparison with várzea (142 sp ha^{-1}) is one of the poorest inundation forests in the Amazon. *Heterostemon mimosoides*, *Aldina heterophylla*, and *Eschweilera atropetiolata* trees are the dominant species and particularly restricted to the Negro Basin (Montero and Latrubesse 2013). The *Chrysobalanaceae*, *Lecythidaceae,* and *Euphorbiaceae* appear to be particularly characteristic families along the Negro River (Montero et al. 2014).

14.6 Geomorphology and Hydrology Interactions in the Igapó Forests

The flood regime is a very important variable in the Amazon fluvial ecosystems, but a simple hydro-ecological approach based solely on the analysis of hydrological variables may fail to explain the different patterns in the igapó forest. Indeed, results demonstrate that other factors affect the

Fig. 14.8 **a** Flooded island in reach III with igapó forest (water depth on the forest ~4 m, July 2013. **b** View of the igapó forest (water depth covering the igapó forest ~4 m)

floristic mosaic in such a large anabranching river with a complex floodplain.

In the Negro River, sediment deposition by the main channel, branches, and tributaries may drive changes in the vegetal community composition toward the occurrence of more opportunistic and generalist species, especially in early succession stages. Geomorphology seems to influence species richness, abundance, basal area, and vertical structure (Montero and Latrubesse 2013). The general pattern of the igapó forest's species composition is largely a function of the position in the morphological system (Montero et al. 2014). Thus, the inputs of sediment and species yield by tributary rivers are crucial factors in determining tree species assemblages.

A combination of factors—acting at different scale, space, and time—are controlling the floristic variation of the igapó forests along the Negro River (Montero and Latrubesse 2013). Diversity patterns and forest structure may be better explained by fluvial geomorphic processes, which operate at smaller spatial scales. The construction of complex floodplains in mega-river such as the Rio Negro is related to the morphodynamics (depositional and erosional processes) but also to the evolution of the floodplain during the Holocene. These floodplains are created and maintained not just by fluctuations in water discharge as traditionally postulated by the eco-hydrological approach promoted by aquatic ecologists, but also by the variety of morphological styles and evolution of the system.

The occurrence of the vegetation mosaic can be explained by the Late Quaternary morpho-evolutionary model presented above. The igapó forest in the Negro River depends directly from the Holocene deposits and its evolution and its expansion followed spatially and temporally the morpho-sedimentary gradient from upstream to downstream during the Late Glacial-Holocene. The average age of the igapó forest communities should be slightly older in the upper reaches than in the lower reaches (Montero and Latrubesse 2013) and the area of igapó coverage has been increasing in the basin since the Late Glacial, reaching the present physiognomy ca. 1,000 BP.

14.7 Conclusion

The Negro River is one of the top-ten rivers of the world in terms of water discharge and the second largest tributary of the Amazon. It contains some of the most complex and intricate fluvial island systems of the world (Anavilhanas and Mariua archipelagos) and the largest area of flooded "*igapó*" forest. In spite of its huge water discharge, the Negro carries a very low concentration of suspended sediment and is characterized by its black acidic water.

A substantial part of the river is controlled by geology (structures and bedrock), and tectonic blocks permit the development of huge fluvial archipelagos that exceed 15 km in width and extend for hundreds of kilometers. Some islands in the Negro River are more than 40 km long.

Since about 14 ka, the river has behaved as a progradational system, infilling a sequence of structurally controlled sedimentary compartments, creating both alluvial floodplains and complex anabranching channel systems (Latrubesse and Franzinelli 2005).

The middle and lower reaches never achieved equilibrium conditions during the Holocene, and continue today in non-equilibrium conditions with sediment unfilled floodplains and open water areas. Thus, the evolution of the Negro River during the Late Quaternary illustrates the peculiar system response of a large river to changes in Late Quaternary base level and sediment supply. A large part of the contemporary floodplain is not related to the modern hydro-sedimentary system but is a heritage of older Quaternary conditions.

The floodplain and igapó forest of the Negro River reached the present-day distribution very recently, not long before 1,000 BP. In addition, the input of sediments and the construction of alluvial areas by tributaries also played a role in the floristic differentiation of the igapó forest.

In times, where river restoration is a scientific hot spot of fluvial research and the short-time frame rules climatic and environmental analysis, the gigantic fluvial archipelagos of the Negro provide us with frequently forgotten lessons: Fluvial systems are a product of the landscape history. Its floodplain morphology and vegetation is not only related to the present dynamics but also to a long and complex geomorphologic heritage. The complex, gigantic islands of the Negro are a testament to morphodynamic processes that no longer occur in the basin. The largest black water igapó forest of the Amazon is settled and constrained to the inherited fluvial landforms that spread on the intricate anabranching system of the Negro. In the case of human impact, such as river regulation and deforestation, river and habitat restoration of the Negro islands and igapó forest successional vegetation would not be possible and these natural features will be lost forever. With more than 160 dams planned by the Brazilian and Peruvian governments for the Amazon basin in the upcoming years, including several of them proposed to be constructed in the Negro River basin, the wonderful pristine fluvial archipelagos and the igapó forest face their most serious threat: The destruction of the Amazon rivers by environmentally irresponsible dam construction.

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The Rio Peruaçu Basin: An Impressive Multiphased Karst System

15

Joël Rodet, Luc Willems, and André Pouclet

Abstract

The Rio Peruaçu basin is located on the left bank of the Rio São Francisco, in the north of the state of Minas Gerais. While its upper portion collects the waters flowing from the sandstone formations of the Urucuia, its lower part cuts into the Bambuí limestones, carving out a narrow canyon about 200 m deep for which the site is known. Over more than 17 km, the stream opens a bed that disappears underground six times. These underground sections are the remainders of an extensive and complex primitive karst network. Although some segments consist merely of simple but majestic arches, others, such as the Brejal and especially the Janelão, offer kilometers of underground galleries that can attain exceptional dimensions. For example, the Janelão cave reaches a ceiling height of 106 m and a width of 60 m. This canyon is punctuated by large and flat areas that function as reservoirs, namely the poljes of Silu and Terra Brava, and at the confluence with the Rio dos Sonhos. The system results from a complex Cenozoic evolution, including several spectacular episodes. As currently reconstituted, this evolution comprises at least three main episodes. The impressive landscapes of this region are not its only interesting feature: humans have occupied the basin since prehistoric times, as attested by about a hundred rock shelters and open-air dwelling sites that have not yet revealed all their secrets.

Keywords

Multiphased karst • Geomorphological evolution • Neoproterozoic Bambuí limestones • Peruaçu

15.1 Introduction

Located in the north of the state of Minas Gerais, the Rio Peruaçu is a perennial left-bank tributary of the Rio São Francisco, which meets between the cities of Januária and Itacarambi (Fig. 15.1). The beginning of the European colonization of the region is dated to 1686 and marked by the foundation of the "arraial of Brejo do Salgado" (former Januária) by a "bandeirante" group came from the south, from São Paulo. With a population of about 65,000 inhabitants, Januária lies today in an agro-pastoral region. Important crops are sugar, manioc, beans, mango, breadfruit, coconut, orange, avocado, cashew, and bananas. Like almost all cities in this area of Minas Gerais, cattle breeding is an important economic activity. Small industries produce vinegar, cotton

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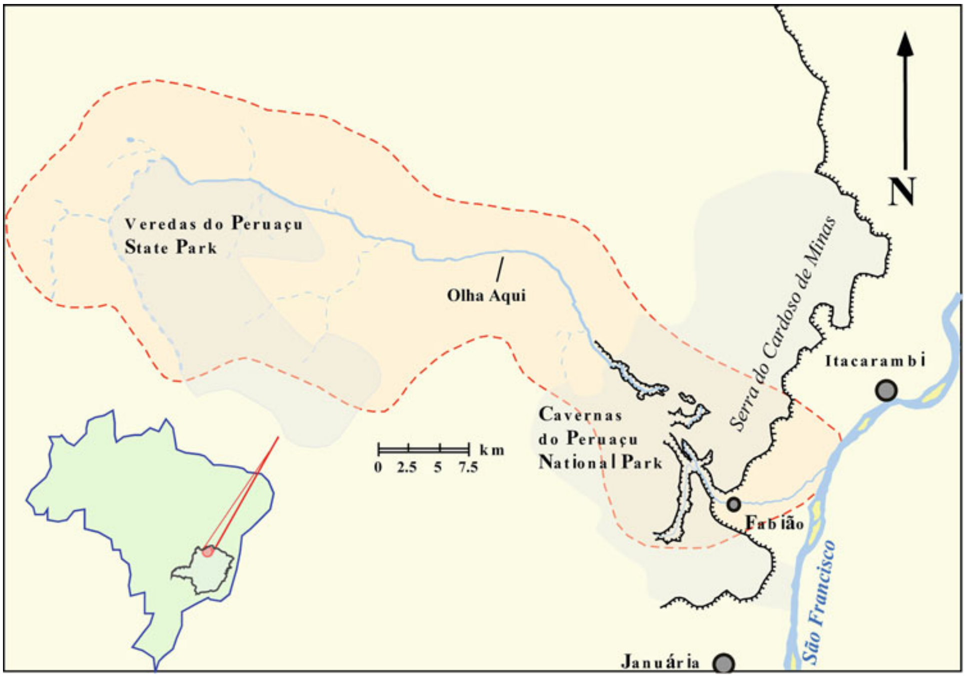

Fig. 15.1 Location of the Peruaçu basin, location in Brazil and Minas Gerais state

products, shoes, furniture, and one of the best rums in Brazil. Some changes have been implemented in recent years such as irrigation and soybean cultivation, while cotton cultivation has declined. Despite great natural potential, tourism in the area continues to be weak.

Over its 195 km^2, the basin offers a relatively simple and homogeneous spatial organization. It extends over 100 km from WNW to ESE and its width varying from about 25 km in the upstream region to about 10 km once the carbonate substratum is reached. Its altitude ranges from 830 m on the upper sandy plateau to 440 m at the confluence with the Rio São Francisco, in a large alluvial plain. From a relatively concentric spring area, the perennial stream crosses the plateau, opening a narrow corridor to the Rio São Francisco valley. The plateau is formed by sandstones of the Urucuia Formation, but the outstanding feature of the Peruaçu basin is the morphology resulting from its passage through the carbonate formations of the Serra do Cardoso das Minas, before it enters the alluvial plain of the Rio São Francisco (Piló 1989). This segment offers a spectacular landscape, including a canyon about 17 km long, carved deeply into the limestones of the Bambuí Group (Fig. 15.2a). This canyon is the feature to which the basin owes its name, "Peruaçu" meaning "great opening" or "gorge" in the Tupi-Guarani language (Silveira Bueno 2008). It is certainly one of the most grandiose karst systems of South America, located within a natural park.

Piló and Kohler (1991) suggested that the Rio Peruaçu formed an enormous cave in the great calcareous massif that extended over tens of kilometers. Collapse of walls and galleries during the Middle to Late Pleistocene contributed to the formation of karst relief (Fig. 15.2b), the major feature of which is the canyon. Regional evolution caused the walls to recede and conduits used until then by water became abandoned or opened up.

15.2 Climate

Winds from the west, south, and northeast are responsible for regional climate features (Radambrasil 1982). In autumn (April–June) and spring (September–December), the climate is governed by warm, dry winds from the northeast (tropical Atlantic climate system), generated by the South Atlantic high-pressure center. Yet winds from the south and west can perturb the system. During winter (June to August), the south polar anticyclone invades the region, causing temperature to drop and humidity to rise, and thus creating the possibility of brief rainfall. At the end of winter, the return of warm winds from the northeast again leads to warmer, drier weather. Tropical instability oscillations bring winds from the west in late spring and from the west or northwest in early fall.

Generally, temperatures are high, with minor oscillations above 20 °C throughout the year. The almost semiarid climate is very contrasted, with a long dry season. In this weather conditions, the average rainfall is 875 mm/year, too weak to impact deeply the geomorphologic features which result from a protracted Cenozoic evolution. The two main impacts are the erosion of residual hills developed in the soft cover formation and the temporary quick flow in gullies excavated in limestone outcrops only during the rainy season. The major effect on karst features is rock sliding.

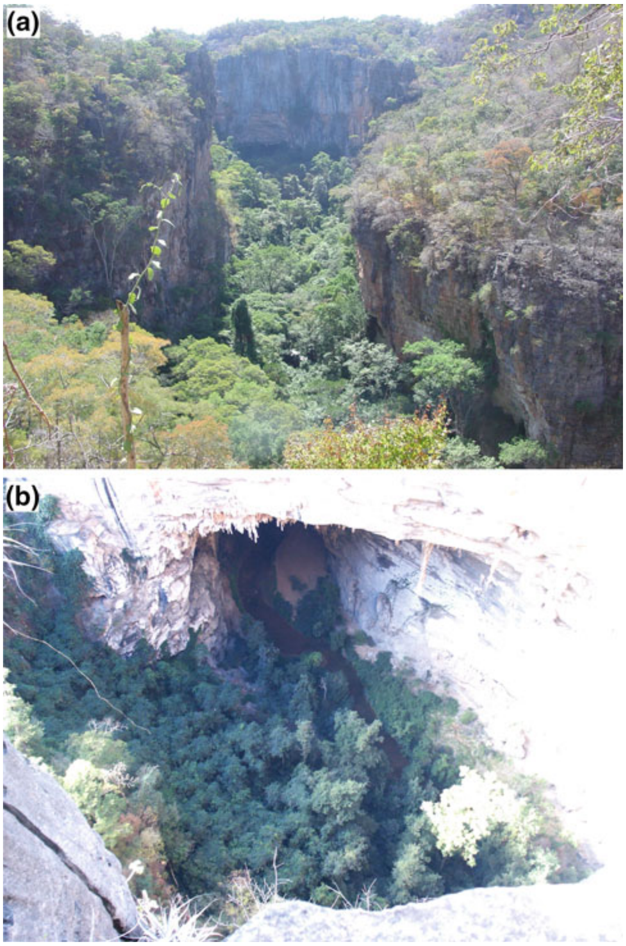

Fig. 15.2 **a** the 200-m-deep canyon between Janelão Cave (16) and Bichos Cave (18) (photograph by J. Rodet); **b** Dolina dos Macacos, 200 m above the subterranean river (photo. by J. Rodet)

15.3 Geological Context

The geological history of the region, as it relates to the evolution of karst morphology, is very long, with alternating large periods of land denudation, marine transgressions, and lacustrine sedimentation (Mantesso-Neto et al. 2004). To the west of the São Francisco valley, the stromatolithic limestones of the Neoproterozoic were deposited directly above the Archean granite bedrock. This granite cropped out as a result of the uplift of the western margin of the large Mesoproterozoic basin of the Espinhaço. The subsidence axis of the basin was shifted westward, allowing deposition of a carbonate ramp. Later on, during the Paleozoic, various episodes of sedimentation and erosion took place. Of these, there remains nothing in the region, because of epirogenesis during the Cretaceous. Pre-Urucuia peneplanation leveled the Archean granite bedrock with its Neoproterozoic carbonate cover that was partly preserved in the São Francisco graben (Dardenne 1978).

It would appear that this graben zone has always remained active, being located between an Archean craton and a block that was cratonized during the Amazonian and Brasiliano orogenies (850–500 My). The Cenozoic tectonic reworking of the São Francisco graben is a fundamental factor in the geomorphological history of the region, and particularly in the evolution of the Peruaçu karst system, for which it constitutes the base level.

Deposition of the Cenozoic Urucuia detrital formation took place above a more or less leveled substratum, but whose limestone residual outcrops could have registered an earlier karstification. Post-Paleocene tectonics reworked the faults of the São Francisco graben. The rift trough collapsed and its edges uplifted. The Urucuia Formation was then eroded and limestones emerged on the raised edges of the valley. Karstification could then resume.

On the basis of field observations and interpretation of Landsat images, we have drawn a simplified geological map of the Peruaçu basin at 1:50,000 scale (Fig. 15.3). As compared to the 1994 and 2003 versions of the general geological map at 1:1,000,000 produced by COMIG (Geological Survey of Minas Gerais State), this map shows the same stratigraphic succession, but provides a refined geological picture of the middle Peruaçu region (Pouclet 2003). Modifications mainly concern the extension of the Bambuí limestones (NP2sl) into the valley's centre, where we identified a major granite inlier. Analysis of lineaments on maps and remote sensing images, associated with field observations, makes it possible to establish a hierarchy of major faults. The following directions can be distinguished: (1) N.155° ± 10°, (2) N.0°–N.15°, (3) N.35°–N.50°, and (4) N.110°–N.125°. All faults observed show a final movement with a normal component and a strike-slip component, most often dextral for the sub-meridian and NW–SE directions.

15.4 Crossing the Limestones: A Spectacular Karst Landscape

The upper basin is developed upon an overlying deposit of sand derived from the sandstones of the Urucuia Formation (Figs. 15.1 and 15.3). Alteration has been so effective that at the surface, it is hard to find a block of solid rock. Local cerrado-type vegetation is thus xerophilic and adapted to the sandy environment, characterized by small, crooked, spiny trees. This vegetation has been markedly degraded by intensive deforestation linked to charcoal production, but over the past twenty years, its restoration has been in progress, thanks to the management of the Instituto Florestal Estadual in its “Veredas” park (30,700 ha).

Further downstream from this monotonous landscape, after crossing the central segment of the basin around Olha Aqui with its more complex geology (limestone, granite,

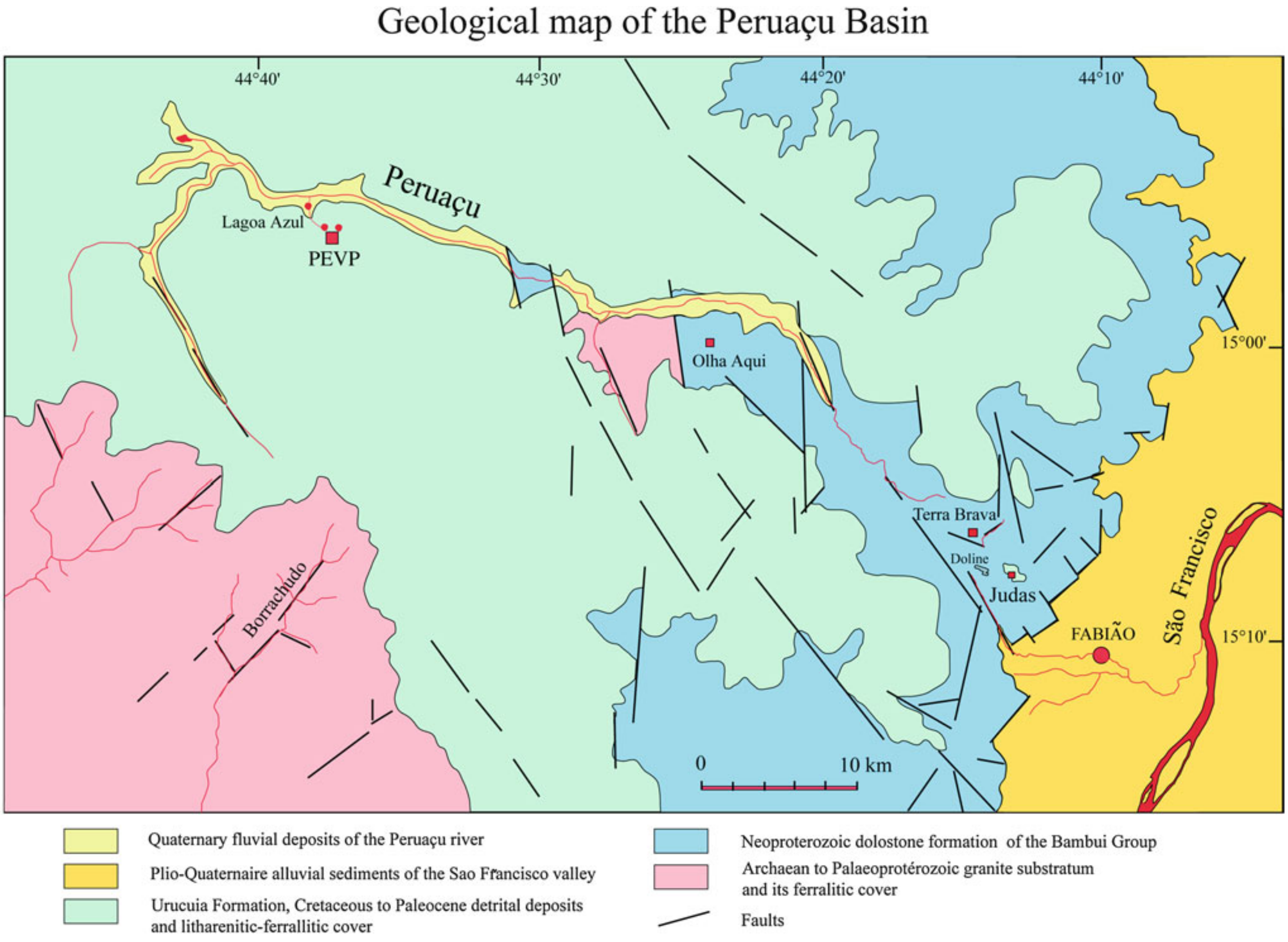

Fig. 15.3 Geological map of the Peruaçu Basin (after Pouclet 2003). *Red squares* locations cited in the text; *red circles* lakes and ponds; *red lines* surface drainage network

faulted bedrock), one gradually enters the canyon to which the basin owes its name, a spectacular domain of karstified limestone (Fig. 15.4a). In addition to the famous 17-km-long canyon interrupted six times by imposing tunnel-caves, one can note the development of numerous underground caverns, while residual landforms at the surface include towers, hums, lapiaz, dolines, chasms, rock shelters, and poljes (Fig. 15.4b). Epigene streams are rare, and many sloping ravines function only when it rains.

This segment is characterized not only by its karst relief (rock shelters, caves, deep canyon, dolines, ravines…), but also by intense human occupation (about a hundred prehistoric sites) that has probably been constant since the Pleistocene/Holocene transition. The area is partially integrated into the Cavernas do Peruaçu National Park (56,900 ha). Linked to the limestone formations, one notes the presence of bromeliads and gameleira trees (*Ficus insipida*), whose deep roots insert into the fissures of the substratum. On limestone outcrops, deciduous vegetation (caatinga) is present, harboring a specific fauna, notably the mocó (*Kerodon rupestris*). Other animals, such as the collared peccary (Tayassu tajacu), are endemic to the sector's gallery forests. This area is also visited by many other animals, since it is a passageway between the high valley and the alluvial plain (IBAMA 2005).

We can divide the canyon in five sectors as follows:

(a) Entrance to the Canyon from upstream
Following the flow (Fig. 15.5), one observes at the entrance to the canyon a large flooded surface with a seasonal marsh (Silu), surrounded by cliffs pierced by karst caves of all sizes. Worth mentioning on the left bank is the Lapa do Carlucio (1 in Fig. 15.5), studied for its fossil fauna (Mascarenhas 2008). On the right bank, there are the Lapa do Caboclo (2), Lapa das Abelinhas, Lapa dos Morcegos, Lapa dos Ossos, and Lapa do Cavalho (3), revealing a more complex endokarstic development than the Brejal cave–tunnel (4), where the Rio Peruaçu flows underground over more than a kilometer. The stream disappears in this way six times before reaching the São Francisco valley.

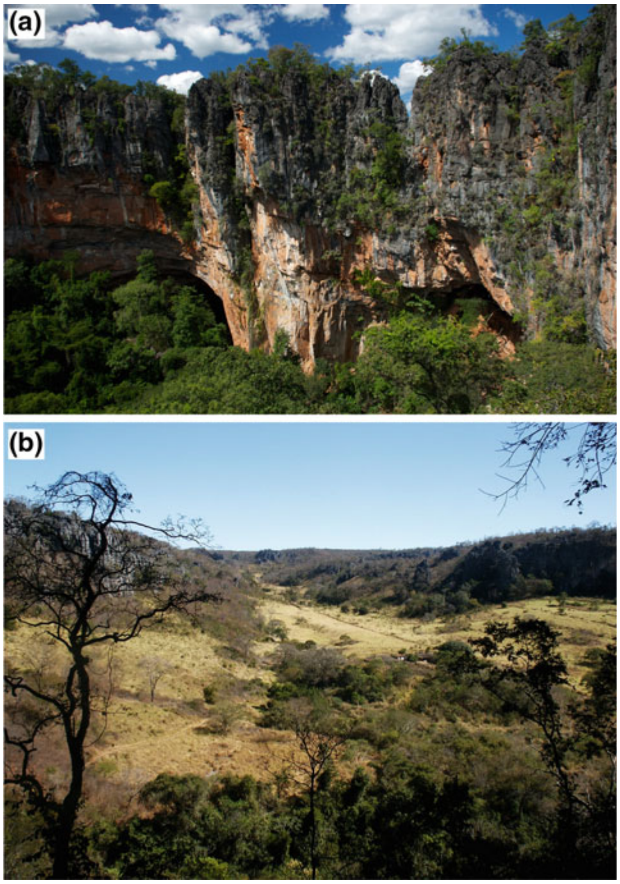

Fig. 15.4 **a** The dual entrance of the Arco do Vento, with its exokarst features (karrens, towers, etc.) (photo. by A. Coelho); **b** The Terra Brava paleo-polje with its two main levels (photo. by J. Rodet)

(b) The Upper Canyon
After the underground passage through the Lapa do Brejal (4) with its wide section, the stream flows again in open air in the middle of a valley, where steep slopes are interrupted by residual towers and vertical cliffs. Twice it passes under residual arches, the Arcos do Vento (5) (Fig. 15.4a) and Arco do André (6), both a testimony to the fact that Rio Peruaçu once flowed underground at this location. This is the segment that is hardest to access and least known. Beyond, one reaches two smaller tunnels with a roughly rectangular section, the Lapa do Cascudo (7) and Lapa dos Troncos (8), which extend below a small canyon.

(c) The Terra Brava Polje
When the river again emerges in open air, the Rio Peruaçu offers a waterfall 2 m high, before reaching the Terra Brava polje of roughly triangular shape (Fig. 15.4b). The polje is typified by a flat upper level with several caves opening onto it: Lapa Bonita, Lapa do Suspiro, Lapa do Indio (12), Falso Janelão (13), and Janelão superior (15). Into this level, a flat lower level is carved and it bears an old farm, supported by a residual hum Antônio Cardoso (14), bordering the modern notch of the Rio Peruaçu. This polje is thus complex and multiphased.

(d) The Janelão Greatest Cave
Downstream lies in the largest underground complex, the Lapa do Janelão (15), explored over about 5 km of galleries (Fig. 15.6).

(e) The Straight Lower Canyon
From this complex, the stream re-emerges into the lower canyon leading to the São Francisco valley (Fig. 15.2). This is the zone of confluence with the Rio dos Sonhos (22) and with the Boqueirão (21)-Malhador (20) valley.

The complexity of the Peruaçu karst system is due to its long evolution. One must distinguish the main exogenous drainage axis and secondary endogenous drainage axis (Fig. 15.5). The main axis, illustrated by the canyon, is a fluviokarst (Piló 1997). Lateral discharge is primarily from the ravines, and any active emergences, notably upstream from the canyon, are very discrete. The hydrochemical studies by Mascarenhas (2011) highlight the low level of exchange between the water flow and its carbonate encasement. The flow volume is low. In the Lapa do Brejal (4), it averages less than 90 m/h. In other sections, the water flows faster, but the flow rate remains well below the drainage capacity of the system.

However, as in the case of the Vale dos Sonhos (22), one should note that the current karst drainage feeds epigene flows or emergences that do not converge toward the canyon. For example, springs at the foot of the Serra do Cardoso das Minas feed flows toward the São Francisco plain (Fig. 15.5), as the Lapa Olhos d'Água (Auler et al. 2001), etc. The chemical signature of the Rio Peruaçu differs from that of the Rio do Vale dos Sonhos. Along the former, there is no trace of travertine formations, whereas they can be impressive (several meters thick) along the Rio do Vale dos Sonhos (22), creating subhorizontal levels in the longitudinal profile of the river. Today, one can no longer speak of a single Peruaçu hydrokarst system, but of several independent systems.

15.5 A Complex Geomorphological Evolution

As the upper section offers no relief and is limited to the sandstone formation, no significant geomorphological evolution can be discerned. It is thus necessary to look at the other sectors, particularly the canyon. According to previous studies (Rodet and Rodet 2001; Rodet et al. 2003a, b), we display a model comprising three major chronological stages, with some overlap between episodes (Fig. 15.7). The first stage named Janelão I is related to the initiation of a

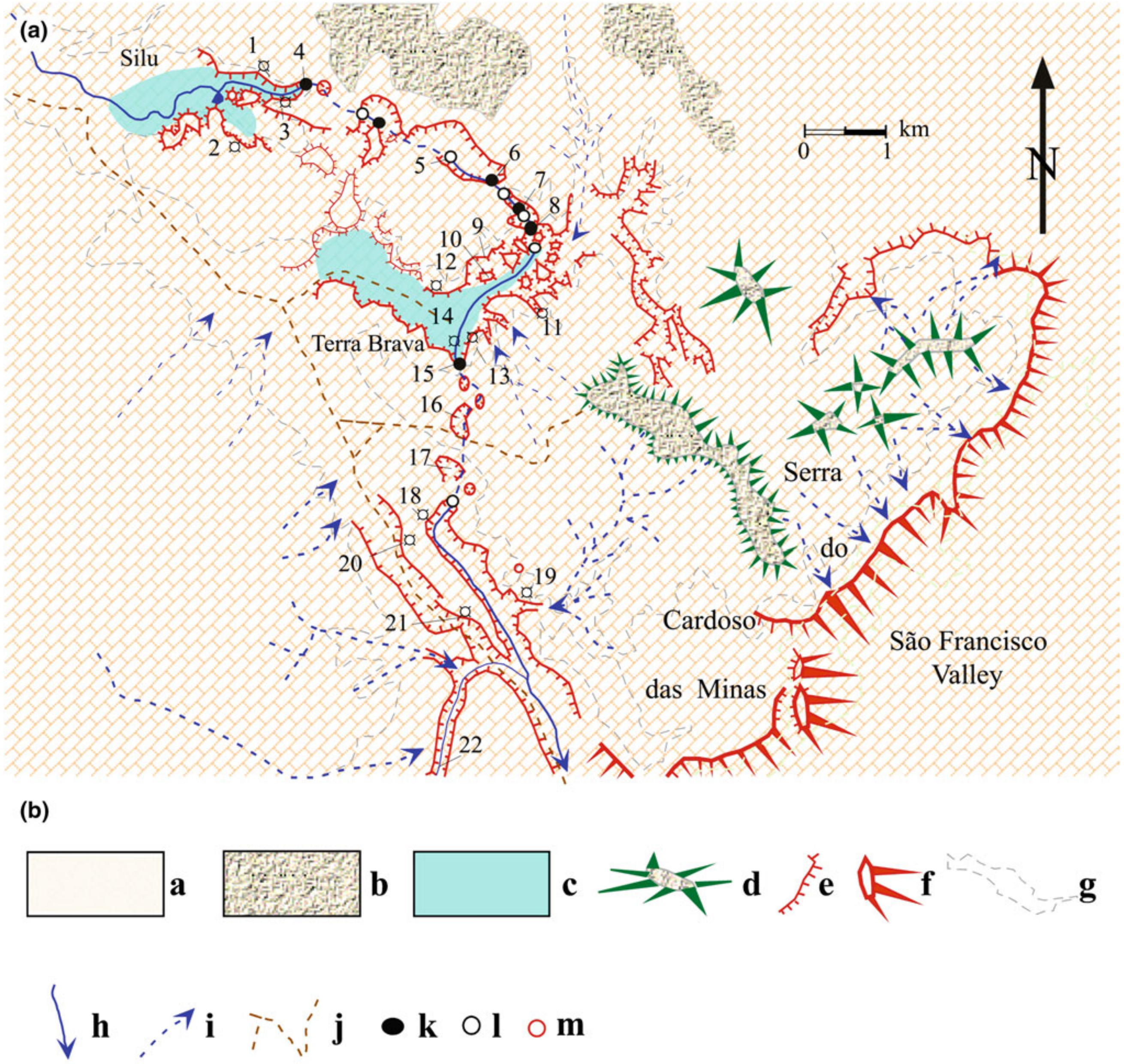

Fig. 15.5 Peruaçu karst canyon. Location of the main sites mentioned in the text. **a** Bambuí limestone; **b** Urucuia cover; **c** paleo-polje; **d** Urucuia residual hill; **e** small escarpment; **f** large escarpment; **g** 700 m asl elevation line; **h** perenne river; **i** seasonal creek; **j** main vehicle track; **k** swallow hole; **l** spring cave; **m** shaft, vertical doline

large karst network of the draining system. The second stage consists to flooding and filling of this network together with sinking of karstic depressions or poljes in several protracted phases. This stage is named "Terra Brava" after the most impressive depression. The third stage named Janelão II consists in a major and sudden lowering of the base level. The draining system is crosscut and reorganized along a single axis (Rodet et al. 2009).

15.5.1 First Stage: Janelão I

An original underground drainage network must have developed as a dense and anastomosed system with confluences and diffluence (Auler et al. 2005). It was moderately hierarchic (with several master caves), a sign of drowned low-energy karstification. Relicts from this first karstification period are numerous:

Fig. 15.6 The Janelão main gallery, a 100-m high complex conduit (photograph by J. Rodet)

- Downstream, between Terra Brava (14) and the São Francisco valley, one observes several caves with large sections, isolated in the current topography but which must have formed a network. These include the Lapa do Rezar (19) and Lapa dos Bichos (18) (Fig. 15.8), each limited upstream by collapse of the cave roof; the underground Janelão ensemble (15), at least the upper part of the mega-gallery, including the Minotauro diffluence (Chabert et al. 2003) and the Dolina dos Macacos (16), which is actually a canyon resulting from the collapse of a primitive Rio Peruaçu master cave (Fig. 15.7), the upper entrance of the Janelão sinkhole, and the various underground passages accompanying the dolines opening into the Janelão drain (Moura 2001). The base of these various features, practically all on the same level, roughly indicates the altitude of the original drainage system.
- In the depression of the Terra Brava (14), which was not yet open, this drainage level is indicated by numerous relict caves: Falso Janelão (13), Indio, Suspiro (12), Bonita (Rubbioli 1999c), Pimpo II (10), Boquete (9), Desenhos (11), etc., which must be part of the same network.
- At the level of the Lapa dos Troncos and Lapa Cascudo (Rubbioli 1999b), which did not yet exist, a hanging canyon illustrates this first drainage level. This canyon may have formed from a primitive underground gallery.
- Further upstream, the Arco do André (Rubbioli 1999b) and Arcos do Vento (Fig. 15.4a) indicate this primitive level with a set of residual drains, to be found also in the Lapa do Brejal (Rubbioli 1999a). Upstream from this large cave, on both sides of the current Silu flood zone, one can see the Lapa do Carlúcio (1) on the left bank, and the Lapa do Caboclo (2), Lapa dos Morcegos (3), Lapa dos Ossos (3), and Lapa do Cavalo (3) on the right bank, to mention only the major ones.
- In the adjoining valleys, much less studied, the large Malhador shelter (20) is certainly a relict cave from this

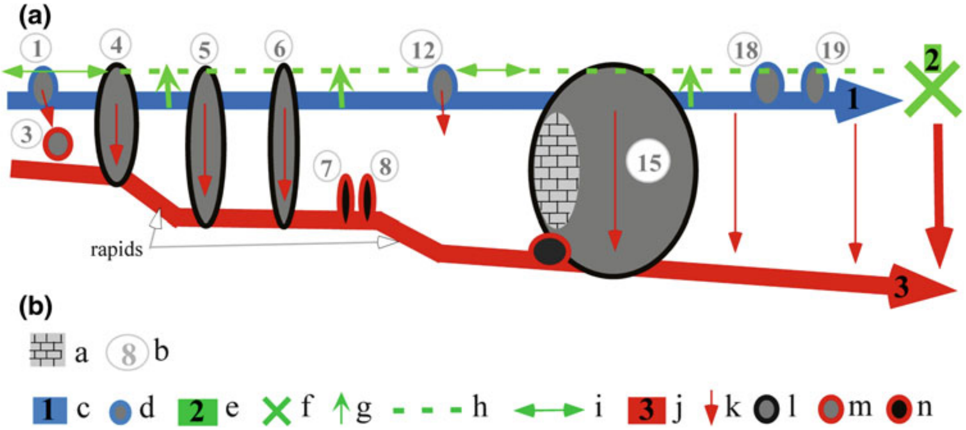

Fig. 15.7 Theoretical model of karst evolution. **a** calcareous substrate; **b** karst feature number mentioned in the text; **c** first karst stage or “Janelão I stage”; **d** operational cave drain during the Janelão I stage; **e** second karst stage or “Terra Brava stage”; **f** damming effect; **g** upward water level (waterlogging); **h** gallery infilling phase; **i** polje opening upstream: Silu (1); downstream: Terra Brava, between (12) and (16); **j** third karst stage or “Janelão II stage”; **k** downward water level with dynamic regressive erosion; **l** current flow gallery adapted from the first karst stage; **m** current inactive gallery adapted from the first karst stage; **n** third-stage swallow gallery of the Janelão Cave

Fig. 15.8 The Bichos Cave, large fossil gallery testimony of the "Janelão I stage" (photograph by J. Rodet)

phase. Several caves of the Vale dos Sonhos must also belong to this phase. Note that the major part of this initial maze, particularly upstream in the transition compartment, has been erased by erosion and is present in the form of cliff recesses, hanging conduits, dells, and depressions invaded by vegetation. Only the major drains contribute today to a vague, nonfunctional hydrographic network.

15.5.2 Second Stage: Terra Brava

Damming by collapses of roof and wall downstream from the underground network resulted in flooding of low-lying zones and the creation of poljes (Terra Brava–14). Dam formation led to dynamic geomorphological adaptations, temporally and spatially staged, and the delay increasing with the distance of the studied point from the dam. This resulted in downstream-to-upstream terracing of flood landforms. The main consequence was decreased flow dynamics, leading to the deposition of alluvial sediments (finer and finer in the upstream direction) on a coarser basal layer, to the setting of flood zones and wandering channels for upstream flows and to peripheral extension of the poljes. Downstream, where the water table rise was earliest and greatest, classically there appeared equilibrium chimneys within the underground drains. On the roof of such a shaft, a horizontal drain could have developed (duplication of the conduit). Upstream, where the consequences of damming occurred later and were more discrete, ceiling half-tubes could have developed in the original drain, especially if the fossilization phase occurred before the water table rose.

Signs of flooding are numerous. The most common are red terrigenous infills covering the speleothems (e.g., the Lapa Bonita–12), associated with equilibrium chimneys: Lapa do Boquete (9), Dolina da Onça caves (17), etc. (Moura 2001). There are also many signs of clasto-alluvial filling: lithified paleo-deposits in the Lapa dos Bichos (18), Lapa do Janelão (e.g., the Galeria do Minotauro–15), Abrigo do Malhador (20), Lapa dos Desenhos (11), Lapa do

Carlúcio (1), etc. It clearly appears that there was not just a single flooding episode but several successive ones, including two major episodes that had an impact on the Terra Brava polje (Fig. 15.4b).

Signs of the opening of the Terra Brava depression (14) are diverse and include more than 10 m of fine lacustrine sediments, with wandering channels, upstream from the Lapa dos Troncos (8), basal notch of the small left-bank cliffs, associated with an alluvial terrace deposit between Troncos and Terra Brava, the residual Antônio Cardoso inselberg (14) covered with the lacustrine deposits of Terra Brava, the upper and lower levels of Terra Brava, the paleo-terrace with sand and pebbles below the upper entry Janelão ponor, etc. Lastly, one can envisage that this infill, responsible for the rise in the water table, might have also been responsible for the creation of ceiling half-tubes and/or upper drains, as found in certain caves of the Silu flood zone (Carlúcio, Ossos).

15.5.3 Third Stage: Janelão II, a Fluviokarst

The flow subsided to a 50 m lower level causing a major process of retrogressive erosion, thereby eroding and remodeling the old drains. The cause is located in the São Francisco valley and seems to be due to sudden collapse of the graben floor. The consequences of this major, rapid subsidence phase are as follows:

- conduits were left hanging,
- partial clearing of drains,
- fissure-guided carving (with shortening) of a new, straight canyon between Fabião and the resurgences of the Lapa do Janelão,
- concentration of flows along a single axis, from the Brejal to the Janelão, and abandonment of secondary axes such as the valley that connected Silu to the confluence with the Rio dos Sonhos (22), via Malhador (20) et Boqueirão (21), creating fluviokarstic dynamics,
- adaptation mechanisms, with drainage subsidence toward the water table through suffosion and scour. The morphoclastic evolution of the canyon caused damming, leading to localized and temporary phases of flooding up to present time, but whose geomorphological traces remain slight because of the brevity of these episodes. This is the case of the flooding between the Arco do André (5) and the Lapa do Brejal (4), studied by Coelho et al. (2011) and evidenced by the presence of floated plant trunks (Rubbioli 1999a, p. 37), or of the flooding further upstream in the Lapa do Carlúcio (1) (Mascarenhas 2008).
- acceleration of the flux, remodeling the main drain and transforming the canyon into a privileged flow axis, generating a fluviokarst.

The signs of subsidence of the water table are numerous along the course of the Rio Peruaçu. At the downstream end, the subsidence of the water table gave rise to the greatest difference in height, sometimes exceeding 50 m, this being the site of the longest exposure to the effects of subsidence. In this section, one often observes duplication of the drain and disconnection of the modern drain from the primitive one. The latter displays “paleokarst”-type elements, isolated when the modern drain was carved out. In the Peruaçu system, this evolution is illustrated by the isolated mega-drains of Rezar (19) and Bichos (18) and also the capture mechanism of the flow of the Abrigo do Malhador (20) by leaks through the pass of the previous Boqueirão cave (21).

The disjunction point between the two “Janelão” morphodynamic stages is evidenced by the following elements. In the downstream part of the Janelão cave, the mega-gallery runs up against a huge, largely calcified rock slide at the downstream part of the drain, while at the foot of the gallery, two smaller openings lead to the modern canyon isolating the primitive drains of Bichos (18) and Rezar (19).

The mega-gallery of the Janelão reaches exceptional dimensions: 106 m in height and 60 m in length (Fig. 15.6). Examination of the drain reveals (i) remains of cemented infill stuck to the walls several meters above the ground, (ii) the diffluent gallery of the Minotaure (Chabert et al. 2003), hanging more than 30 m above the stream bed, and (iii) all lateral galleries or openings of the main drain hang tens of meters above the current bed, including the Dolina dos Macacos (16), which is in fact a canyon (Fig. 15.2b).

The mega-gallery actually results from duplication of the drain (Fig. 15.6), which reaches its utmost dimension without resulting in disjunction, as attested by the superimposition of two drains on successive levels, the upper, primitive fossil drain and the new drain through which the stream runs. This can be seen at the ponor where the Peruaçu penetrates upstream into the Lapa do Janelão (Figs. 15.5 and 15.7). The cave can be accessed via an upper opening, distinct from the relatively small ponor which contrasts with the gigantic dimensions of the drain immediately downstream (Rodet et al. 2005).

At the periphery of the Terra Brava polje (14), the Bonita-Suspiro-Indio cave ensemble (12) offers elements indicative of chronological evolution of the depression. The well-developed caves underwent a fossilization phase, with intense speleothem formation in the drains. Then, the underground cavities underwent a flooding phase that buried the lowest stalactites and caused partial dissolution of speleothems by floodwater. This phase was contemporaneous with the upper level of the two flat extensions of the Terra Brava polje (fine reddish sediments forming flat ground). In the third phase, emptying of the polje occurred, causing the fine elements accumulated in the drain to be carried away through suffosion and drying (Indio cave is suspended above the depression, one notes racking of sediments in Bonita cave, and terrigenous relicts in Suspiro cave, etc.). These caves are no longer active and are disconnected from the Rio Peruaçu drainage system.

Upstream from the Terra Brava depression, below a canyon (an initial drain re-carved by the topography), one can observe a new drain of smaller dimensions than the Janelão. It consists of the Cascudo (7) and Troncos (8) caves located immediately upstream from the first rapids. These rapids show that the stream has not yet re-equilibrated its longitudinal profile. The cumulative height of the canyon and of the newly formed drain is smaller than that of the Lapa do Janelão.

Upstream, relict endokarst elements (Arco do André–6, Arcos do Vento–5; Fig. 15.4a) alternate with widely open canyon segments where rapids are more numerous but of lesser amplitude, before reaching the Lapa do Brejal (4) whose basal incision is only a few meters and whose base is greatly encumbered with terrigenous sediments. The secondary drains of the Brejinho appear several tens of meters above the modern stream.

Upstream from the Brejal, around the large Silu flood zone, the canyon is flanked by two sets of caves, Carlucio (1) on the left bank and Ossos/Abelhas (3) on the right bank. These two ensembles display signs of subsidence of the water table from an upper level to a level 20–30 m lower, from drains with a large cross-section (1–3 in Fig. 15.7). Further upstream, we exit the canyon and the morphological elements become less evident and harder to interpret. No significant data are available because the water table variations were very small and exploration of the caves has not yet been completed.

Even in the Vale dos Sonhos (22), tributary of the Peruaçu, there is a 22-m difference in level between the emergence and the basal platform, in the narrow passage duplicated by a high, narrow cave with several drainage levels and a spectacular ceiling half-tube. This difference is highlighted by many temporary dams generated by abundant accumulation of biochemical travertine.

What caused subsidence of the water table? It seems that one can rule out a local cause, as Bitencourt (1998) and Bitencourt and Rodet (2001, 2002) observed a water table subsidence of the same magnitude (40–50 m) in the Morro Furado Canyon (Serra do Ramalho), 200 km further downstream in the state of Bahia. This canyon is also a tributary of the Rio São Francisco. It thus seems logical to envisage a regional cause, on the scale of the São Francisco basin, in its mid-lower part (state of Bahia). Brazilian structural geologists have identified several tectonic phases (Saadi 1991) that might have caused this major activity of the graben (Lopes 1981). This infra-plate tectonic activity is still ongoing, with several earthquakes since May 2007 reaching a magnitude of 3.5–4.9 on the Richter scale (França and Barros 2007), with some epicenters located in the Peruaçu basin.

15.6 Conclusions

The Rio Peruaçu basin is a spectacular example of karst system evolution accompanying the Cenozoic history of the Rio São Francisco valley, resulting from interrelations between the carbonate substratum, tectonic re-shifting of the graben, and climate forcing. It offers an illustration of karst evolution with its major initial phases, its juvenile organization, its mature concentration along a fluviokarstic axis with spectacular morphologies, and its relicts of abandoned and disconnected paleokarst. The result is a unique, grandiose, highly diverse landscape that struck the imagination of its first inhabitants. These people decorated many rock shelters, buried their dead there, hunted, camped, looked for stone material with which to make their tools, and crossed the great canyon to seek upstream, on the sandstone Veredas plateau, the products needed for their well-being. In their eyes, it became the "Peruaçu," the same "Peruaçu" that attracts tourists and researchers from Minas Gerais, from Brazil and beyond, even from the other continents. This is why the Parque Nacional Cavernas do Peruaçu was created.

Acknowledgments In memory of two great friends, Helena David (1955–2010), speleologist of the heart depths and Claude Chabert (1939–2009), leader of the survey project of the Janelão Cave. We wish to thank everyone who helped us access information and locations, in particular the IEF (State Institute for Forests) and its manager of the "Veredas do Peruaçu" State Park (João Roberto), the IBAMA and its Fabião office (Emerck Cipriano, Danilo, Flavio), and the Grupo Bambuí de Pesquisas Espeleologicas who enabled us to discover the underground Peruaçu (Luís B. Piló, Augusto S. Auler), without forgetting the friendly and unconditional support of Sueli Aparecida do Nascimento.

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Lagoa Santa Karst: Cradle of Brazilian Cave Studies

16

Augusto S. Auler and Luis B. Piló

Abstract

The Lagoa Santa Karst is the best known karst area in Brazil and has been studied since the early 1800s. This area is developed over Precambrian limestone of the Sete Lagoas Formation, Bambuí Group, and displays scenic surface karst landforms, especially limestone cliffs, karst lakes, and karst plains, in addition to numerous solution dolines. Thick soil sequences derived from overlying phyllites cover a significant portion of the karst, but exhumation is presently taking place, exposing karst outcrops with subsoil karren features. Karst hydrology is primarily autogenic, with short groundwater flow routes. Limestone outcrops are vertically dissected, exposing ancient paragenetic caves intersecting cliff faces. More than 700 caves are known in the area, the majority of which are short (<100 m long) with abundant sedimentation. The area's early fame derived from the remarkable Pleistocene fossil remains excavated by pioneer Danish naturalist Peter Wilhelm Lund. This material is derived primarily from cave breccia and has formed the basis of vertebrate paleontology in Brazil. U-series and radiocarbon dating yielded fossil ages between Late Holocene (~9 kyr B.P.) and mid-Pleistocene (>350 kyr). Lund was also the first to describe ancient human remains frequently found in caves and rock shelters. Lagoa Santa is now known to contain hundreds of archaeological sites dating from the Early Holocene/Late Pleistocene and has been at the center of the debate on the origin and age of human colonization in the Americas. The Lagoa Santa Karst faces severe environmental threats due to limestone mining and the expansion of the metropolis of Belo Horizonte and its surrounding towns. A number of preservation areas have now been established, improving the conservation status of this landmark Brazilian karst area.

Keywords

Lagoa santa • Karst • Caves • Paleontology • Archaeology

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16.1 Geographical Location and Geological Setting

Karst terrains in Brazil develop primarily over Precambrian limestone and dolomite in a cratonic environment. Among the many karst regions, the Bambuí Karst is by far the largest, covering approximately 105,000 km^2, over one-half of all carbonate karst areas in Brazil (Auler 2004). The Lagoa Santa Karst (Fig. 16.1) is arguably the best studied karst area in Brazil, with a rich and diverse assemblage of surface and underground karst landforms (Fig. 16.2), many of which contain internationally significant paleontological and archaeological remains. The importance of the Lagoa Santa Karst was first brought to the attention of the world through the studies of Danish naturalist Peter Wilhelm Lund (1801–1880). Lund first arrived in the area in 1833 and remained there until his death. He examined over 1,000 caves, with an emphasis on paleontological remains.

The Lagoa Santa Karst is located in south central Minas Gerais state, approximately 30 km north of the metropolis of Belo Horizonte (the state capital with a total population exceeding 5 million), with its core area encompassing the municipalities of Lagoa Santa, Pedro Leopoldo, and Matozinhos. The average annual rainfall at the Pedro Leopoldo meteorological station reaches approximately 1,300 mm. The mean annual temperature at Lagoa Santa is 23 °C. The highest temperatures during summer are in the upper 30s, and the lowest temperatures during winter reach approximately 7 °C. The original vegetation in the area has been substantially modified since the arrival of the first settlers in the late 1600s. Currently, grasslands used as cattle pastures predominate in most of the region, although limestone outcrops, and several dolines still harbor patches of deciduous forest.

In the area, the Bambuí Group is represented by its two major basal formations. The carbonate rocks of the Sete Lagoas Formation and the pellitic Serra de Santa Helena Formation form most of the outcrops. The Sete Lagoas Formation can be separated into two members. The lower Pedro Leopoldo Member is characterized by impure limestone with intercalations of fine-grained clastic rocks, whereas the upper Lagoa Santa Member is of purer

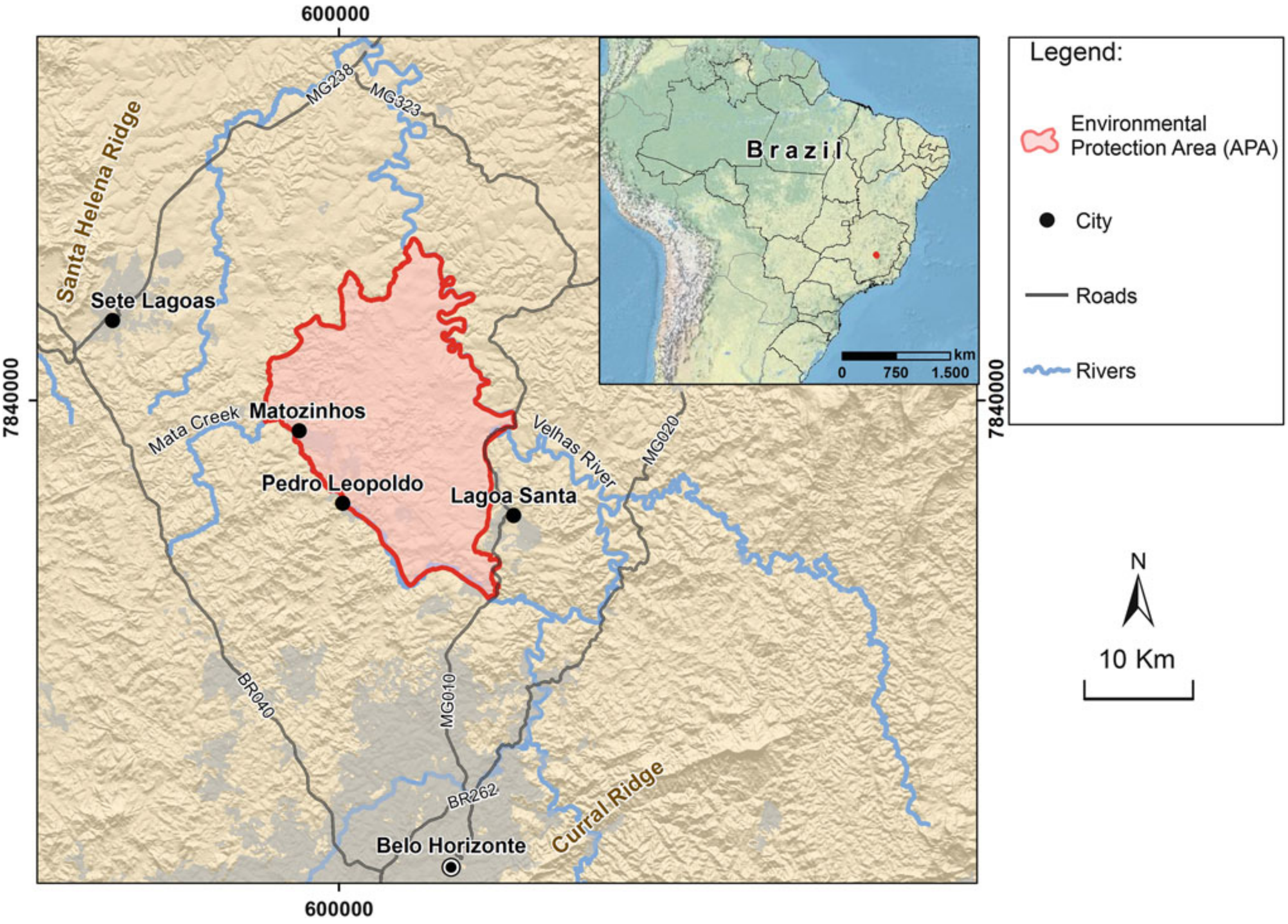

Fig. 16.1 Location of the Lagoa Santa Karst, showing the limits of the environmental protection area of the Lagoa Santa Karst

Fig. 16.2 The Cerca Grande limestone cliff and caves, an important speleological, paleontological, and archaeological site. *Photo* by Ataliba Coelho

limestone. Chemical analyses reported by Piló (1998) show a marked increase in silica and decrease in calcium carbonate in the lower Pedro Leopoldo Member. The thickness of the limestone varies between 250 m in the highest elevations and approximately 50 m in the lowermost areas. The Serra de Santa Helena Formation comprises mostly phyllites and siltites. The limestone shows a well-marked joint pattern produced during the Brasiliano orogenic event (c. 550 Myr). The more common joint directions are N10-28E and N50-69E. The carbonates have thin, nearly horizontal laminations. Dips in the area normally do not exceed 5°.

The Lagoa Santa Karst is essentially an autogenic karst with only limited allogenic water from phyllite areas to the north. The area lies in a water divide zone between the Velhas River and Mata Creek at elevations of 650–900 m. Discharge measurements in several springs have shown that approximately 88 % of karst groundwater discharges toward the Velhas River, the remainder draining toward Mata Creek (Auler 1994). Karst landforms are concentrated in two distinct, more elevated areas drained by Palmeiras and Samambaia Creeks, both tributaries of the Velhas River, and in the low-elevation Mocambeiro Depression, which separates these areas.

16.2 Surface Karst

The tropical Lagoa Santa Karst shows well-developed karst topography (Fig. 16.3). It can be described as an exhumed karst in which both phyllite and soil cover have been eroded to expose the denuded karst topography. Small-scale dissolutional forms (karren) are widespread in the area. Rillenkarren and rinnenkarren occur in the denuded high portions of several hills. The most frequent karren type is the joint karren (Tricart 1956; Knez et al. 2011) which develops as horizontal shallow alveoles along horizontal bedding or foliation planes. Most likely, this type of karren has an initiation in the subsoil zone. Kamenitzas have also been observed in selected outcrops. Subsurface karren can be observed in many quarries throughout the area. They can form sediment-filled depressions up to 5 m deep, amid an assemblage of irregular rounded pinnacles (Fig. 16.4). These subsoil towers (hums) are only partially exposed in most places, forming small knobs of limestone.

Dolines are well represented in all karst domains, especially in the High Plains. Dolines range from a few meters to more than a hundred meters in width, and their depth is usually less than half the total width. Dolines usually contain a limestone outcrop at one side, resulting in an irregular shape and profile. The soil-filled doline bottoms are commonly used for agriculture. Dolines in the Mocambeiro Depression are large and shallow and are usually filled by temporary lakes. The density of dolines increases with elevation.

Imposing limestone cliffs are the most characteristic landforms in the area (Coutard et al. 1978). They comprise abrupt vertical to nearly vertical cliffs up to 60 m high, usually along the margin of asymmetric dolines. Lakes and caves are common at the cliff base (Fig. 16.5). The genesis of these features is interpreted in terms of the process of differential dissolution by a swallet or lake (Journaux 1977). Orientation of cliff faces is related to major joints and is approximately perpendicular to groundwater flow routes (Auler 1994).

Fig. 16.3 Denuded limestone outcrop showing subsoil karren and incipient rillenkarren. *Photo* by Ataliba Coelho

Fig. 16.4 Irregular pinnacles with joint karren in a recently exposed limestone outcrop. *Photo* by Ataliba Coelho

16.3 Caves

More than 700 caves have been identified in the Lagoa Santa Karst. In general, these caves are short sections of much longer systems that have been exposed or segmented by doline deepening and general surface and valley lowering (Fig. 16.6). The majority of caves are dry passages that occur at the bottom of dolines or at the base of limestone cliffs. Network caves are frequent and are usually associated with lakes (Auler 1995), but by far the most characteristic cave pattern in the area is an anastomotic maze, usually comprising tall and narrow meandering canyons with smooth walls that tend to intertwine with others of a similar type.

As in the case of many caves in eastern Brazil, the bedrock floor is nearly always masked by sediments, preventing determination of the true height and morphology of the passages. Based on the exposed sections, the canyon passages are usually triangular in shape. The canyon heights can reach up to 15 m but are usually less than 10 m. The ratio of

Fig. 16.5 Caetano Cliff and lake. This cliff contains Caetano Cave, in which important human remains were found. *Photo* by Ataliba Coelho

Fig. 16.6 Túneis Cave, showing smooth paragenetic walls and pendants. *Photo* by Ataliba Coelho

height/width of the passages is usually greater than 3 (but exceptions exist). The passage walls are very smooth and scallops are normally absent. The sinuosity due to meandering at the ceiling generally tends to be attenuated downward along the passage walls, and the meandering curves are usually not obvious at the floor level. There is no joint control at the ceiling level. Smooth curved surfaces dominate the walls. Pendants, parasitic wall tubes, and small anastomoses are common. In many caves, closely spaced meandering canyons can be joined together by breakdown along horizontal joints. This feature appears to be a common way of generating larger passages in the area.

Morphological evidence suggests that the initial and major stage of speleogenesis involved paragenesis, as proposed by Coutard et al. (1978). Following the draining of a cave, cyclic episodes of clastic and chemical sediment input and removal occurred, controlled by paleoclimate oscillations (Auler et al. 2009), and further paragenetic features were generated, together with a complex assemblage of sediment sequences (some fossil-rich) intermixed with calcite deposits. Timescales of cave development are not easy to determine, because the deposits are older than the U-series dating method. Based on regional denudation rates, a Late Tertiary age is assumed for cave initiation.

16.4 Paleontology

The fossil remains from the Lagoa Santa Karst caves have been subject to systematic studies since Peter Lund's first excavations in the area. Later reviews by Winge (1888–1915), Paula Couto (1970), and Cartelle (1999) have expanded the knowledge of vertebrate paleontology from the cave sediments. Although extensive excavations by saltpeter miners have made the recognition of the original stratigraphy difficult, observations (including Lund`s original excavated material) suggest that fossils are usually found intermixed in coarse cave breccia with an indurated clayey matrix. The bone content of terrigenous matrix shows high intra- and inter-site variations, with no clear increase near entrances. Bones are usually fragmented, and articulated skeletons represent an exception. As suggested by Lund (1845), the majority of the fossiliferous sediments were brought into the cave by runoff, either from doline slopes associated with cave entrances or from former swallets. Pitfall deposits have also been identified (Hubbe et al. 2011), although they represent a less frequent mode of bone emplacement. The presence of several calcite layers intercalated with bone-rich matrix indicates the complexity of such deposits, with no synchrony between caves or even between sites within the same cave (Auler et al. 2006). Dates obtained through collagen radiocarbon dating (Neves and Piló 2003) and U-series in calcite associated with bones (Auler et al. 2006) show that fossil ages can vary from the Holocene/Pleistocene transition to older than 350 kyr B.P.

The fossil remains from the Lagoa Santa Karst caves have received worldwide attention. This attention has been not only due to many new megafaunal species described but also to the heavily debated assertion by Lund (1845) that the extinct Pleistocene fauna coexisted with humans (see review in Piló et al. 2005), a hypothesis later confirmed by modern studies (Neves and Piló 2003).

16.5 Archaeology

The Lagoa Santa Karst contains hundreds of archaeological sites. It is a key area for the understanding of early human colonization in South America. Peter Lund discovered the largest collection of Early Holocene human skulls ever to be found in the Americas in Sumidouro cave (Fig. 16.7) in September 1843. He then proposed that the date of human arrival in South America was much older than previously thought and that humans had coexisted with the extinct megafauna. Since Lund, major archaeological excavations have been performed by various groups. All sites tested or excavated at the area have shown skeletal remains of considerable antiquity, making Lagoa Santa one of the few regions in which studies on early human colonization can be carried out from a populational perspective (Araújo et al. 2012). Up to now, approximately 300 human skeletons have been exhumed, including the well-known "Luzia," a female

Fig. 16.7 Sumidouro lake and cliff. Sumidouro Cave lies at the cliff base and remains flooded during most of the year. *Photo* by Ataliba Coelho

Fig. 16.8 Rock art at Capão das Éguas rock shelter. *Photo* by Ataliba Coelho

skull with an indirect age of 11,000 yrs B.P. (Neves and Hubbe 2005). About 40 human remains containing enough collagen submitted to AMS dating show a clustering of early ages between 8,500 and 7,500 yr B.P. (Araújo et al. 2012), with the "Luzia" skull as an outlier.

Lagoa Santa paleoindians produced a lithic industry characterized by small unretouched quartz flakes (Araújo et al. 2012). Bone artifacts, such as perforators, spatulas, and fish hooks, were also recovered (Kipnis et al. 2009). Subsistence relied on small prey, with no evidence of hunting of the megafauna. Lagoa Santa contains remarkable rock art (Fig. 16.8) including some of the oldest in the Americas, such as the recently dated pecked anthropomorph from Lapa do Santo, at approximately 10,500 yr B.P. (Neves et al. 2012).

16.6 Conclusions

The Lagoa Santa Karst is an outstanding area of both scientific and cultural value. It represents the first karst area to be systematically investigated in Brazil, and it may be considered a typical tropical karst. Nevertheless, it has several specific sets of landforms not commonly found elsewhere, such as the scenic cliffs and karst lakes. Brazilian speleology, paleontology, and archaeology began in this area in the early nineteenth century thank to the work of Danish naturalist Peter Wilhelm Lund. The numerous caves are not only of speleological significance but have also formed the basis for Brazilian vertebrate paleontology due to the frequent and extremely rich Late Pleistocene fossil cave deposits. Caves and rock shelters have provided evidence of early colonization of the area, with dates indicating a very early human arrival at the end of the Pleistocene. Rock art, human burials, and remarkable archaeological remains make the Lagoa Santa Karst not only the best researched Brazilian karst area from an archaeological standpoint but also a reference for any studies dealing with the early occupation of America.

The Lagoa Santa Karst lies only 30 km from the major urban metropolis of Belo Horizonte. The expansion of Belo Horizonte toward the karst has accelerated in recent years, partially due to the growth of Belo Horizonte International Airport, built on a phyllite plateau close to the eastern limit of the karst. Satellite cities such as Matozinhos and Pedro Leopoldo are also experiencing explosive growth, with no restriction barring expansion over dolines or recharge zones. Urbanization has caused groundwater pollution, cave depredation, and loss of the original vegetation. Several quarries for cement and lime production have caused losses of caves and karst features. The creation of the Environmental Protection Area of the Lagoa Santa Karst has helped foster interest in the preservation of the area but has done little to prevent environmental degradation. Fortunately, a new and very restrictive law has helped with enforcement, facilitating cave studies and conservation. The recently established Sumidouro State Park as well as other preservation areas have allowed the conservation of a significant portion of the karst.

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Jalapão: Sedimentary Heritages in Central Brazil

17

Fernando de Morais and Sandro Sidnei Vargas de Cristo

Abstract

The Jalapão region, a region with undefined boundaries located in central Brazil, has unique scenic beauty and unmatched physical features. It has a set of residual landforms with flat tops and scarped slopes resulting from the regressive erosion of large tabular features such as the Serra Geral and the Ocidental da Bahia and Mangabeiras plateaus. Geologically, it generally consists of a crystalline basement and the Parnaíba and Sanfranciscana sedimentary basins, which are covered by recent deposits. However, geomorphology of the region is still poorly recognized, although some specific features are known, such as canyons, dunes, caves, bubbling springs, and several residual landforms caused by intense local erosive action. This chapter aims to describe the geomorphology of the area and to explain the existing features and geomorphologic processes.

Keywords

Jalapão • Caves • Canyons • Dunes

17.1 Introduction

Located in central Brazil, the Jalapão region comprises the states of Maranhão, Bahia, Piauí, and most of Tocantins (Fig. 17.1). The name Jalapão is derived from the Jalapa (*Operculina macrocarpa*) shrubs that are very common in the region and have been historically used for medicinal purposes by local population (Naturatins 2003). The boundaries of the region are not well defined, sometimes extending to southern Maranhão and western Bahia and sometimes including only the area within the state of Tocantins.

Since the nineteenth century, the Jalapão region has attracted scientific interest of several researchers from different fields. Travelers like Gardner (1975) and Pohl (1976) provided descriptions of natural features of the region and everyday life of the people in the first half of the nineteenth century. Geographers like Pereira (1942, 1943) sought to delineate boundaries of hydrographic basins of the São Francisco and Tocantins rivers. Pereira cites a popular subdivision of the region into High Jalapão and Low Jalapão, inferring, based on his own field description of geomorphological dynamics of the sandstone plateau that forms the Serra Geral de Goiás (Serra Geral), that destruction of this geomorphological unit by denudation processes could lead to the formation of a great desert (Pereira 1942). Though incorrect, many media outlets currently use the term “desert” to refer to Jalapão, but this usage is mainly for the promotion of tourism.

The Jalapão region is generally an assemblage of residual landforms, consisting of plateaus, mesas, tablelands, hills, and hillocks with flat tops and steep slopes (Fig. 17.2a). Geomorphology of this part of the Brazilian territory is still poorly recognized, and it is mainly known for specific features only such as canyons, dunes, caves, bubbling springs, and various residual landforms (Fig. 17.2b) that were generated by intense erosive action on the water divide of three major Brazilian river basins (Tocantins–Araguaia, São Francisco, and Parnaíba).

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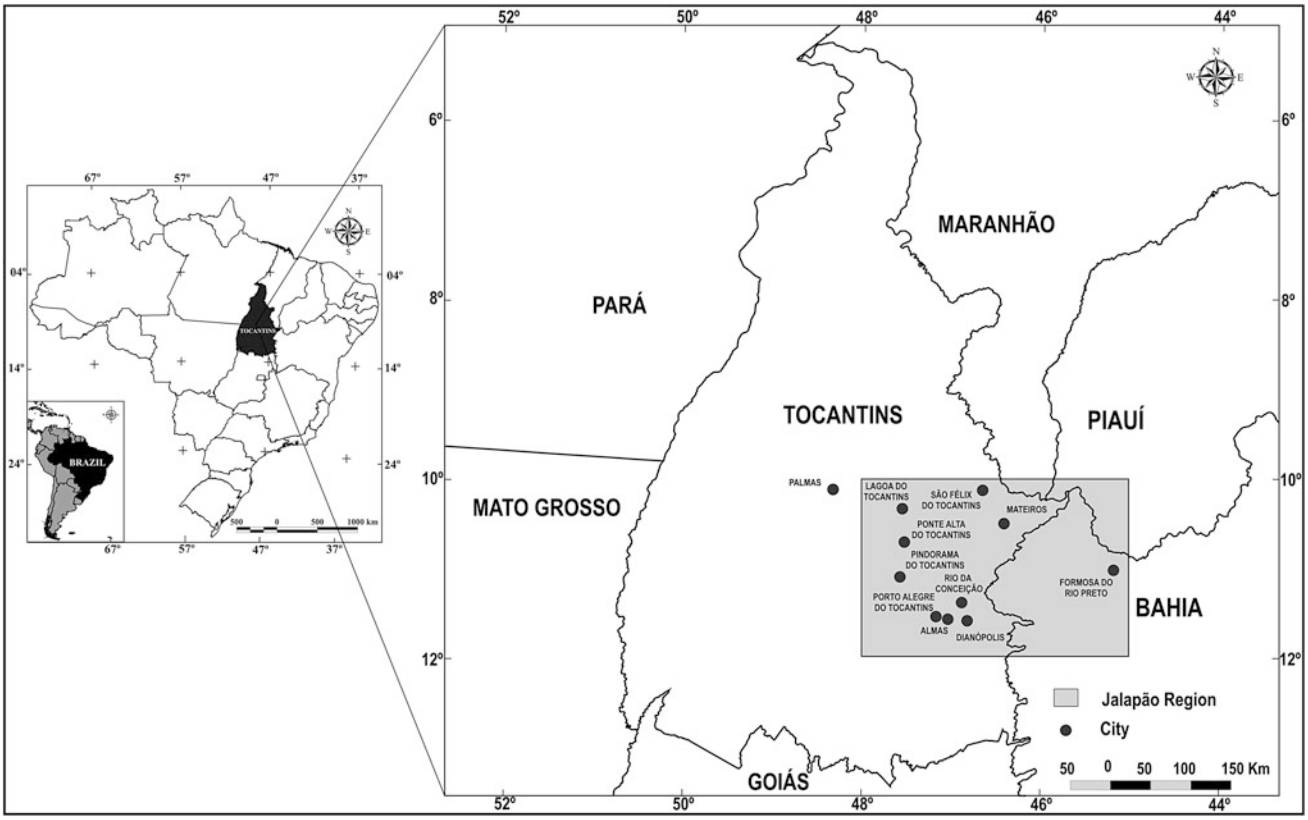


Fig. 17.1 Location of Jalapão

17.2 Geology, Climate, and Vegetation

The geology of Jalapão consists of a crystalline basement and cover rocks of the Parnaíba and Sanfranciscana sedimentary basins, which are overlain by recent deposits (Fig. 17.3). The crystalline basement outcrops are observed in the northeastern and southwestern portions. The northeastern outcrop consists of rocks belonging to the Cristalândia do Piauí Complex, which is characterized by the presence of mylonitic granitic muscovite–biotite orthogneiss with mafic–ultramafic enclaves; muscovite–biotite augen orthogneiss; sometimes mylonitic and sometimes migmatitic orthogneiss and paragneiss with levels of mylonitic metamafic, meta-ultramafic and calc-silicate rocks; and ferruginous metachert. The southwestern outcrop is represented by the Almas Cavalcante Complex, which is composed of migmatitic gneisses, tonalites, granodiorites, trondhjemites, quartz monzodiorites, and quartz diorites rich in amphiboles and monzogranites (Souza et al. 2004).

Between the crystalline basement and the Sanfranciscana Basin sediments, the Bambuí Group is exposed, which, according to Souza et al. (2004), is of Neoproterozoic age and composed of calcareous sandstones, dolomites, rhythmites, marls, mudstones, siltstones, and limestones. The Bambuí Group is most notable in the southern portion of the study area, where it presents karst features of great scenic beauty. This group is represented by carbonitic and pelitic sequences interbedded with marbles, metamarls, and metasiltstones. In the east-southeastern portion, the same group is composed of pyrite feldspathic quartzite, carbonitic quartzite, sericite schist, metasiltstone, and metadiamictite.

The Parnaíba Basin occupies the northern portion of the area, where bedrock belongs to the Canindé and Balsas groups. The Canindé Group contains mainly sandstones and siltstones interbedded with shales, siltstones, conglomerate, and subordinate microconglomerate. These rocks were deposited in estuarine, fluvial, and shallow marine environments (Góes and Feijó 1994). Sandstones, siltstones, shales, and limestones are found in the Balsas Group, and they appear to have formed in continental, fluvial, and coastal environments with marine interbedding. The Balsas Group also contains bimodal sandstone with large-scale cross-stratification, which is thought to have originated in a desert environment with eolian dunes.

The Sanfranciscana Basin deposits, which form the Phanerozoic cover of the São Francisco Craton, are mostly represented by sandstones of the Urucuia Group, in addition to recent deposits. This geological group dominates most of the Jalapão region, covering approximately half of the area.

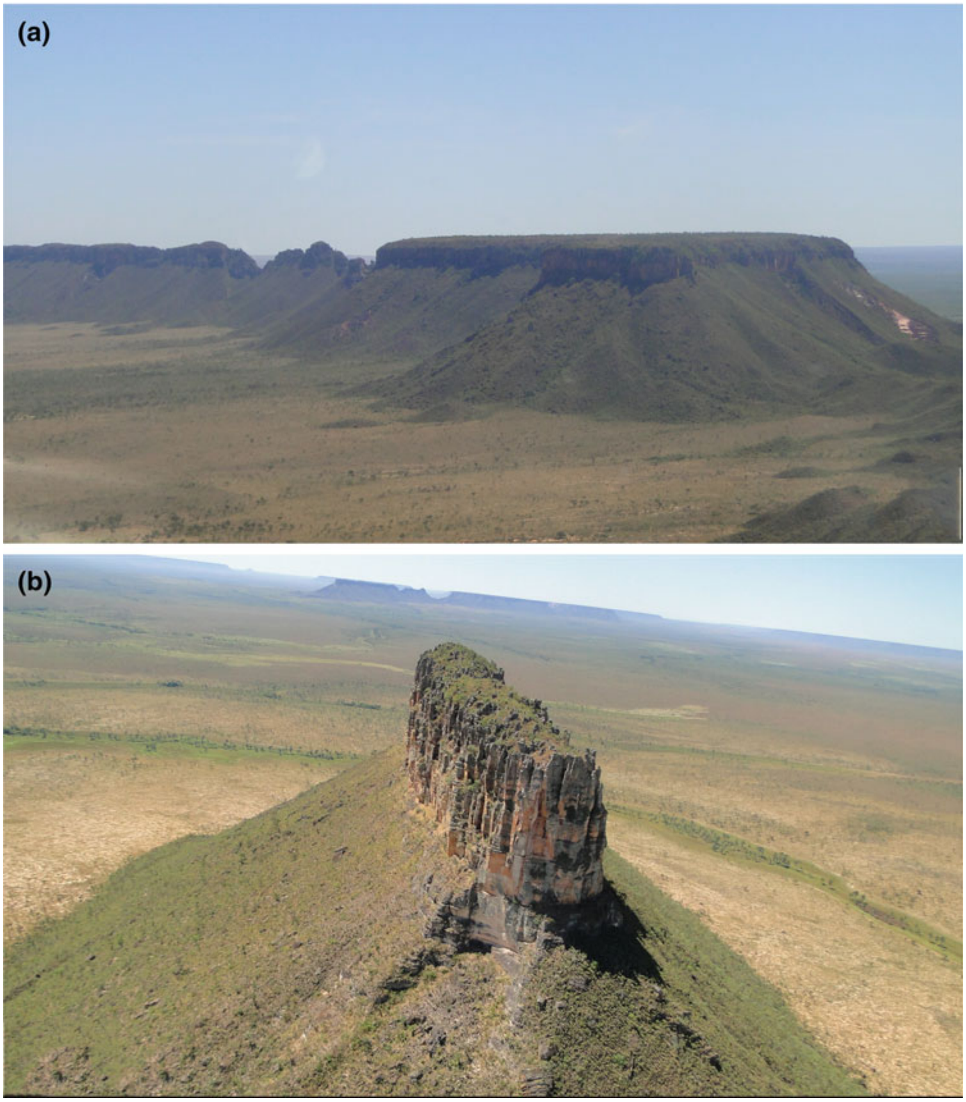


Fig. 17.2 Aerial view of residual relief of the Jalapão region (**a** and **b**). *Photographs* L. Côrtes, 2010

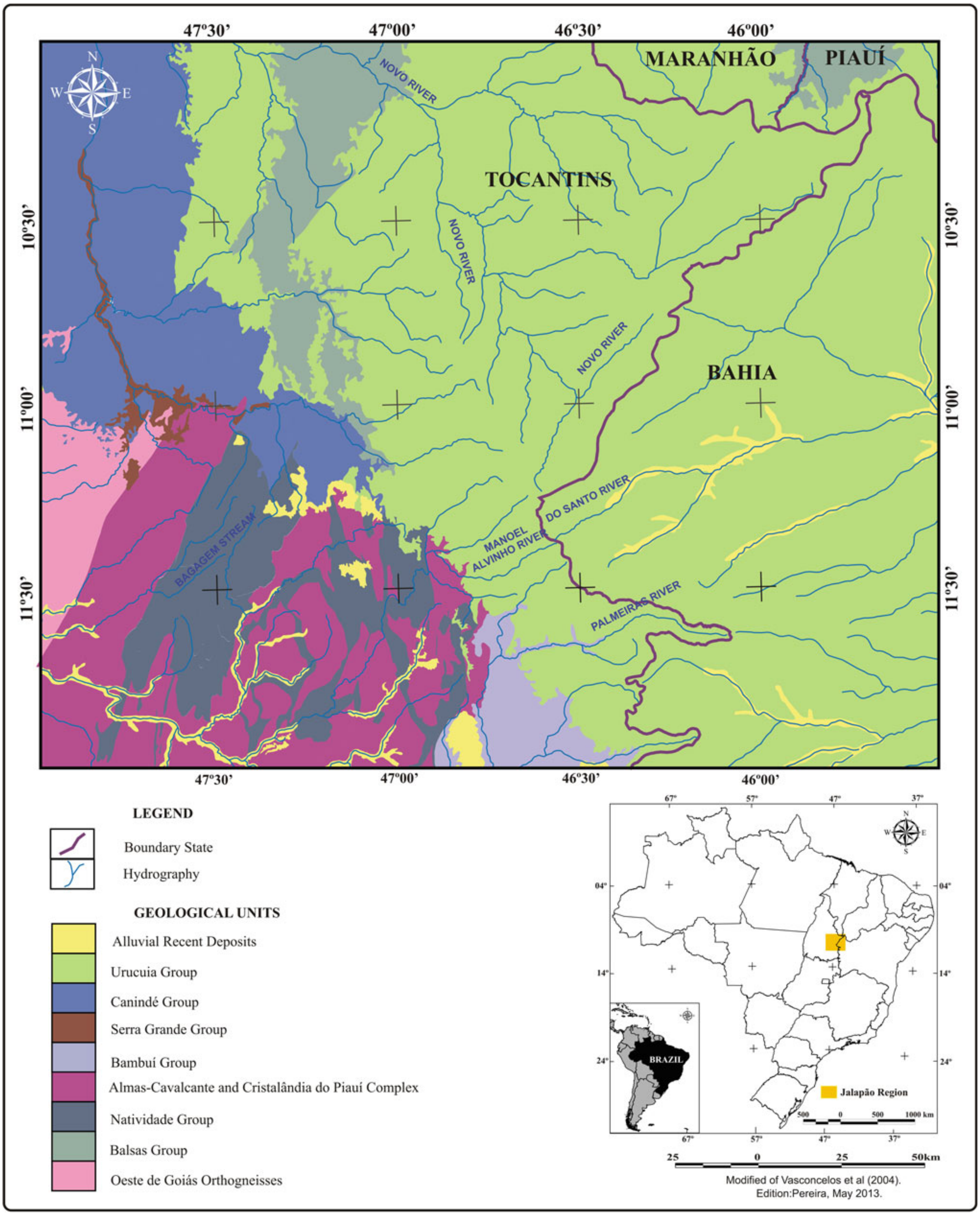
According to Souza et al. (2004), the same group extends over a broad range covering the southern, central, and northern portions of the area, basically consisting of sandstones with large-scale cross-stratification, conglomerates, and subordinate mudstone packages. According to Gaspar (2006), the rocks of the Urucuia Group are between 100 and 600 m in thickness and date from the Late Cretaceous period.

Recent deposits are composed of detrital laterites, consisting of sand with levels of clay, gravel, and lateritic crust. The occurrence of Holocene alluvium is also observed; there are recent alluvial deposits of sand with interbedded clay, gravel, and organic matter remnants.

The climate of the region can be characterized as subhumid, with two well-defined seasons, rainy and dry, in addition to moderate drought in the winter. The average annual rainfall ranges from 1,400 to 1,600 mm, and the mean annual temperature is between 25 and 26 °C (Seplan 2012).

Vegetation is characterized by the predominance of Cerrado (savannah) which is distributed over several sections and shows variation between different types, such as Campo Limpo (tropical grassland), Campo Sujo (savannah), Cerrado Senso Restrito (cerrado sensu stricto), Mata Ciliar (riparian forest), Mata de Galeria (gallery forest), and Veredas (palm swamps). The latter is mainly composed of buriti palms (*Mauritia flexuosa*) that are sparsely distributed. The individual canopies do not touch one another, and they are surrounded by moderately dense layer of herbaceous–shrub species that are very common in the headwaters of streams and their surroundings, until the streams develop a defined trough (Ribeiro and Walter 1998).

According to Embrapa (2006), the predominant soils in the eastern portion of the research area are oxisol and Quartzarenic Neosol. Litholic Neosols and Quartzarenic Neosol occur in the central-north portion. In the central-south portion, in addition to the aforementioned soils, there



Modified of Vasconcelos et al (2004).
Edition:Pereira, May 2013.

Fig. 17.3 Simplified geological map of the Jalapão region are Petric Plinthosols. The lack of more detailed pedology studies means that soils of the western portion tend to be labeled as indiscriminate soils in scientific reports. In that area, Petric Plinthosols, Red–Yellow Latosols, and Quartz-sand Neosols are mixed together.

17.3 Regional Geomorphology

The Jalapão geomorphology mainly shows large tabular features, such as Serra Geral and the Ocidental da Bahia and Mangabeiras plateaus. The altitude ranges from 200 m in the least elevated portions, generally located to the west, to approximately 950 m in the higher terrain to the east (Fig. 17.4a).

There are also erosive forms of interplateau pediment valleys with well-conserved pediments which converge, usually with no slope break, toward the fluvial trough. Finally, through the continuous processes of erosion, structural forms of the structural tabular surface type (Fig. 17.4b) are subjected to pedimentation processes. Plateaus that are usually capped by sandstone and, depending on the dip, show cuesta landforms or tabular relief, bounded by scalloped edges, can also be seen (Fig. 17.2a).

These geomorphological features show stratified layers of sandstone rocks with whitish color caused by siliceous cementation in their upper portions, while in the lower portions reddish layers due to iron oxide pigment occur. In the same sense, several cross-stratifications are seen with long sets in the typical exposures of wind deposition. On lower slopes, there are significant talus and colluvium deposits caused by disaggregation and rockfall. Differential erosion that acts on the local sandstone leads to disintegration of the most brittle portions, resulting in transportation of the less silicified sediments. This leaves the most resistant portions, which are rich in iron oxide, and these generate a beautiful landscape.

Geomorphological processes acting on Jalapão are similar to those responsible for the evolution of landscapes in other regions with tabular and cuesta relief. They include, for example, the constant relocation of sand from the higher portions to less elevated areas where veredas (paths) are installed. Dissolution forms are discontinuously distributed over the areas dominated by carbonate rocks of the Bambuí Group. These forms mainly occur in the terraces between São Francisco and Tocantins River hydrographic basins.

In the northern sector, erosion was strong and caused retreating of slopes. Consequently, only ridges were preserved in the landscape. Mesas are significant in the western and southwestern areas, and they represent broad flat-topped areas formed by erosive retreat that leaves behind scarped edges (Fig. 17.2b). Variable resistance of rocks generates stepped profiles in the slopes with wide flat areas at top of the resistant rock (rock terrace). In the southeastern area, erosion of gullies cut these rock terraces. Tabular interfluves appear in some dispersed areas in the central-eastern portion, and ravines and embedded valleys are also present.

Among geomorphological features and processes that occur in Jalapão, some are distinctly related to the characteristics of sedimentary relief. These include the presence of widespread deposits in flat areas along the drainage channels that go through hills with smooth declivities. They also include mesas and plateaus that represent the higher areas produced by denudation processes through slope retreat. In this sense, features standing out due to their scenic beauty and particular physical characteristics include canyons, dunes, caves, and bubbling springs.

17.3.1 Canyons

In general, it is thought that canyons of the Jalapão region have resulted from the preferred routes of surface and subsurface drainage flows acting on the local geology and geomorphology, generating mechanisms of vertical erosion along the river courses. These preferential routes are also present in areas near the headwaters of drainages. There are high elevations in these areas, which increase flow velocity and hence erosive power.

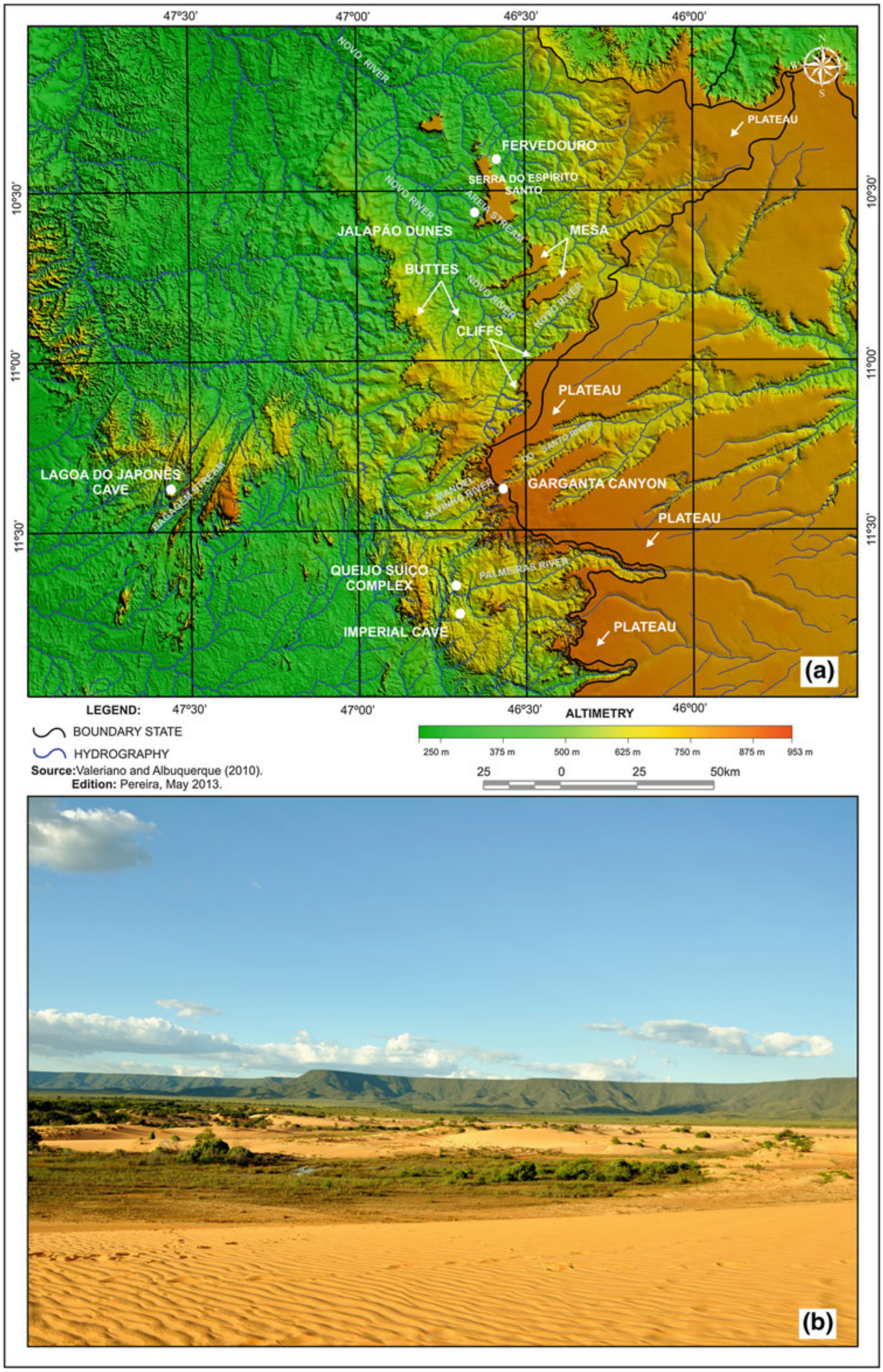
The Garganta Canyon (Fig. 17.5a), which is located in the plateau relief and has geological features similar to those of the Urucuia Group, is among the most elevated sites of this kind in the region. The canyon connects two headwater reaches of rivers which flow in the opposite directions (the Manoel Alvinho River flows toward the state of Tocantins, and the Santo River flows toward the state of Bahia) (Fig. 17.4a). In this feature, the drainage network is under strong structural control by a system of faults, which are aligned with the main channels (Fig. 17.5b).

Parallelism can also be seen between the regional drainage pattern, where water divides are formed by sedimentary rocks (sandstones with planar stratification) which support tabular forms with flat tops and cliffed escarpments (Figs. 17.2a, b and 17.4b), which shows intense regressive erosion at their edges. Similarly, many runiform features have formed, and they are distributed over both valleys. These features are generated by differential erosion that operates on the sandstone bedrock.

17.3.2 Jalapão Dunes

The Jalapão Dunes (Figs. 17.4b and 17.6) are inserted in the Rio Novo hydrographic sub-basin, a site of eolian deposition. These features are in an area of about 400–500 m in altitude a.s.l., corresponding to the Serra do Espírito Santo. These

Fig. 17.4 **a** Altitude and location of major geomorphological features. **b** Typical tabular landscape of Jalapão. *Photograph* Clóvis Cruvinel



areas, characterized by extensive deposition of sandy white-reddish sediments in the form of active inland dunes, are found on the margins of the Areia Creek. The dune sediments come from the slopes of Serra do Espírito Santo and follow the course of the Areia Creek. Next to the mouth, the valley expands laterally and opens into the shape of a fluvial fan. The sediments are reworked by wind at this location, and this process gives the dunes their specific characteristics.

It is worth noting that the sandy sediments exposed in the Jalapão Dunes come from the reactivation of paleodunes that are present at the site. Additional observations can be made regarding the formation of these features: (1) the geologic

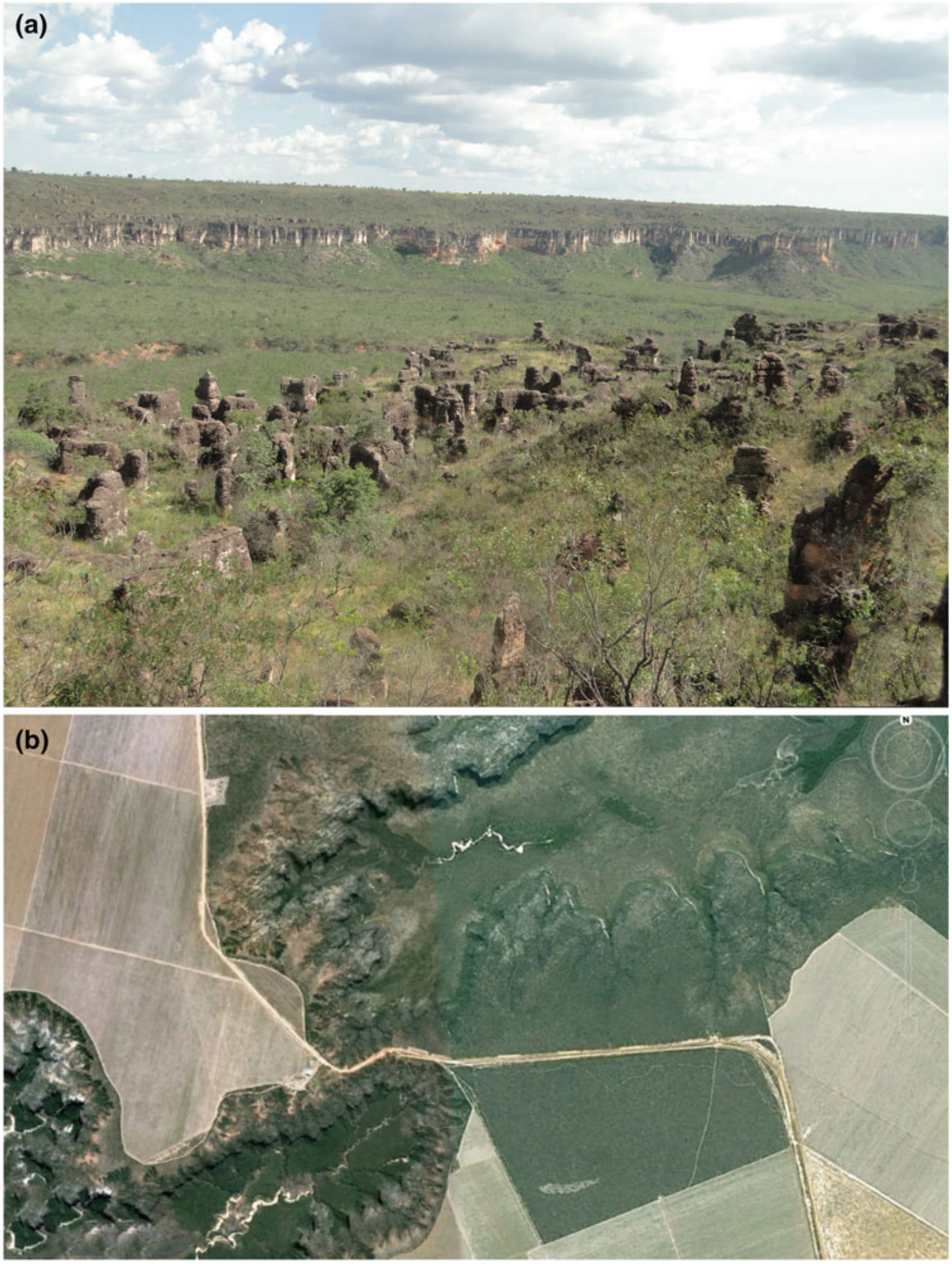


Fig. 17.5 Garganta Canyon, which has significant structural geologic control over the local drainage (**a**) and shows differential erosion resulting in runiform features, seen in the foreground. The erosion also exhumes an old flat surface, seen in the background (**b**) *Image* Google Earth, captured in February 2013 (**a**) and *photograph* M. Costa, 2013 (**b**)

fragility of brittle sandstones from the Urucuia Group located in the southwestern portion of the Serra do Espírito Santo which act as the source of sediments; (2) the Areia Creek flows through the Serra do Espírito Santo and has a great capacity for fluvial transport along its main course; (3) the local wind circulation favors erosive action on the slopes of the Serra do Espírito Santo, and it also assists in the transportation and reworking of the deposited sediments; (4) the form of the scarped slope of the Serra do Espírito Santo increases wind speed and favors the mobility and reworking of sediments; (5) the action of the rain on the scarps of the Serra do Espírito forms ridges and ravines that serve as the source of sediments; and finally, (6) there is a river course that is perpendicular to the direction of transportation of sediments, and the riparian vegetation along the river assists in sediment retention and dune formation.

It is important to highlight the action of local wind, facilitated by the variation between the rainy season and the dry season. During the dry season, the water table is low and sandy sediments are loose. Also, these loose sediments are

Fig. 17.6 Dunes with adjacent drainage, in the foreground, and a tabular relief, forming the Serra do Espírito Santo, in the background. *Photograph* Clóvis Cruvinel

reworked by wind, whose predominant direction is east–west (from June to November).

As a key element in the formation of the dunes, the wind is channeled in the valley formed by the Serra do Espírito Santo, increasing its speed and transportation capacity of sandy sediments deposited at the base of the slope. These sediments, deposited on upstream hills, result in a dominant barchan-type dunes. According to Ab'Saber et al. (2010), barchan dunes are the active dunes of the Jalapão area, while parabolic dunes are paleodunes. These two forms represent different generations of dunes in the region and provide sedimentary records of two stages of increased wind activity, which are possibly related to drier periods that occurred during the Holocene.

17.3.3 Caves

In the Jalapão region, there are limestone hills, and many caves occur in the area, such as the Lagoa do Japonês and Imperial caves (Fig. 17.4a). The area also contains covered karst, exhumed karst, and uncovered karst, and the covered forms and those in the process of exhumation mainly occur in the south-southwestern part of the area. They become less visible as they approach the Serra Geral. The uncovered karst, with its lapies, dolines, uvalas, poljes, and caves, is most noticeable in the outcrops of the Bambuí Group to the west.

The Imperial cave has 202 m of linear development in a limestone outcrop. Archeological records were found in its interior indicating past human occupation, and several speleothems were found, such as curtains, stalactites, stalagmites, glittering calcite deposits, and microtravertine. There are also archeological records indicating past human occupation, such as deposits of bones and cave paintings, which make this geomorphological site very important.

The fluvial channel of the Bagagem stream is embedded in a horizontal syncline, where dissolution processes carved the Lagoa do Japonês cave (Fig. 17.7). This cavity has its genesis conditioned by the concentration of surface flows coming from the quartzite flanks of the syncline in the direction of the limestone lens inside it. Northeast of the Lagoa do Japonês cave, there is a circular dissolution doline.

In addition to isolated features, the Palmeiras River basin has a system of caves called the Queijo Suíço Complex (Fig. 17.4a), featuring over 400 m of conduits. The genesis of this system can be linked to the evolution of the Palmeiras River basin, which, when its thalweg was carved, generated a topographic declivity between the river and the area where the caves of this system are located. In addition to this complex, several karstic features conditioned by the regional geologic structure occur near Dianópolis, such as karstic lakes and several other caves.

17.3.4 Bubbling Springs

Bubbling spring are geomorphological features characterized by circular crystalline water wells about 10 m in diameter. They are basically caused by upwelling of a confined aquifer. The "Fervedouro" (Fig. 17.4a) is formed by the local exposure of underground water, with strong upward pressure, seeking hydrostatic equilibrium. The pressure causes

Fig. 17.7 Speleothems inside the Lagoa do Japonês cave. *Photograph* F. Morais, 2010

Fig. 17.8 Erosion front of the plateau. *Photograph* Clóvis Cruvinel

suspension of objects and people that enter it, providing a "floating sensation." Inside the feature, the water is clear, and there is concentration of very fine white sand that is reworked by water dynamics. The surrounding vegetation is characterized by Cerrado species and some other species that are cultivated in the region. These features give the site a peculiar scenic beauty.

17.4 Conclusions

Populated by immigrants from northeastern Brazil during the nineteenth and twentieth centuries, the Jalapão region is home to great geological and geomorphological attractions, giving it prominence in the Brazilian natural physical context. In the westernmost portions, cuesta relief of the Parnaíba sedimentary basin stands out, and in the eastern portion, large planar surfaces are represented by tabular features of the Sanfranciscana sedimentary basin.

Intense denudation processes occur at the edges of these large features, promoting parallel retreat of slopes (Fig. 17.8). Denudation is sometimes conditioned by climate factors and sometimes by structural geologic effects. Such processes promote individualization of large rock masses in tabular forms, with an emphasis on the Serra Geral, Chapada Ocidental da Bahia, and Chapada das Mangabeiras.

Underlying the sandstones of the Parnaíba and Sanfranciscana basins are the carbonates of the Bambuí Group, which is home of karstic features with known archeological and paleontological potential. In addition, the Bambuí Group has natural value for tourism. Also, regarding the relationship between sandstones and carbonates of the Sanfranciscana basin, some discharge zones (upwellings) represent true bubbling springs, as evidenced by peculiar behavior of ascending water flows inside.

Due to its geographical characteristics, this region shows significant environmental sensitivity, which should be considered during planning and environmental management. Moreover, this portion of Brazil remains understudied from the perspective of regional geologic and geomorphologic evolution.

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Chapada das Mesas: Unknown Geomorphological Heritage

18

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Abstract

The Chapada das Mesas, located in the north/northeast region of Brazil, in the states of Maranhão and Tocantins, is an area of stunning natural beauty, with rivers, waterfalls, caves and canyons, associated with a wealth of traditional peoples and diversity of flora and fauna. This important Brazilian geomorphological heritage was structured by the uplifting of the Parnaíba sedimentary basin, with the formation of majestic residual reliefs supported by diabase dikes and lateritic sandstones. Part of this natural heritage is protected by the creation of the Chapada das Mesas National Park, a promising tourist destination, but the area is still little explored.

Keywords

Chapada das Mesas • Parnaíba sedimentary basin • Geomorphological heritage • State of Maranhão

18.1 Introduction

Located on the border between the states of Maranhão and Tocantins (Fig. 18.1), within the Amazon region, is the Chapada das Mesas, a geomorphological unit of exuberant scenic beauty, with canyons, waterfalls and lagoons of crystal blue waters. Due to its position in a transition area between semi-humid and humid climates, associated with the different forms of relief arising from successive stages of differential erosion (Figs. 18.2a, b), important biogeographical diversity is found in the region, with plant and fauna species from the Amazon (equatorial rainforest), Cerrado (tropical savannah) and relicts of Caatinga (Brazilian semi-arid steppe).

Located mostly in the Tocantins River Basin, whose main river divides the states of Maranhão and Tocantins, the Chapada das Mesas area is approximately 763,000 ha, partially covering 10 municipalities, of which Carolina, Estreito, Riachão and Balsas are the regions of southern Maranhão with the greatest tourist activity. The occupation of the area, still scarce, has occurred in three phases, with the indigenous people of Timbira being the first to inhabit the region. In the early nineteenth century, the indigenous people were gradually decimated or driven out, giving way to agropastoral occupation by sertanejos (backlanders), adapted to the environment, who remained in a territory virtually isolated from the dynamics of large cities of the country until the mid-1980s, when agribusiness related to soybean, sugarcane and eucalyptus monocultures came to the region, leading to major ecologic and social instability. To protect a part of this area of great geo-ecological importance, the Brazilian Institute of Environment and Renewable Natural Resources (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis—IBAMA) created the

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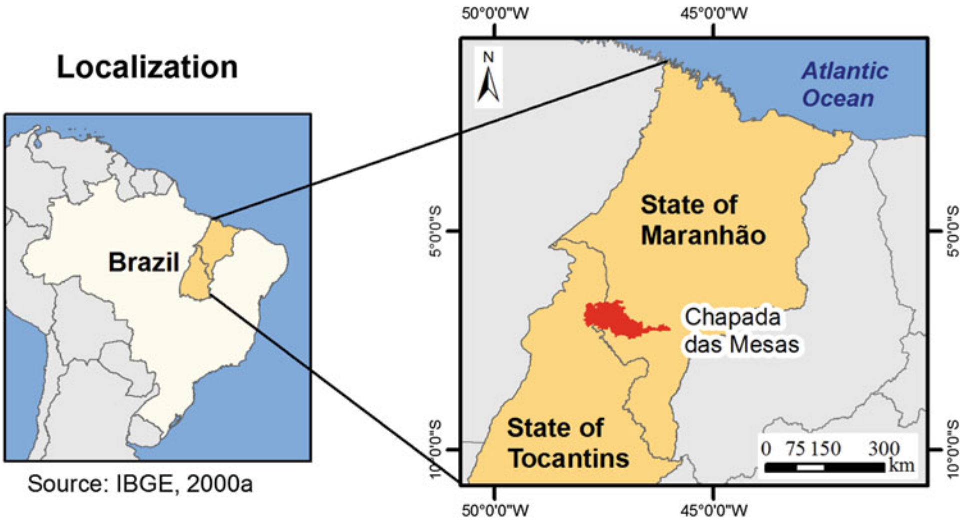

Fig. 18.1 Map of the location of the Chapada das Mesas region

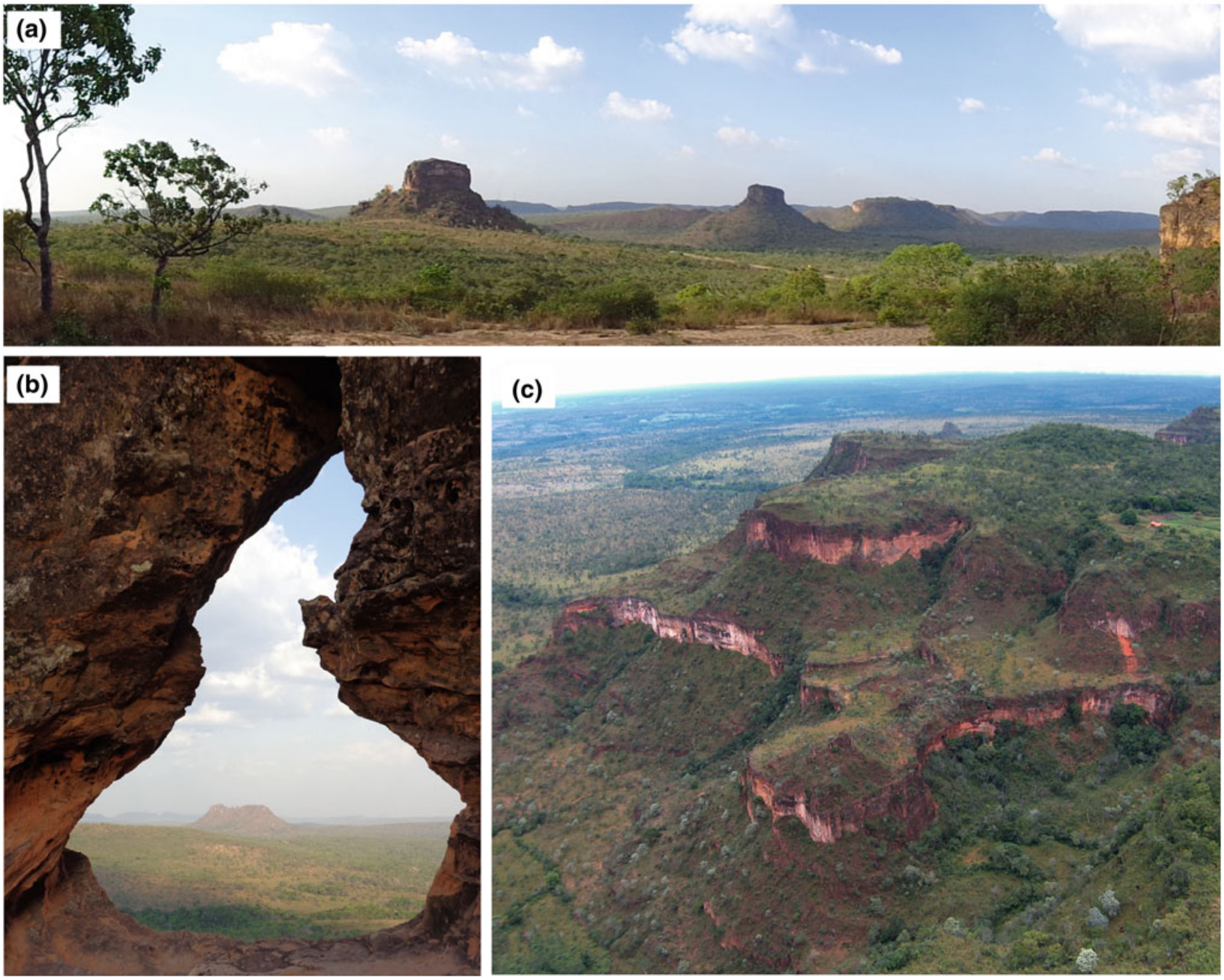

Fig. 18.2 **a** Isolated buttes capped by sandstones of the Sambaíba Formation and the Neogenic detritic lateritic coverage. **b** Landscape view from the natural arch Pedra Furada. (*Photo* by Helen N. Barreto). **c** Aerial view of stepped escarpment with a succession of exposed sandstones faces. (*Photo* by Ana Rosa Marques)

Chapada das Mesas National Park (Parque Nacional da Chapada das Mesas—PNCM) (Fig. 18.2c) in December 2005 as a protected area of 160,000 ha, with the main goal being "to conduct scientific research and to develop environmental education and interpretation activities, recreation in natural settings and ecotourism" (BRASIL 2005).

The creation of the park has led to an increasing interest in the phenomenon of "ecotourism". However, despite the extensive geological and geomorphological heritage, the area is still virtually unknown by both lay people and the scientific community because there is a regrettable lack of research in this area.

18.2 Geoenvironmental Characterisation of the Chapada das Mesas

The Chapada das Mesas is located in the south-western portion of the unit known as the Parnaíba Sedimentary Province (Góes 1995). This sedimentary basin was created in a large cratonic area according to a staggered and parallel fault system. The intersections of these rupture lines generated large mosaics or blocks responsible for the arrangement of the rock strata in the main NE/SW, NW/SE and N-S directions.

The Parnaíba sedimentary basin covers approximately 600,000 km^2 and is characterised as a structurally depressed area of oval shape and NE-SW extension, located within the South American Platform in Brazil (Almeida 2000). The basin is located on the Cambro–Ordovician rifts of Jaibaras, Jaguarapi, Cococi, São Julião and São Raimundo Nonato (Brito Neves 1998). Over geological time, the basin has been continuously filled by sedimentary sequences, so that a sedimentary succession composed of fine and coarse siliciclastics over 3,000 m thick has formed, of which 2,500 m are Palaeozoic-age sediments (Veiga 2000).

In the Silurian period, a major continuous sedimentary deposition cycle occurred in the Parnaíba Basin, represented by the rocks from the Serra Grande Group (Góes et al. 1990; Sousa et al. 2012). The cycle began with the deposition of coarse clastics in the continental environment, with marine transgression being recorded (CPRM 1978), represented by marine shales of the Tianguá Formation. The cycle ended with regressive sedimentation consisting of sandstones and fluvial conglomerates of the Jaicós Formation (Góes et al. 1990).

From the Devonian to the Permian, a sequence of transgressive and regressive events occurred in the basin, starting with the deposition of the Canindé Group sediments, represented by fine to medium sandstones. The Itaím Formation marks the transgressive event, whose peak occurred during the deposition of the bioturbed, greenish grey marine shales with interbedded sandstones with ferruginous oolites of the Pimenteira Formation. A deposition of Devonian glacial diamictites and deltaic sandstones of the Cabeças Formation followed, gradating to the transgressive shales of the Longá Formation (Devonian–Lower Carboniferous). The deposition cycle ended with the regressive sandstones of the Poti Formation (Góes et al. 1990; Góes and Feijo 1994).

The Carboniferous a new sedimentary cycle started in the basin with the deposition of the Balsas Group, which integrates the Piauí, Pedra de Fogo, Motuca and Sambaíba geological formations. The Balsas Group consists of a set of coarse and fine sediments resulting from a sequence of marine transgressions and regressions associated with records of climate changes. In this environment, the rocks from the Chapada das Mesas and vicinity were formed, especially those of the Sambaíba and Motuca formations. At the beginning of the sedimentation cycle, a continental aeolian environment prevailed, with brief marine incursions represented by sandstones, limestones and anhydrites of the Piauí Formation. Subsequently, climate conditions changed causing regressive regime, represented by the deposition of the Pedra de Fogo Formation, consisting of sandstones, limestones, evaporites and microcrystalline quartz (Sousa et al. 2012). The last major biological event of the Palaeozoic occurred in this environment, represented by the silicified wood trunks. Hot and arid climate conditions intensified during the deposition of the Motuca Formation, represented by aeolian dunes, salt lakes, *redbeds* and evaporites (CPRM 2013). The presence of barite ($BaSO_4$) in the reddish clayey siltstones indicates an arid environment with sulphate precipitation (CPRM 1978). Deposition continued uninterrupted with the climax of fluvial continental environment (poorly sorted, rounded to spherical, dull sandstones with crossed stratification) and with aeolian contribution, during which well-sorted, pure sandstones with no interstitial clays and low contents of boron were deposited, providing evidence for the continental environment (CPRM 1978; Sousa et al. 2012).

Arid conditions during the Mesozoic coincide with the period of mega-desert formation in the Earth's history (Almeida et al. 2012). In Brazil, at the end of the Permian, under the same climate conditions, the sedimentation of the inland basins began, such as the Passa Dois Group in the Paraná basin and the Balsas Group in the Parnaíba Basin, where the Piramboia and Sambaíba palaeodeserts developed, respectively. Furthermore, according to the same authors, the definitive withdrawal of the sea and the progressive increase in aridity at the end of the Permian and beginning of the Triassic provided favourable conditions to the wind reworking of the formed deposits, originating an extensive dune field (Sambaíba Formation), greatly preserved from erosion by the covering with the Neo-Jurassic volcanic rocks of the Mosquito Formation.

The first instance of fissure eruption volcanism in the Parnaíba basin occurred during the sedimentation of the Sambaíba sands, most likely related to the North Atlantic rupture, which was associated with intense tectonics. Numerous tholeiitic diabase dikes and sills of E-W direction were emplaced in the strain zones, following the configuration of the sedimentary strata. The sandstones of the Sambaíba Formation exhibit silicified tops in contact with the lavas of the Mosquito Formation (CPRM 1978; Vaz et al. 2007).

After deposition of the Mosquito lavas, intensive erosion occurred in the Jurassic throughout the Parnaíba Basin. In the lower areas, surrounding the topographically high basalts in the south-eastern portion of the basin, the Neogenic Detritic Lateritic Coverage was formed, composed of semi-unconsolidated to incoherent sediments with a poorly sorted, clayey sand matrix with quartz pebbles, dispersed kaolin and limonite, sometimes containing lateritic, fractured and discontinuous bands (Sousa et al. 2012).

The tectonic stress from the Early Miocene, which coincides with the uplifting of the South American continent, was also responsible for raising the general baseline of the southern portion of the state of Maranhão, establishing altimetric levels of approximately 200–800 m (Tarouco and Santos 2007), which allowed the development of a regional erosion cycle. Thus, under humid climate conditions, the implementation of erosive processes and the advance of the weathering front shaped the sedimentary strata, preserving the summit surface and giving rise to the tabular and subtabular relief. Later, with the fluvial incision, dissection of this surface was promoted, followed by slope retreat, to form extensive planar surfaces at topographically lower levels whose regional baseline is the Tocantins River.

The erosive genesis of these surfaces resembles the landscape evolution cycle proposed by King (1953), known as pediplanation. This model describes the formation of extensive surfaces of low relief through fluvial incision and embedding of the valleys followed by parallel scarp retreat, maintaining slope inclination of escarpments. Thus, at the end of the cycle, residual reliefis preserved in the landscape at a higher topographic level, reflecting the reaction of a lithologically more resistant substrate, whilst at the base of the cliffs, detritic ramps (pediments) extending up to the river valleys occur, mantled by colluvial sediments.

The tectono-structural evolution of the regional landscape and diverse lithological framework allows one to distinguish three major geomorphological units (IBGE 2000c). From north to south, these are as follows: (a) the Patamar Porto Franco-Fortaleza dos Nogueiras, dominated by poorly embedded hills and valleys; (b) the Chapadas e Planos do Rio Farinha, with vertical, intensely fractured sandstone cliffs, tabular tops and extensive planed surfaces; (c) the dissected surface of the Depressão do Médio Tocantins.

The Chapada das Mesas is a part of the second geomorphological unit (b) because of the predominance of relief forms with tabular tops, with rocky and abrupt slopes, and extensive planed surfaces. Most residual landforms, regionally known as “mesas”, are supported by the sandstone covers of the Mosquito and Sambaíba Formation (Balsas Group) and Neogenic Detritic Lateritic Coverage, positioned at the top and more resistant to erosion, defining a distinct topographic level with altitudes ranging from 300 to 400 m (Fig. 18.3).

The preservation of this elevated surface is also associated with the laterisation that has occurred in the sandstone sedimentary cover. The slightly convex hillslopes with pronounced dissection become more concave as they reach the lower sections, evidencing peculiar shapes (Fig. 18.4).

At a slightly topographically lower level around the “mesas” occurs a profusion of planar surfaces (200 m) carved by erosion resulting from the disaggregation of sandstones. The formations of these surfaces correspond to the Pleistocene colluvium and alluvium that fringe the Depressão do Médio Tocantins unit (IBGE 2000b) and develop as ramps from the edges and foothills towards the depression. The colluvium becomes thicker at the base of the scarps, where they are deposited in the form of cones and fans.

Due to the lithological characteristics of the region and predominance of erosion processes away from fluvial valleys, soils that develop at the top are shallow and assume the form of sandy pavements, sometimes laterised. In the lower portions, between the embedded valleys, pedogenised colluvium ramps accumulate, built of thick packages of sandy soils and spots of yellow and yellow-red latosols. The predominantly sandy texture of these deposits is also associated with disaggregation of reddish and brown siltstones interspersed with white to pink sandstones of the Motuca Formation, whereas silty clay texture and reddish colour predominate on top of the basalticflow rocks of the Mosquito Formation (IBGE 2000d).

The Chapada das Mesas is an important regional hydrographic divide. In the west, the Farinha and Manuel Alves Grande rivers stand out, both right margin tributaries of the middle Tocantins River, whose hydrographic network drains most of the area of the national park. This region also contains the water divide of the Parnaíba, Mearim and Itapecuru rivers (Alencar et al. 2004).

In addition to its status as a water divide, the litho-structural characteristics play a key role in the organisation of drainage system, adapted to structural lineaments in the densely fractured sandstone formations, which provide significant water infiltration and storage capacity. The drainage is controlled by the fracture lines, which unfold in beautiful canyons, gorges, waterfalls and rapids.

Several waterfalls in deeply incised valleys stand out. The Cocal River, located in the region of the city of Riachão, is one of the most visited tourist spots in the region and shows a sequence of knickpoints that give rise to the Namorados, Santa Paula, Santa Bárbara (Fig. 18.5), Dona Luiza and Poço

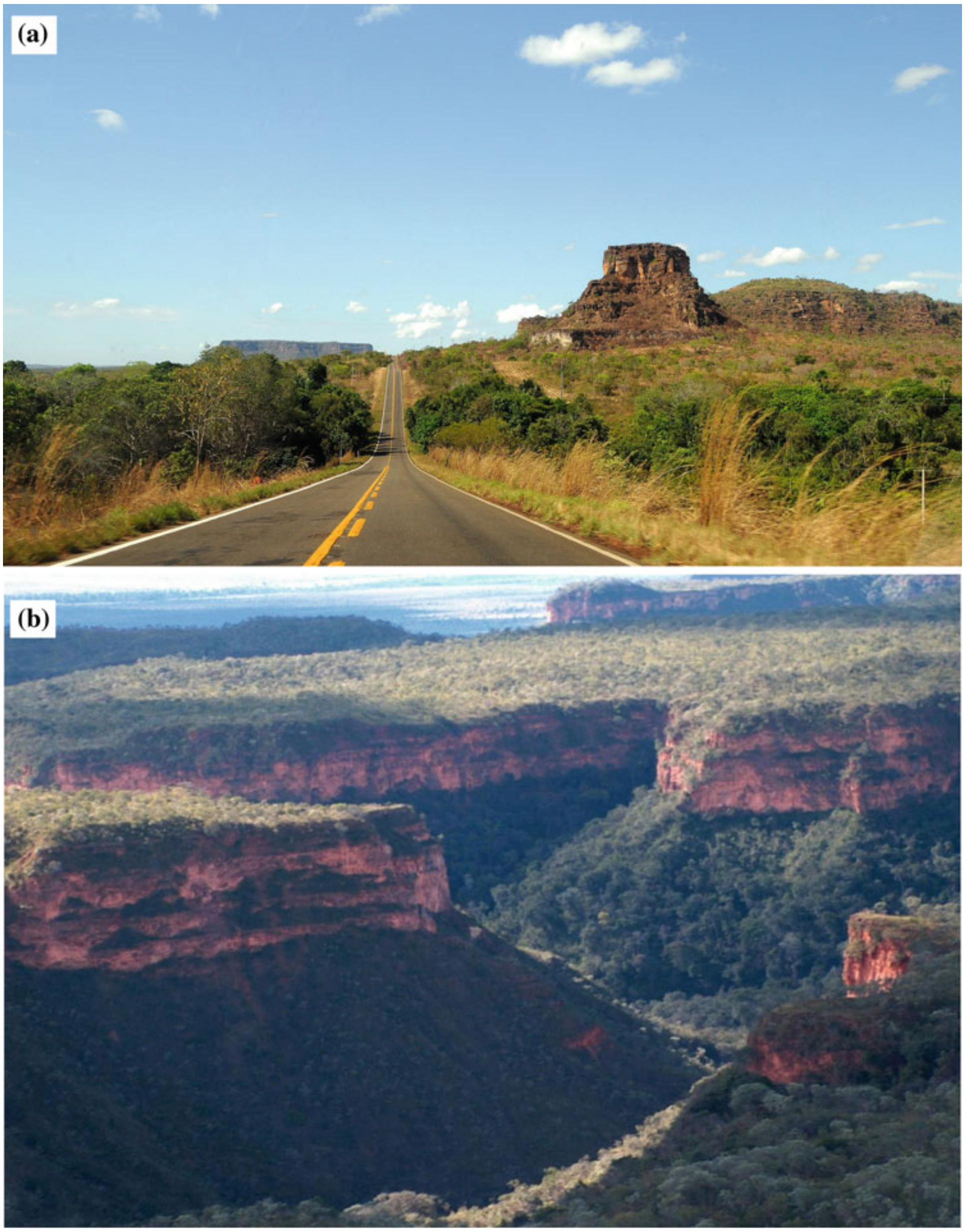

Fig. 18.3 **a** Landscape along the BR-230 highway, with the presence of hills in Carolina, state of Maranhão, Brazil. (*Photo* by Meireles Júnior). **b** Sandstone scarps with narrow and deep canyons within the Chapada das Mesas National Park. (*Photo* by Ana Rosa Marques)

Azul waterfalls. The greenish waters of Poço Azul and Poço Encanto Azul (Fig. 18.6) evidence a contribution from limestone rocks of the Motuca Formation.

In the west of the PNCM, in the region of the city of Carolina, one of the most important tourist complexes of southern Maranhão is found, the Pedra Caída Sanctuary. In this area, the Santuário, Pedra Caída, Caverna, Capelão and Garrote waterfalls stand out, all located in the basin of the Pedra Caída creek, a tributary of the Tocantins River.

The Farinha River, 207 km long, is also important in the area. The vertical drop along the Farinha River is approximately 260 m, ranging between the altitudes of 403 m asl, near the headwaters, to 140 m asl at the mouth (Consórcio Rio Farinha 2001). There are two major waterfalls along the river: the Prata and São Romão. The Prata waterfall is formed when the river plunges from a height of 17 m and passes through two large canyons, separated by a large rock outcrop, splitting into three parts: the first, on the left side, is arranged into steps; the second is a central waterfall in a large U shape; and the third is positioned on the right side of the photograph (Fig. 18.7).

The São Romão waterfall is a water drop approximately 25 m high. Before it falls, the stream is distributed into two branches separated by a rock outcrop: the first drop is

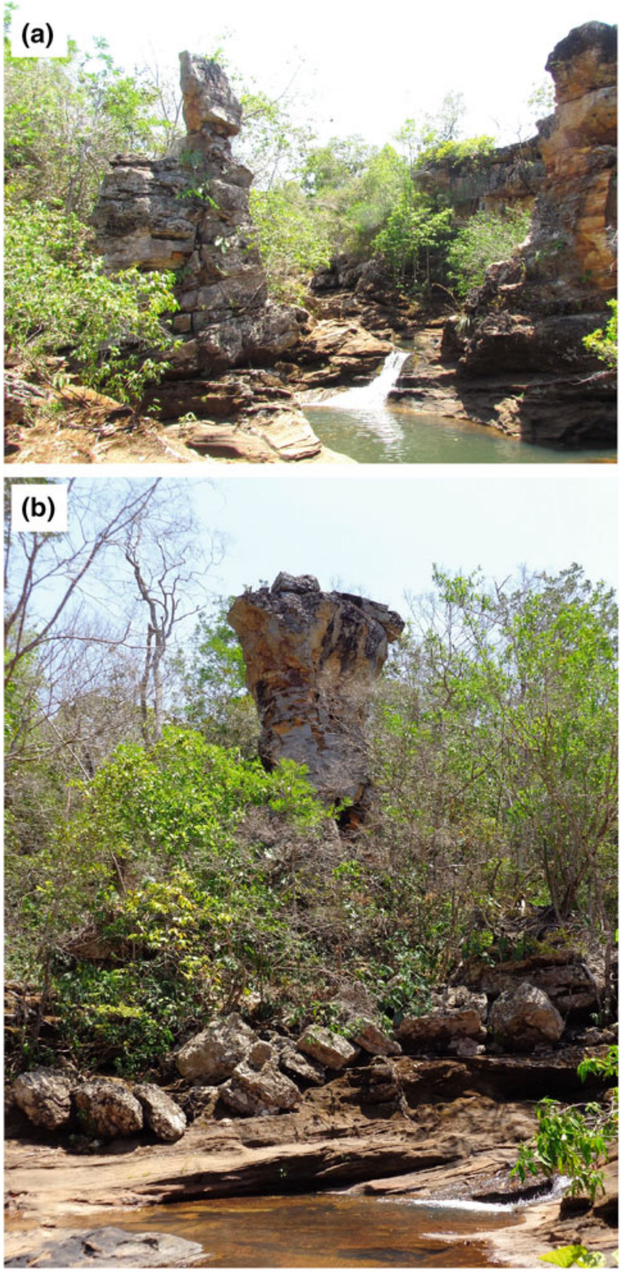

Fig. 18.4 View of morphological features in the Santa Paula and Namorados waterfalls area. **a** Dedo de Deus and **b** Cálice. (*Photo* by Helen N. Barreto and Jorge H. S. Santos)

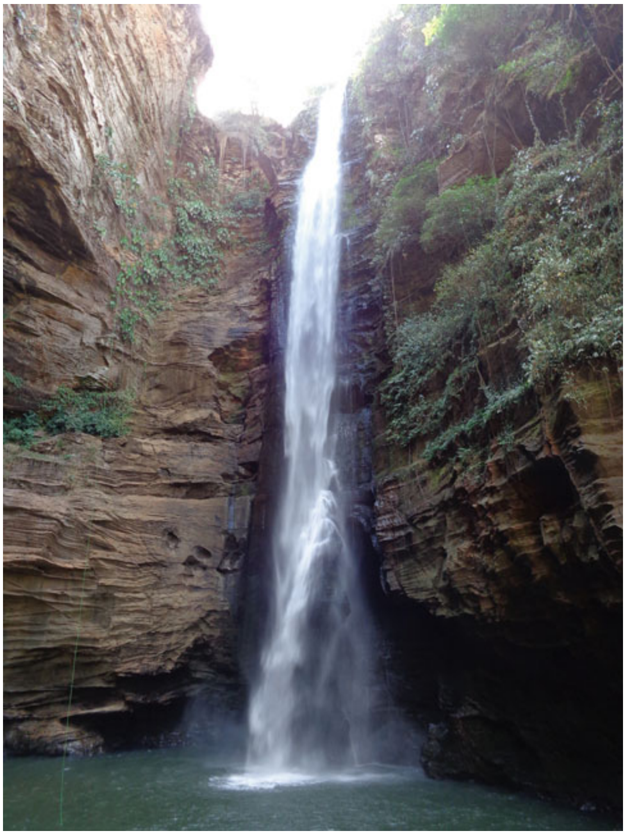

Fig. 18.5 The Santa Bárbara Waterfall, Cocal River (city of Riachão), with a 75 m water drop, is used for rappelling. (*Photo* by Helen N. Barreto)

similar to an arch, forming a curtain; the second branch falls in three steps, forming cascades. Due to its beauty and the presence of warm waters and crystal clear pools, it is one of the most visited waterfalls of the Chapada das Mesas National Park.

Rocks of the Mosquito Formation are exposed at these two waterfalls, which are lithologically characterised by the presence of basalts, with lenticular interbedded whitish sandstones with cross-stratification, levels of pink siltstones and silex blades. At the base, the Sambaíba sandstones occur interbedded with basalts that show dark green to black colours as fresh rock and greenish to purplish colours when weathered.

18.3 Geo-ecological Potential of the Chapada das Mesas Region

Because of the magnitude of the landscape and aspects related to relief, the Chapada das Mesas can be considered a geomorphological heritage that, according to Pereira (2006), belongs to the geological heritage category defined as the set of geomorphological elements (geoforms, deposits and processes) at several scales, that acquired one or more value types through its scientific assessment, which must be protected and valued. According to the author, the first part of an inventory is considered for the assessment of geomorphological heritage according to the following criteria: (i) scientific, (ii) aesthetic, (iii) association between ecological and geomorphologic elements and (iv) association between geomorphological and cultural elements. All these criteria are met in the Chapada das Mesas area.

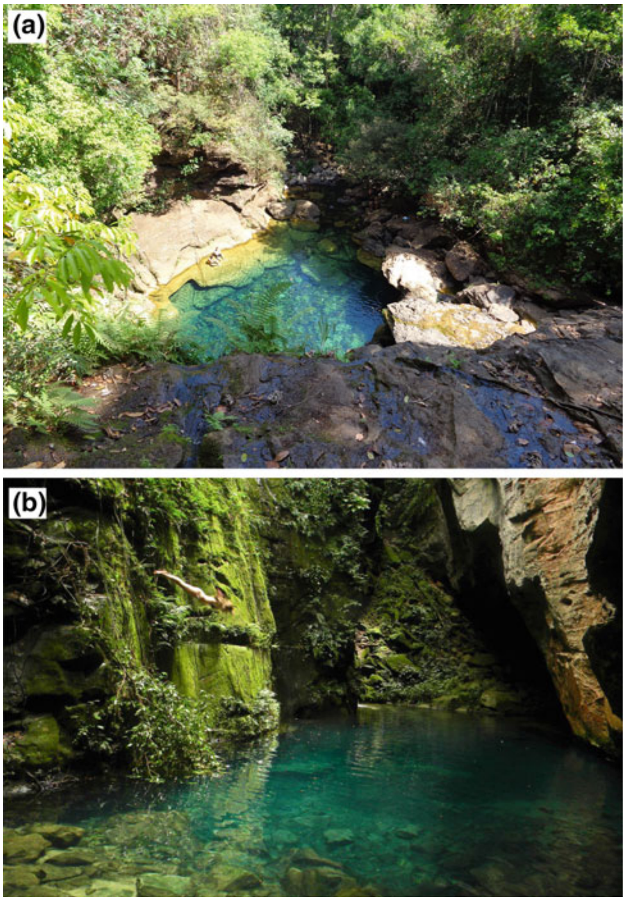

Fig. 18.6 **a** The *greenish* waters of Poço Azul, along the Cocal River, are excellent bathing places for visitors and/or tourists. **b** Poço Encanto Azul, located on a tributary of the Cocal River. (*Photo* by Helen N. Barreto and José C. Soares)

18.3.1 Scientific Value

The current relief configuration—a product of long-term denudation accomplished in several erosive stages—brings to light in the geological/geomorphological discontinuities a history of millions of years. It provides information about the genesis of waterfalls, canyons, tunnel systems, gorges and caves, morphodynamic conditions responsible for their occurrence, as well as about palaeoenvironments, particularly the transgressive and regressive events and the desertification process responsible for the creation of the palaeodesert called Sambaíba in southern Maranhão state. Moreover, the presence of rupestrian paintings at the "Morro das Figuras" and the recent discovery of dinosaur footprints in the sandstones of the Sambaíba Formation by Assis and Macambira (2007), Almeida (2012) show how much we have yet to discover about the archaeological, paleontological, geological and hydrogeomorphological aspects of this region, among others. From this perspective, the region can be considered to have high scientific value.

18.3.2 Aesthetic Value

The lush scenic beauty of the plateaus, numerous waterfalls and mosaics of different types of phyto-physiognomies also confer great aesthetic value. The presence of beautiful landscapes and several tourist routes, especially for the members of the tourism hub of the Chapada das Mesas, has enabled the development and intensification of ecotourism activities in recent years. Other factors contributing to the growth of this activity are the good receptivity of the local population and the growing infrastructure of tourism enterprises (inns, hotels and resorts) in the region.

18.3.3 Association Between Ecological and Geomorphological Elements

The Chapada das Mesas, located in an area of semi-humid climate, with an annual average rainfall of 1,140–1,740 mm, is characterised by two well-defined periods, a rainy period between the months of October and May and a dry period from June to September, with annual temperature averages of 26 °C in Carolina. The average of the annual maximum temperatures is between 34 and 36 °C, and the minimum temperatures are between 18 and 19 °C in the region (Alencar et al. 2004). The area shows considerable morphological diversity and also serves as an ecotone in the transition between the Amazon (equatorial tropical forest), cerrado (tropical savannah) and Caatinga (Brazilian semi-arid steppe). Despite the lack of studies in this regard, Marques (2012) states that only in the area of the Chapada das Mesas National Park, is it possible to find, in addition to extensive areas of cerradão and cerrado *strictu senso*, typical species of the Amazonian vegetation, especially in the gallery forests, and relicts of xeromorphic vegetation on the tops with detritic lateritic coverages linked to the arid environmental conditions or semi-arid ones from the past (Fig. 18.8). Endemic fauna are also found in these diverse environments (Garcez; Fonseca; Tchaika 2011 apud Marques 2012). It is important to emphasise that the savannah, the main vegetation type found in the area, is one of the most threatened biomes in the world, despite being considered a *hotspot*, due to the high concentration of endemic species and the very fragility that the biome shows, with 20 % of the native vegetation of the entire planet (Conservation International 2010).

18.3.4 Association Between Cultural and Geomorphological Elements

Regarding the last aspect considered by Pereira (2006), the sertanejo people currently predominate in the region, with their way of life intimately connected with abundant natural

Fig. 18.7 Aerial view of the Prata Waterfall, one of the most visited attractions in the Chapada das Mesas National Park in Carolina, MA. (*Photo* by Ana Rosa Marques)

Fig. 18.8 In the planar areas of the mesa tops, there is grass vegetation, rock fields, patches of savannah or relicts of xeromorphic vegetation, whilst on the colluvium ramps, with fan-shaped deposits, denser vegetation is developed, called cerradão. In the valleys, there are dense riparian forests, and in the wetlands, the presence of the veredas stands out. (*Photo* by Ana Rosa Marques)

resources in the region, building their houses and work utensils with materials from the soils and vegetation and extracting much of their food from the native species. According to Marques (2012), the territoriality of the backland savannah is printed on the landscape through his culture, and his coexistence with the environment is very intense, taking over and transforming the space where he lives, with little change to the landscape.

The Timbira people, who survived contact with white population, were brought to live in regions surrounding the indigenous lands demarcated by the Brazilian government. However, these lands do not always correspond to the locations of greatest identity. Marques (2012) states that there is a close connection between these indigenous peoples and this territory, which they consider of sacred origin because they believe that the origin of the Timbira people is in this soil, having as starting point the Chapéu hill, an residual relief that is located near the urban site of Carolina. This connection makes them stay in constant movement towards the region of the Chapada das Mesas because their lands are currently located in neighbouring cities.

Conservation of this natural heritage will be more effectively achieved with the preparation of the still non-existent management plan of the Chapada das Mesas National Park. This legal document must be elaborated in a participatory manner, encouraging geo-ecological tourism because a call for this activity was detected during the creation process of the park and also encouraging the development of research with the aim of understanding the natural and social dynamics of the region. The effective implementation of this conservation unit should be the key to local development in a sustainable manner, taking advantage of the communities that live there to generate income, improve the living conditions and inhibit, to some extent, the expansion of monoculture in this territory of countless and unknown beauties.

18.4 Final Considerations

The Chapada das Mesas has a unique beauty, with residual relief that stands out amid extensive planar surfaces and valleys often assuming the form of deep canyons and gorges, with crystal clear rivers and waterfalls. Most of these rivers derive from springs in the national park, where they begin their course in the Savannah domain, draining different mosaics of vegetation towards more humid region, where the rivers meet the lush Amazon vegetation. The secular traditions and rituals of the Timbira people and the unique customs of the sertanejos, pioneers of the region, add to the environmental wealth. However, this important Brazilian geomorphological heritage has been threatened by the expansion of agricultural monoculture and extensive cattle breeding, a fact that can be changed with scientific studies that aim to provide a better understanding of the environment and its relationships with the local communities and encouragement of ecotourism.

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Chapada Diamantina: A Remarkable Landscape Dominated by Mountains and Plateaus

19

Carlos César Uchôa de Lima and Marjorie Cseko Nolasco

Abstract

Chapada Diamantina is located in the central portion of Bahia state in northeastern Brazil and is marked by mountainous relief with pronounced scarps, deep valleys, and high plateaus. Lithologically, this region is dominated by metasedimentary rocks formed over a period of 900 million years during the Proterozoic. Between 500 and 600 million years ago, the last major tectonic event raised the sedimentary package in a sequence of alternating synclinal and anticlinal folds that are cut by faults in several directions. This arrangement, combined with the current fluvial system, has resulted in a relief marked by flattop elevations that reach over 1,800 m in altitude. Two major geomorphological domains are observed at Chapada Diamantina. The karstic domain is dominated by flat relief and slightly undulating terrain. The main features include collapse sinkholes and caves that extend into galleries for up to tens of kilometers. The lithostructural domain consists mainly of quartzite rocks and is divided into three subdomains: (1) Rio de Contas in the western portion, with a very irregular relief and marked by lowered anticlines and hanging synclines with centers emptied by differential erosion, which exposes its flanks in hogbacks; (2) Paraguaçu in the eastern portion, where the flank of a large anticline that is raised and slightly inclined toward the east predominates, and (3) Central Pediplain in the central-southern portion (marked by flat to hilly terrain with some residual elevations). In addition to fluvial morphodynamics, several anthropogenic features have developed over the past 200 years from mining activity.

Keywords

Scarpland • High plateaus • Fluvial morphodynamics • Mining

19.1 Introduction

Chapada Diamantina is located in central Bahia state in northeastern Brazil (Fig. 19.1) and covers an area of approximately 38,000 km^2. This region is characterized by complex mountainous relief, with an altitude above 600 m. In addition, this region is characterized by flat-topped highlands with altitudes of up to 2,000 m and with an average altitude between 1,000 and 1,500 m. The mountains are flanked by vertical escarpments and deep valleys that resulted from the interactions of tectonics and erosion rocks. Erosion is dominated by fluvial processes, which contribute to the development of morphological features of great scenic beauty such as canyons (Fig. 19.2).

The highest altitudes occur in the quartzite areas with more irregular relief, especially in the western portion of the region where the highest peak in northeastern Brazil occurs, with an elevation of 2,033 m. In the eastern portion, the relief is less irregular despite the predominance of quartzitic rocks, and thick soils occur in the valleys. The central-northern region and a part of the eastern portion of Chapada Diamantina are characterized

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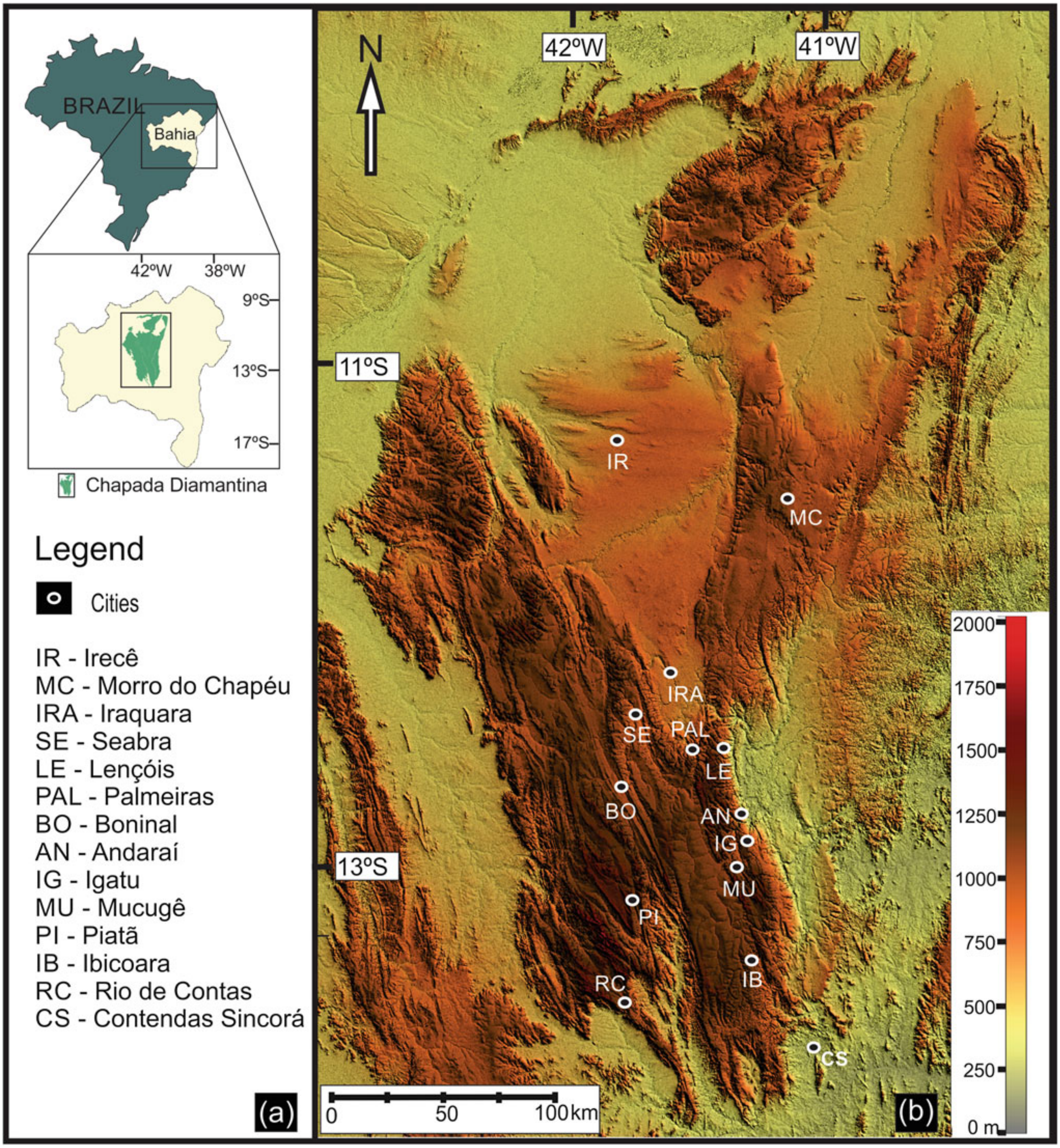


Fig. 19.1 **a** Location map of Chapada Diamantina. **b** Hypsometric map made from SRTM images that show relief distribution and indicate that the altitude at Chapada ranges from approximately 600–2,000 m. In addition, the distribution of the main cities in Chapada Diamantina is shown

by a predominance of carbonate rocks and are marked by flat to slightly undulating areas, with sinkholes and caves.

The climate at Chapada Diamantina is strongly influenced by altitude, characterized as humid to subhumid, and has two well-defined seasons. The temperature varies greatly, reaching over 30 °C in the summer and as low as 8 °C in the winter, with averages of 26 and 15 °C, respectively. The period of greatest rainfall occurs from November to May, and drought occurs from June to October, with a total annual rainfall of between 800 and 1,400 mm (INMET 2009).

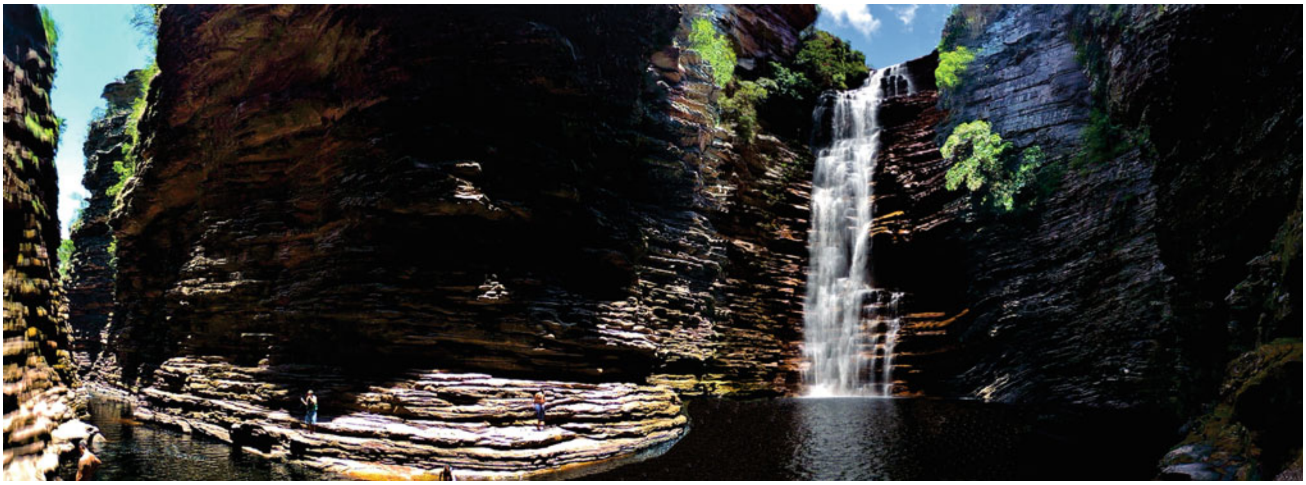


Fig. 19.2 One of several canyons that resulted from the interactions between fluvial systems and structural weakness zones in the rocks (tectonic faults and joints). The waterfall to the *right* is 80 m high

Due to its environmental relevance, the unusual richness regarding rock outcrops, flora, fauna, and archaeological sites found in the numerous caves in the area, and its historical and cultural aspects, several environmental and historical protection areas were created within the boundaries of Chapada Diamantina. Among these areas, the Chapada Diamantina NationalPark and the Contendas do Sincorá National Forest are notable. In addition, the cities of Rio de Contas, Lençóis, Mucugê, Igatu, and Palmeiras are important and are national historic landmarks.

Diamond mining activity was historically established at Chapada Diamantina. Consequently, several human settlements have emerged and formed major cities, which resulted in intense environmental changes. This profound man–nature interaction has developed anthropic landscapes that are recorded by anthropogenic forms, processes, and deposits (Nolasco 2002).

19.2 Geological and Stratigraphic Aspects

The rocks that outcrop at Chapada Diamantina are predominantly metasedimentary and date from the Proterozoic, and according to Pedreira and Margalho (1990), they are stratigraphically divided into four groups (Fig. 19.3). The Rio dos Remédios Group (whose age is considered to be 1.7 GA) is dominated by quartzites, metaconglomerates, and weakly metamorphosed siltstones and mudstones. These rocks resulted from deposition in fluvial, desert, and marine environments (Pedreira 1994). This unit outcrops on a narrow range in the southwestern portion of Chapada Diamantina. In addition to the metasedimentary rocks, acid effusive rocks such as rhyolite and dacite are present.

The Paraguaçu Group was mainly formed in fluvial and deltaic depositional systems (Pedreira and Margalho 1990; Bonfim and Pedreira 1990). However, rocks typical of desert environments were found at some sites. The sandy sediments that turned into metasandstones were deposited where rivers occurred. In addition, deltas were responsible for the deposition of fine sediments that formed metasiltstones and metamudstones.

The Chapada Diamantina Group is divided into three formations. At the base, the Tombador Formation appears with dominant metasandstone and metaconglomerate lithologies. These rocks were formed from sediments originally deposited in alluvial fans, braided fluvial systems, and eolian systems Lima and Nolasco (1997). The second formation is named Caboclo and originated as the sea level rose. This rise occurred slowly and gradually and deposited tidal-flat sediments in shallow settings and storm sediments in deeper settings (Dominguez 1993). In addition to the siliciclastic sediments, this formation has stromatolitic limestone lenses (Bonfim and Pedreira 1990). As the sea level declined, continental environments became dominant, and the Morro do Chapéu Formation originated. This formation is dominated by fluvial and eolian environments, with mainly sandy and gravelly sediments.

The sediments in the Una Group were deposited since approximately 700 million years ago. This group is divided into two formations. The lower one is the Bebedouro Formation, which originated during global glaciation. During that period, glaciers and seas deposited sediments that formed diamictites and laminated siltstones, indicative of a glacial–marine environment (Dominguez 1993; Pedreira 1994). As the glacial period ended, the flatter areas were flooded and formed an inland sea rich in salts (Lima 2011).

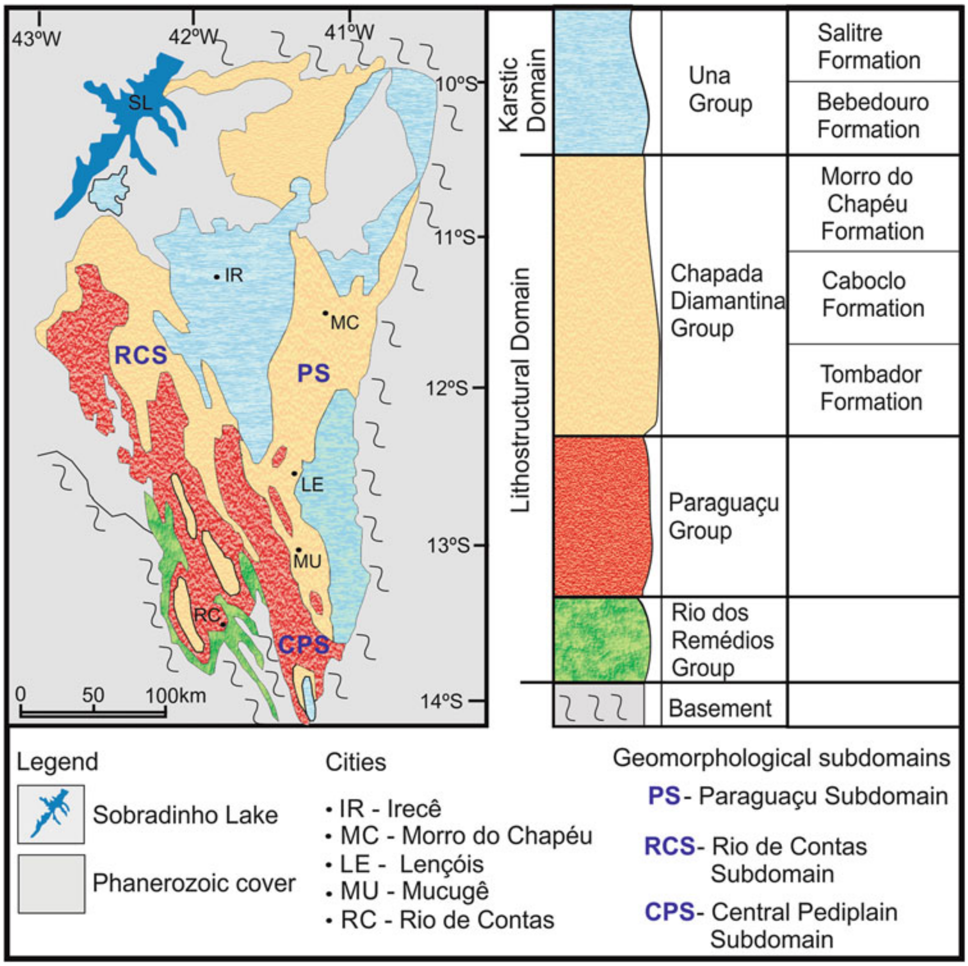


Fig. 19.3 Lithological map, stratigraphic distribution, and geomorphological domains of Chapada Diamantina. The karstic domain is lithologically represented by the Una Group, while the lithostructural domain is represented by the Rio dos Remédios, Paraguaçu, and Chapada Diamantina groups

This sea deposited carbonate sediments in the Neoproterozoic, which correspond to the upper Salitre Formation (Bonfim and Pedreira 1990). The shallow depth of the sea resulted in the development of the algal mats that currently outcrop in the form of stromatolites. These algal mats were formed by cyanobacteria or blue-green algae.

19.3 Morphogenesis and Morphodynamics

The structuring of the highlands that nowadays form the Chapada Diamantina began between 600 and 500 million years ago when the Brasiliano tectonic cycle led to uplift of a mountain range and folding (Fig. 19.4a). In addition to the folds, many fractures became zones of weakness in the rocks. In these zones, weathering and erosion subsequently occurred and has modeled the current relief.

The complex system of folds in Chapada Diamantina is characterized by alternating antiforms and synforms. Although some of these folds have narrow flanks, folds with wider flanks are dominant. These folds are cut by faults that are arranged in several directions. The most prominent faults are orientated NNW-SSE. The folds with more inclined or asymmetrical flanks have a greater number of layers exposed, which causes the erosion processes to occur faster at the interface between the more competent and less competent layers. This process resulted in more irregular relief in these areas (Fig. 19.4b).

The structural morphogenetic and fluvial morphodynamic aspects regulate the shaping of the terrain due to the alternation between the more brittle rocks and the more competent rocks and fracture density throughout the entire Chapada Diamantina. In addition to the variations in resistance to erosion, tilting of the rocks exposed different lithologies, which favored the action of differential erosion and caused the terrain to become more irregular where the layers were at a greater angle or had a greater fracture density. Regarding the lithological resistance, the clayey and silty rocks were originally eroded more effectively than the metaconglomerates and quartzites, whose erodibility is low to intermediate.

In the karstic domain, bedded limestone outcrops occur. These outcrops are horizontally structured or slightly tilted, indicating the occurrence of tectonic activity after their formation. In addition to the tilted layers, several small folds

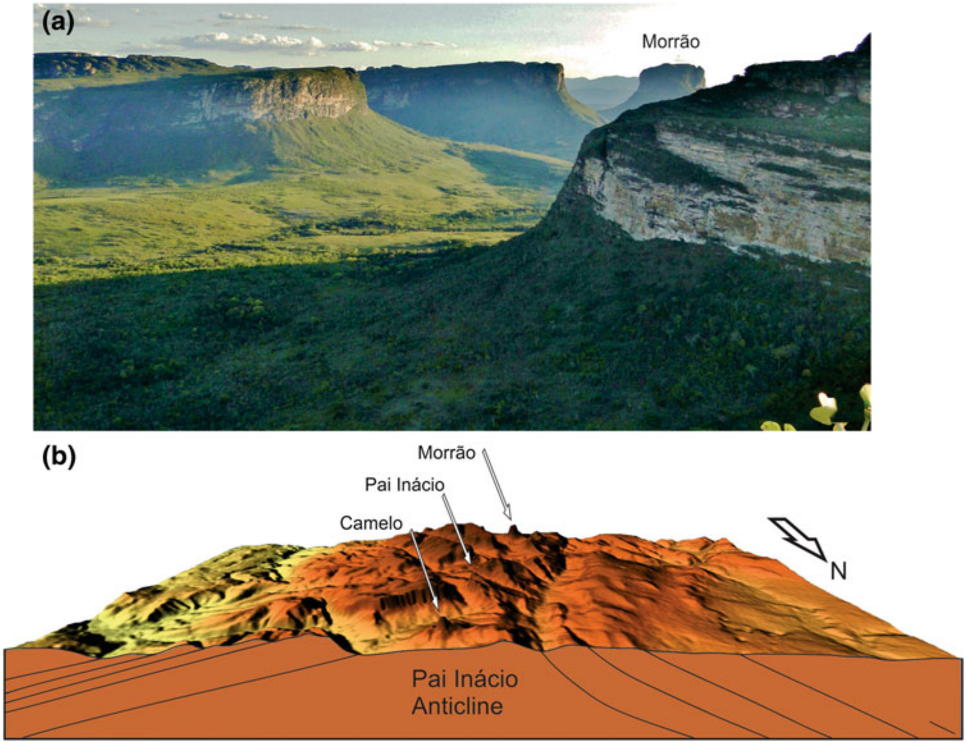


Fig. 19.4 **a** The slightly asymmetric Pai Inácio Anticline. The fold axis is emptied and forms wide valleys. The bare rock scarps differ from the vegetation-covered talus. The photograph was taken from the top of Morro do Pai Inácio. Morrão appears in the background. **b** Three-dimensional diagram showing the Pai Inácio Anticline. Some natural monuments, locally known as Pai Inácio, Morrão, and Morro do Camelo, are indicated by *arrows*

and a complex system of fractures confirm the occurrence of post-depositional tectonic activity. At the sites where fracture density was more pronounced, water infiltration resulted in the dissolution of limestone and lowered the terrain.

In addition to the macroforms of fluvial–structural origin, the area features anthropic modifications along the valleys. These have mainly resulted from diamond mining processes, which overlapped in some areas in the last 200 years. Consequently, the valleys were modified and widened, which promoted emptying of fracture zones and steepening of smaller valleys. In addition, smoothing and lowering occurred in mining areas (Nolasco 2002).

19.4 Geomorphological Domains

Chapada Diamantina was divided into two large domains (Fig. 19.3). In the karstic domain, the largest outcropping area occurs in the central and northern region of the Chapada. The lithostructural domain covers the southern region of the Chapada and extends into its northeastern and northwestern regions.

19.4.1 Karstic Domain

The karstic domain occupies the central-northern portion of Chapada Diamantina and includes important exposures in the southeast and northeast regions. The main outcrop area in the karstic domain is roughly triangular in outline, with a wide base at the north and tapering toward the south, showing a flat to undulating terrain. Small circular depressions, with diameters that range from a few to several tens of meters and with depths that range from a few decimeters to a few meters, appear at several places. These depressions are small solution sinkholes.

Among the most prominent karstic structures, collapse sinkholes are prominent and reach diameters and depths of several tens of meters (Fig. 19.5a). Some dissolution valleys are present, and several caves exist in the subsurface. Many of these caves have been partially mapped. These maps indicate the presence of complex galleries that reach lengths of tens of kilometers. In addition, many caves expose the water table. For example, the Poço Encantado cave has a maximum water level depth of 61 m (Fig. 19.5b). Other caves occur above the water table and have galleries with speleothems from a few centimeters to several meters in length. Stalactites, stalagmites, columns, and curtains are among the most common speleothems. Surface currents flow at some sites, but disappear into sinks and blind valleys.

19.4.2 Lithostructural Domain

The lithostructural domain in the Chapada Diamantina was divided into three subdomains: Paraguaçu, occupying the

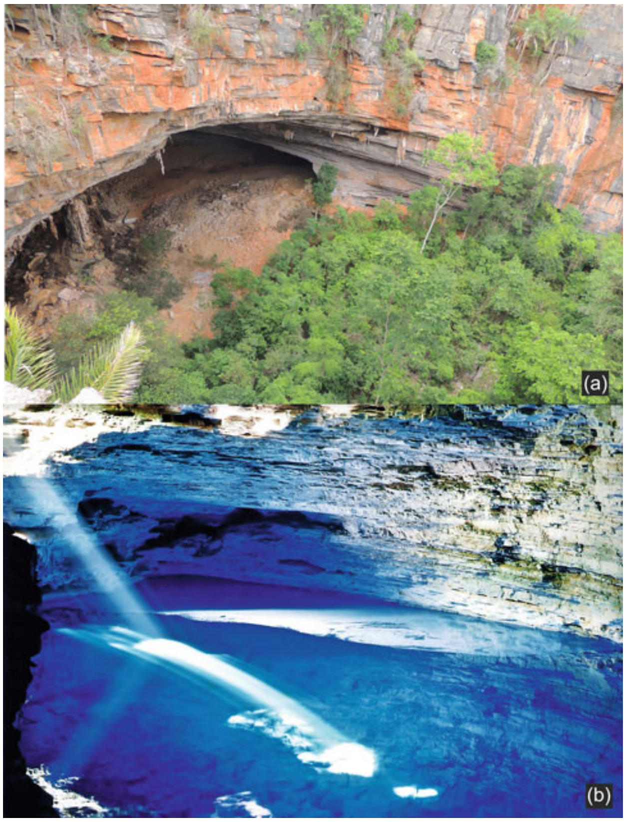


Fig. 19.5 **a** Collapse sinkhole marking the entrance of the Lapa Doce cave in the city of Iraquara. The depression is over 60 m deep. **b** The Poço Encantado cave. The transparency of the water is typical of limestone areas. The incidence and refraction of sunlight in the water occur between May and August

eastern region, Central Pediplain, occupying the central-southern region, and Rio de Contas, occupying the western region (Fig. 19.6).

The Paraguaçu subdomain is an important area of springs and hosts the second largest hydrographic basin in the state of Bahia. In this subdomain, the terrain is smoother, and tectonics has changed the original rocks to a lesser extent. As a result, wide and smooth folding occurred in this subdomain, which usually resulted in a low inclination of strata. This low inclination assisted in the preservation and arrangement of many geomorphic features that outcrop on the eastern edge of Chapada Diamantina (Fig. 19.6a). Two areas with different geomorphological characteristics stand out. The first area is Serra do Sincorá, and the second area is the Morro do Chapéu Plateau. Both these areas are dominated by metasediments of the Chapada Diamantina Group.

The Serra do Sincorá occupies the southeastern portion of this subdomain, where important cities, such as Lençóis, Andaraí, and Mucugê, are located. The Serra do Sincorá has a slightly tilted and tabular top that is represented by the preserved flank of a large anticline, gently tilts toward the east, and is composed of metasediments from the Tombador Formation. The highest and lowest elevations in the Serra do Sincorá are approximately 1,400 and 400 m, respectively. The lowest altitudes correspond to the valleys and the confluences between the river courses (Nolasco et al. 2008).

The axis of the anticline that forms the Serra do Sincorá has an empty center and is marked by a sequence of residual flattop highlands. These highlands have differences in elevation that can reach up to 200 meters. In addition, they have gone through different stages of denudation and may form pronounced free faces. These faces make up some of the most known and visited landforms in the region, such as Morro do Pai Inácio (Fig. 19.7a). Other residual highlands, locally known as Morro do Camelo and Morrão (shown in Fig. 19.4b), appear within the valley and define the anticline axis. The top surface is bound by vertical fronts, followed by talus that consists of boulders from rockfalls. Rockfalls are the most common form of mass movement in this morphological domain.

The presence of main zones of weakness has resulted in significant elevation differences, leading to the formation of circular basins. Among them, the Vale do Capão, Paty, and Campo Redondo (Fig. 19.7b) are notable, bounded by vertical fronts, and can reach topographic unevenness of more than 400 m.

The Morro do Chapéu Plateau is composed of rocks from the Tombador and Caboclo formations and occupies the northeastern region of the Chapada Diamantina. The relief is predominantly tabular. However, the most dissected areas occur in this region and include hills with convex slopes and deep valleys flanked by scarped slopes. Throughout the Paraguaçu Domain, interconnecting talus may be cut by streams, originating glacis. In some places, these glacis are dissected by shallow and wide valleys.

The Central Pediplain subdomain is mainly composed of rocks from the Paraguaçu Group. This area has mainly flat relief and altitudes of more than 1,000 m. Some residual highlands can reach up to 1,400 m, and the terrain is dissected on the southern and northern borders in the lowest altitude areas. Due to its topographic arrangement and subhumid climate, the Central Pediplain has intense agricultural activity (see Fig. 19.6b).

The residual highlands in this immense flat area are arranged as hills with convex flanks or as isolated tops with tabular arrangement. These areas correspond to a structural surface and elevation differences are between 200 and 400 m. In addition, highlands with elongated crests that extend up to tens of kilometers appear. Some of these highlands occurring to the south of the Central Pediplain demarcate places where folds close and are mainly hanging synclines (Nunes et al. 1981).

The low gradient of the pediplain sets the stage for dense drainage that follows a dendritic pattern. Many streams and rivers run perpendicular to the residual relief and take

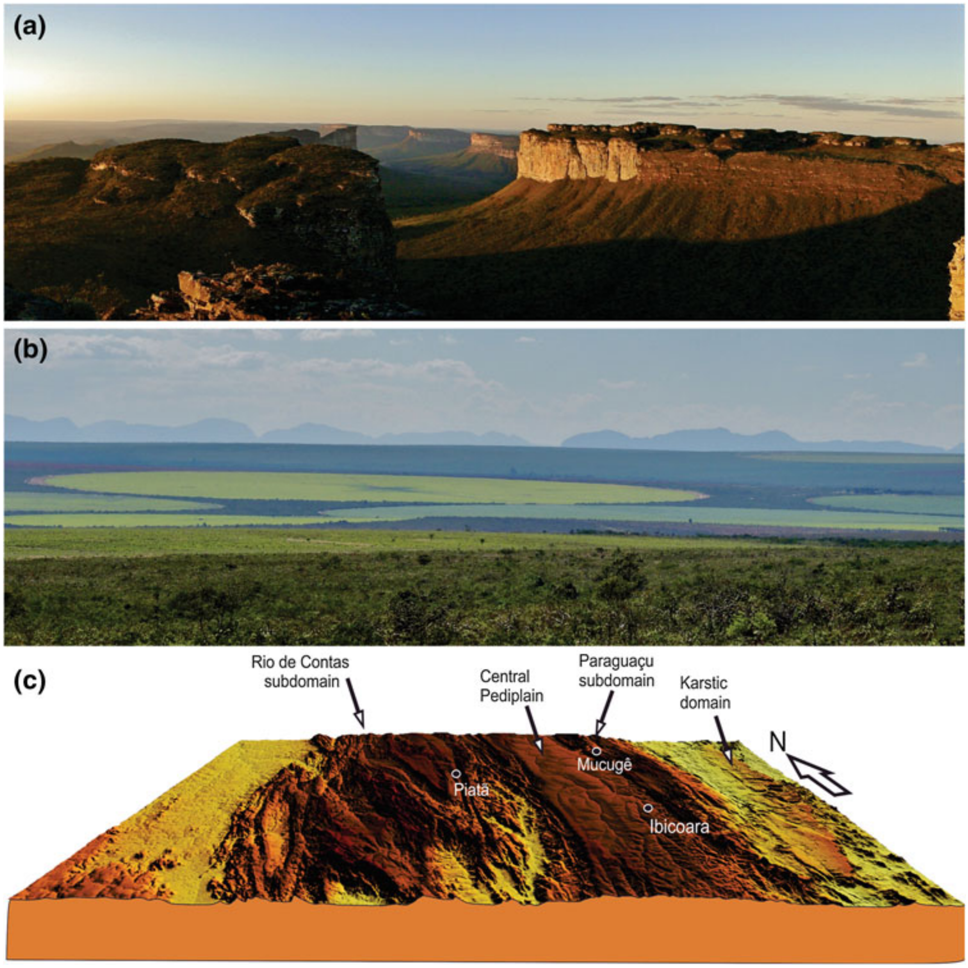


Fig. 19.6 Landscapes that represent the three lithostructural subdomains: **a** the Paraguaçu subdomain, which consists of mountains with low-gradient flattops; **b** the Central Pediplain subdomain, which features a smoother relief. The highlands of the Rio de Contas subdomain appear in the background; and **c** three-dimensional diagram of the geomorphological domains in the southern portion of Chapada Diamantina

advantage of zones of weakness in the rocks. The larger channels run parallel to the edges of the mountains that surround the Central Pediplain and have low sinuosity.

The Rio de Contas subdomain (Fig. 19.8a, b) is an area of springs from the homonymous hydrographic basin. This basin is the largest one in terms of area among those that contribute flows in Bahia. In addition, this subdomain is located on the western boundary of the Chapada Diamantina, where important cities, such as Rio de Contas and Piatã, are located. The terrain is characterized by peaks higher than peaks in the Paraguaçu subdomain and by irregular relief due to intense tectonic activity. The highest elevations in the Brazilian northeast occur in this subdomain. These elevations are generally greater than 1,000 m and often above 1,400 m. For example, Pico do Barbado (located in Serra da Mesa) is 2,033 m high (Fig. 19.8b), and Pico das Almas (located in Serra das Almas) is 1,958 m high.

The morphology of this region is sculpted in metasediments of the Chapada Diamantina and Paraguaçu groups and marked by residual highlands carved in ancient folds. Of secondary importance, but still with good representation, is the Rio dos Remédios Group, located in the southwest portion of this subdomain and consisting of fine- and medium-grained metasandstones and acid volcanic rocks.

Similar to the Paraguaçu subdomain, the shaping of the Rio de Contas occurred through differential erosion controlled by morphotectonic aspects and lithology. However, these two domains are different because the tectonic process that raised the Rio de Contas terrain created narrower and longer folds with some alternating wider folds. Consequently, the relief is more dissected than at the eastern boundary of the Chapada Diamantina. Among the folded structures, the Piatã syncline is the most prominent (Fig. 19.8a, b). This syncline is a wide symmetric fold known locally as the Serra da Mesa and extends from the headwaters of the Rio de Contas.

The combined action of fluvial systems and the previous tectonic activity resulted in irregular relief, exposed older rock groups, and carved highlands with steep slopes and sharp tops, arranged as hogbacks (Fig. 19.8b). The rocky parts of scarps are usually formed by free faces on the top of the scarp with a vertical front and detrital talus that joins the

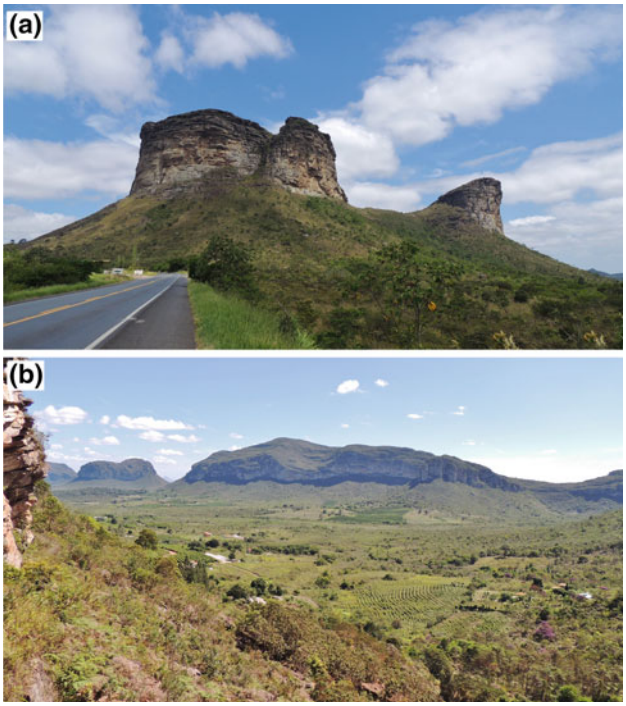


Fig. 19.7 **a** Morro do Pai Inácio is one of the best known residual highlands in the Paraguaçu subdomain. **b** The circular basin of Campo Redondo in the city of Ibicoara

partially dissected glacis. According to Nunes et al. (1981), many interfluves at lower elevations are arranged in hills with irregular slopes or with a concave–convex profile.

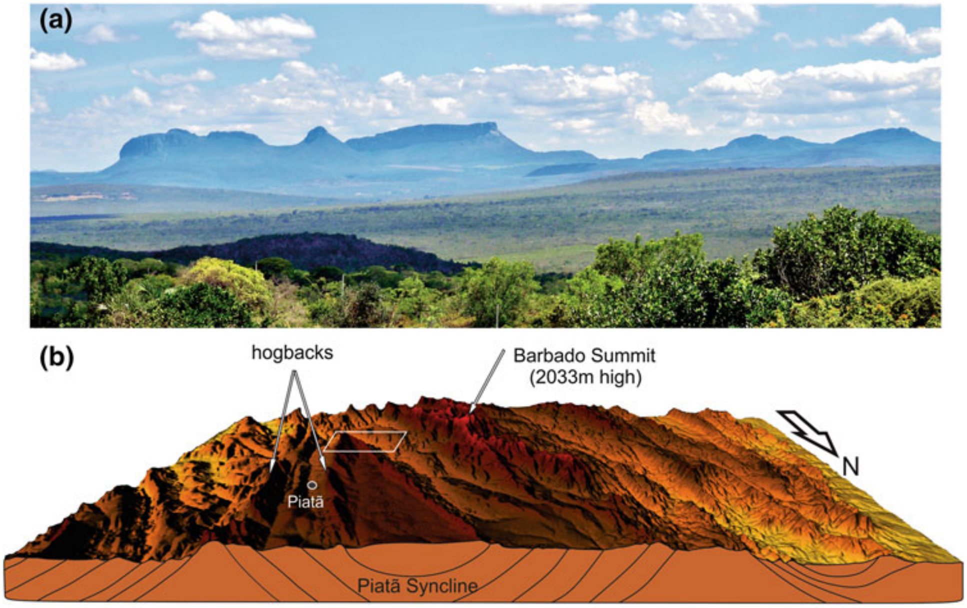
Similarly to the entire lithostructural domain of the Chapada Diamantina, the anticlines have been preferentially eroded, while the edges of the synclines constitute the highest elevations. Many hanging synclines have developed in the central areas that correspond to the partially dissected pediplains. These areas are filled by colluvial glacis that sometimes are overlapped with rocky fragments, originated by rockfall.

19.5 Anthropogenic Geomorphology

For the Chapada Diamantina, Nolasco (2002) and Nolasco et al. (2000) reported that anthropic geomorphological change began in the second half of the nineteenth century. This can be inferred from the text of the Empire inspectorate titled “The bones of the Chapada are exposed” (“As ossadas da Chapada estão expostas,” Acauã 1885; Allen 1870), which was presented in regional novels, such as Maria Dusá (Lima 1932), the Practical Description of the Provinces of Bahia (Descrições Práticas das Províncias da Bahia, Aguiar 1888), or the works of Gonçalo de Athaide Pereira (1907, 1910, 1937) and Sales (1955, 1966). These studies showed the effects of mining activities that were linked to the occupation of the region at regional (macro) to detailed (micro) scales. These studies characterized these effects by investigating the behavior and dynamics of sedimentary systems under human impact.

Diamond mining at Chapada has deeply modified the relief in the headwater areas of the Paraguaçu River in the following way (Nolasco 2002): (1) by removing soils and unconsolidated sediments to reach the gravels subject to mining (both on the surface and in the subsurface) or by widening the fractures to expose the less weathered or fresh rock and (2) by modifying the water paths and interfering with the river basins to create an anthropic drainage network associated with previously existing networks (by diverting water from the headwaters for developing the mining front

Fig. 19.8 **a** Partial view of the Piatã syncline. This image shows the region of the fold axis and a portion of its western flank. **b** Three-dimensional diagram of the Rio de Contas subdomain that emphasizes alternating synclines and anticlines. The *white rectangle* roughly marks the area that is covered by Fig. 19.8a. Differential erosion created a very irregular terrain on the eastern edge of the Piatã syncline, with hogbacks. The Barbado peak reaches the highest elevation in the northeastern region of Brazil



areas). The water adduction structures in question were formed by trenches and ditches, man-made channels, dams, high passages, and staircase structures (locally known as *corridas*) (Nolasco 2002). When connected, these structures transported water by gravity through ridges (originally sub-basin divides) and distributed it over fishbone structures (kilometric scale) as an anthropogenic river basin.

These processes have generated many anthropic geoforms. These geoforms include major structures of regional character, which resulted in the topographic lowering that started less than 200 years ago. Furthermore, these major structures include (1) the ruiniform relief, which was produced as the fractures that comprised the ancient aquifers of the region were emptied, and (2) the accumulation of rock masses. The latter have various shapes with diameters of a few meters and heights that vary from meters to tens of meters. These piles can be followed for kilometers (even when discontinuous), being usually aligned with the emptied or rounded fractures, and accompany and mark the outline (or boundaries) of the mined areas. These piles are known locally as *montueiras* (Nolasco 2002).

Due to secular mining, several current river channels have become anthropogenic structures. These rivers have been widened by lateral cuts at the mining fronts and flattened due to channel silting by sediments carried from the mountains to the valleys. Some drainage from the mountain slopes and closed fractures resulted from anthropic arrangement and central deepening by explosives.

Smaller but widely found structures include the *grunas* or *engrunados,* which are anthropogenic caves and sinkholes. These structures were created by emptying sediment traps filled by subsurface sediments and are supported by columns built by the miners. In addition, large anthropogenic gullies were observed. These are easily confused with natural structures, but they constitute old mine scars in the regions with high lateritic latosols with vertical walls connected to channels and water catchment ditches at their top.

Anthropic lakes are found in the fluvial valleys, filled with sandy and clayey–sandy sediments and are a product of dredging (the last type of mining work that was intensely developed between 1986 and 1996). These reservoirs were formed following the abandonment of gullies from diamond prospecting. The gullies reached up to 100 m long, 70 m wide, and 15 m deep. They are located in the ancient river base areas, where the river channels were completely altered and silted, which resulted in the complete loss of their configuration.

19.6 Conclusions

The irregular relief of the Chapada Diamantina was divided into two geomorphological domains, including the karstic domain and the lithostructural domain. In the karstic domain, the relief is flat to undulating, and the collapse of sinkholes resulted in most of the observed structures. These structures reach diameters and depths of several tens of meters. In addition, some dissolution valleys are present and a large number of caves appear in the subsurface. Many of these caves are partially mapped, and their gallery complexes can reach tens of kilometers in length.

The lithostructural domain is characterized by mountains flanked by vertical walls and deep valleys. These features resulted from tectonic disturbance of original sedimentary rocks and erosion by the fluvial systems. Extensive flattened areas are present that expose the oldest rocks. The folded structures were created during the intense tectonism that raised the terrain of Chapada Diamantina. In addition, formation of these structures was associated with erosion processes that generated wide valleys in the anticlines, tabular tops supported by free faces, and rectangular drainage pattern due to the fracture system. However, the dendritic pattern occurs in the flattened areas.

The partitioning of the relief was determined by lithostructures of rocky substrates during differential erosion. The irregular relief has vertical slopes with accumulated talus below, which may be dissected to form glacis. In other situations, erosion processes highlighted fragments of the folds that were carved asymmetrically to form hogbacks. The tops of the highlands were marked by distinct erosion surfaces resultant of a long period of dissection.

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Chapada dos Veadeiros: The Highest Landscapes in the Brazilian Central Plateau

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Abstract

The Chapada dos Veadeiros National Park is a nature conservation protected area, which was included in the World Heritage List by UNESCO in December 2001 because of the geomorphological and ecological sites that characterize the Brazilian Central Plateau and the Cerrado Biome. The forms of the Veadeiros plateau have been developed mainly on gently folded rocks from the Neoproterozoic Araí and Paranoá groups. The elevation of the plateau is about 1,200 m above mean sea level and is characterized by smooth topography. The edges of the Veadeiros Plateau are controlled by fault zones showing precipitous escarpments. The highest step is located in the western part of the plateau where many waterfalls occur along the rivers descending from the plateau surface. Thus, the park is well known for its natural landscape of great beauty, particularly due to the waterfalls, vertical escarpments, canyons, and bedrock rivers. Such a wonderful scene results from differential landscape dissection controlled by a variety of Neoproterozoic rocks crossed by faults and fractures, mostly subvertical. In this chapter, we present geological and geomorphological aspects that have influenced region, considering four environments: (a) Veadeiros Plateau; (b) Preto River in the region controlled by faults; (c) Escarpment; and (d) Moon Valley.

Keywords

Savanna • Tectonic control • High plateaus • Bedrock rivers

20.1 Introduction

Chapada dos Veadeiros National Park (CVNP) is located in Central Brazil. The park was included in the World Heritage List by UNESCO in December 2001, because of the flora, fauna, and key habitats that characterize the Cerrado Biome (Fig. 20.1). In addition, the region is of considerable scenic beauty and is composed of wide plateaus with waterfalls and springs. The uplands give way to deep rocky canyons and valleys. The main watercourse is the Preto River, which flows in a northeast to southwest direction; the northern extremity of the park is drained by the Santana and Bartolomeu rivers.

The CVNP is part of the Brazilian Central Plateau (BCP) (altitudes ranges from 577 to 1,676 m) (Fig. 20.2) that forms a vast level surface which divides three of Brazil's largest river systems: Paraná, São Francisco and Tocantins-Araguaia. The main features of BCP are high plateaus and intra-plateau depressions, limited by erosional scarps or gradual transitions. The CVNP corresponds to the uppermost parts of the BCP, having its peak in the region of Pouso Alto with an altitude of 1,676 m. In this chapter, we describe the

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Fig. 20.1 Panoramic view of the Chapada dos Veadeiros National Park presenting its two major waterfalls: Salto 1 and Salto 2

diversity of landscapes present in the CVNP and its buffer zone with a width of kilometers, which shows spectacular scenic beauty.

20.2 Geological and Geomorphological Evolution

The assembly of Gondwana occurred through a long succession of Neoproterozoic collisional events, known as the Brasiliano or Pan-African event (Brito Neves et al. 1999; Meert 2003). The CVPN is localized in the northern sector of the Brasília fold-and-thrust-belt, which is a major tectonic unit of the Tocantins Province in central Brazil, resulting from the collision episode between São Francisco and Congo cratons. Thus, the Brasília Belt comprises crustal thrust sheets that converged toward the east against the western São Francisco–Congo platform. Therefore, the Brazilian Central Plateau was always a high region in the postcratonization period, constituting one of the source areas of sediment to the intracratonic basins of the Amazon, Paraná, and Parnaíba. The geomorphology of CVNP presents a strong lithological and structural control.

The geology of the CVPN is formed mainly by the Araí and Paranoá groups (Fig. 20.2). The Araí Group occurs in the northern portion of the external zone of the Brasília Belt, covering the basement granite–gneiss and the Ticunzal Formation, and is covered by the Paranoá Group metasediments. The Araí Group includes quartzites and conglomerates in the basal levels, which give way to predominant calcareous–pelitic rocks toward the top (Dardenne 2000). Felsic metavolcanic rocks are intercalated with the basal clastic units and are broadly contemporaneous with c. 1.7 Ga anorogenic tin-bearing plutonic suites intruded into the basement of the Araí Group (Pimentel et al. 1991). The Araí Group and associated magmatism are the result of the major Statherian rifting event which affected the São Francisco–Congo paleocontinent, producing correlative sedimentary sequences of the Espinhaço (São Francisco craton) and Mayombe supergroups (Congo craton) (Martins-Neto 2000). This group is subdivided into the Arraias and Traíras formations (Dyer 1970; Araújo and Alves 1979; Martins 1999). The Arraias Formation represents the main rifting phase, with deposition of alluvial fan conglomerates and sandstones as well as fluvial sandstones with intercalations of acid volcanic and volcaniclastic rocks (rhyodacite, rhyolite, ignimbrites, pyroclastic rocks). There are also intercalations of continental basalt flows with quartzites and metasiltstones, but the basalts always overlay the acid volcanic sequence (Alvarenga et al. 2007). The Traíras Formation represents the postrift sedimentation, with the deposition of a heterolithic assemblage of stratified siltstones and sandstones in transitional and shallow marine environments (Alvarenga et al. 2007). Metamorphic grades of the Araí Group vary from slightly metamorphic (anchi-metamorphic) to lower greenschist facies. In this paper, we used the most recent geological map developed by Campos (2012), which covers a large part of the CVNP, containing eight units interleaved with quartzite and metasiltstone, where one belongs to the Traíras Formation and the others to the Arraias Formation.

The Neoproterozoic Paranoá Group covers discordantly the Araí Group. The sedimentary rocks of the Paranoá Group comprise a mature siliciclastic sedimentary pile including thick quartzite layers, with the intercalation of metasiltstones and minor lenses of limestones and dolostones (Faria 1995). Dardenne and Faria (1985) divided the Paranoá Group into nine lithostratigraphic units, beginning with a

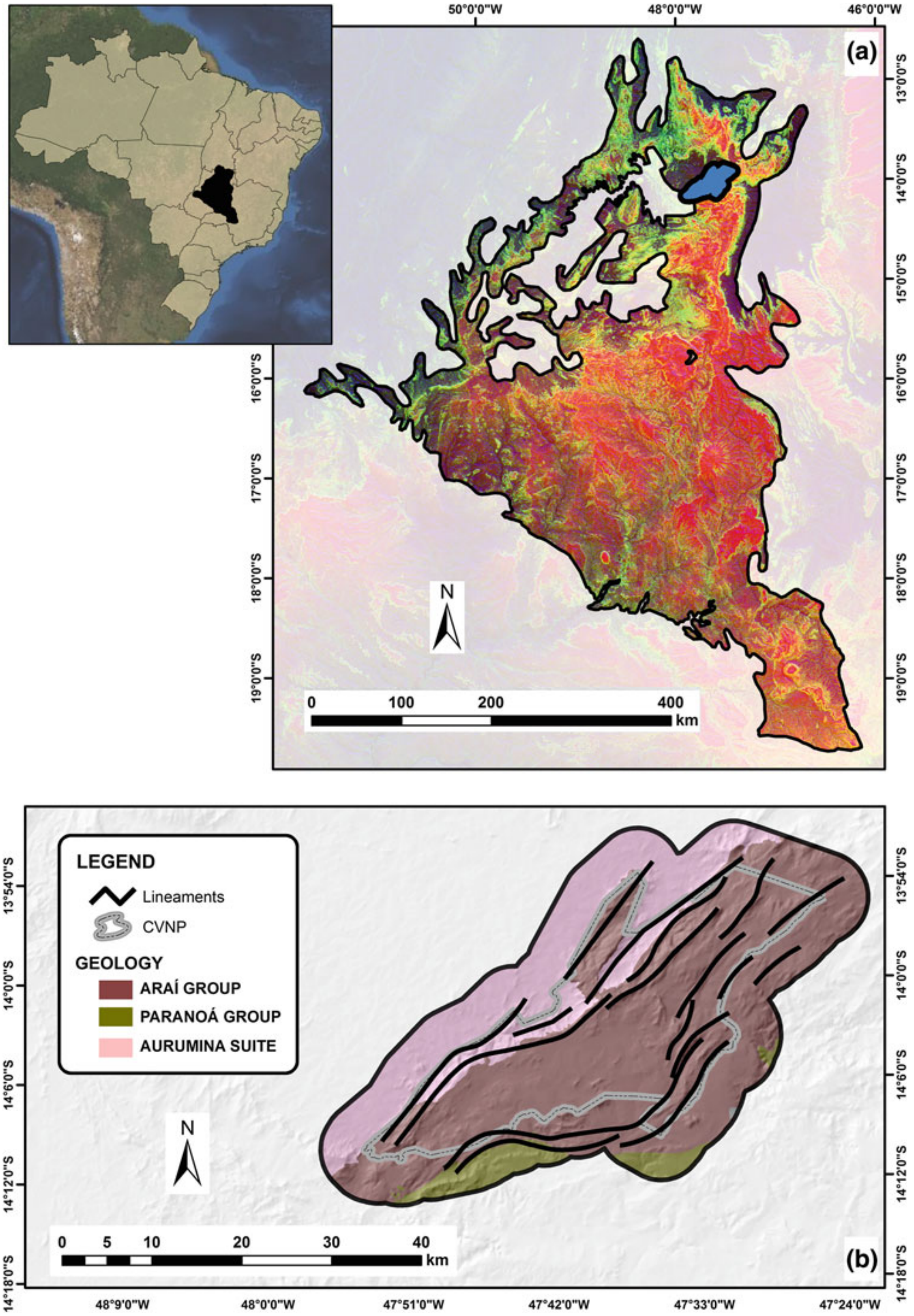

Fig. 20.2 **a** Chapada dos Veadeiros National Park location in Brazilian showing different relief pattern from colour composite using terrain attributes: elevation (*Red*), slope (*Green*), and aspect (*Blue*), and **b** geological map and structural lineaments map

paraconglomerate, followed by transgressive and regressive siliciclastic dominated cycles, ending with pelites and dolostones containing *Conophyton metulum Kirichenko* stromatolites that were described by Cloud and Dardenne (1973). The Paranoá sediments have been interpreted as representatives of a passive margin sequence deposited on the western margin of the São Francisco craton (Dardenne 1979; Pimentel et al. 1999). The base of the Paranoá Group is formed by the São Miguel paraconglomerate that is overlain by rhythmites with mudcracks and evaporite layers, which are typical of tidal to supratidal environments. These are followed by marine rhythmites and quartzites deposited in a platform environment dominated by tidal currents. The sediments in the upper portion of the Paranoá Group display features indicating more varied environments, reflecting important fluctuations of the sea level. In the study area, four units of the Paranoá Group are present: São Miguel, Córrego Cordovil, Serra da Boa Vista, and Serra Almécegas.

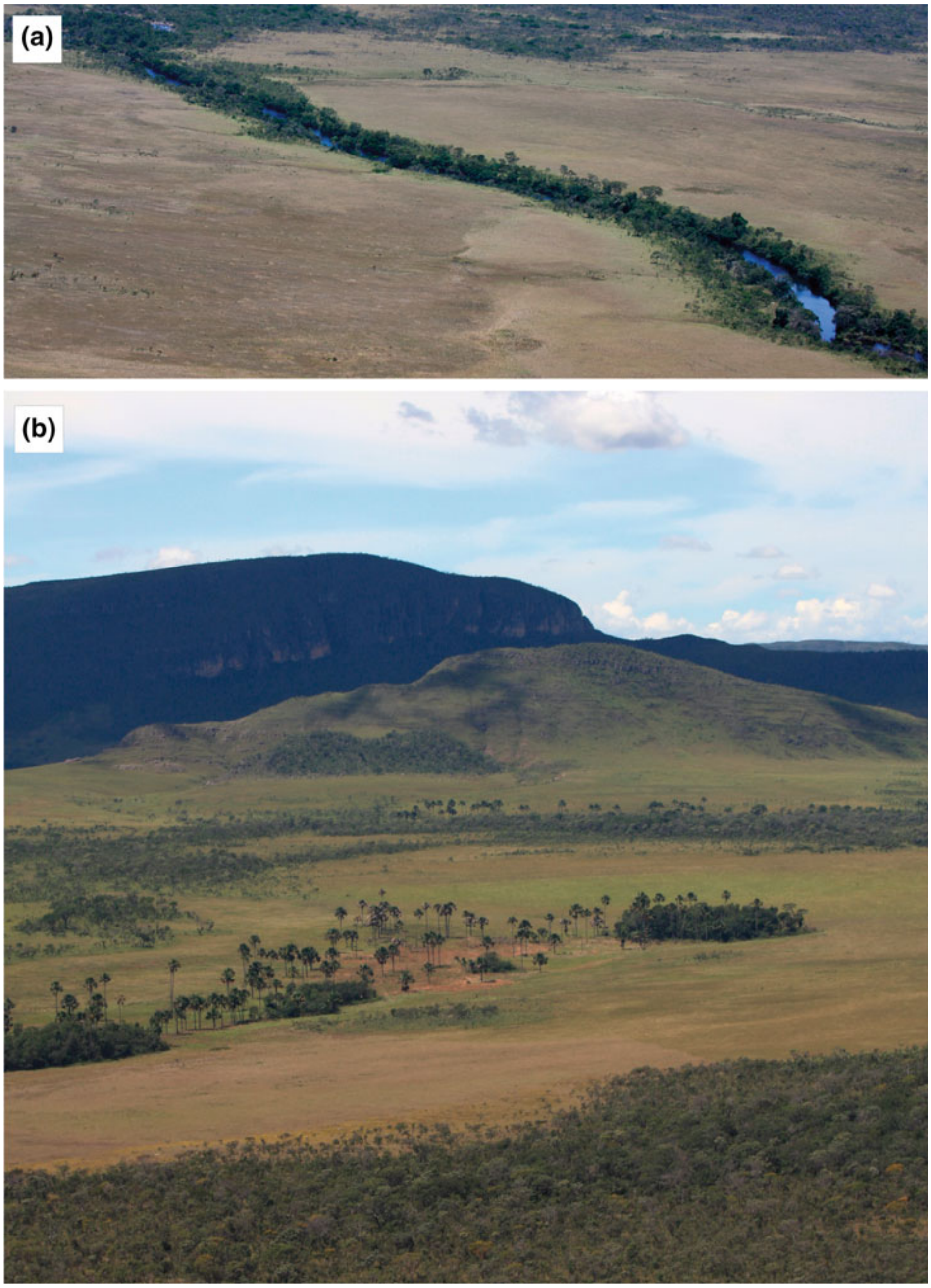

Fig. 20.3 Veadeiros Plateau aerial view highlights river bordered by grassy marshes containing "buriti" palms crossing open herbaceous vegetation (**a**) and abrupt contact between upland savanna and grassland (**b**)

Fonseca et al. (1995) described two parallel fault zones near CVPN region: São Jorge-Alto Paraíso-Cormari fault zone (SJACPFZ) and Cavalcante-Terezina fault zone (CTFZ). The SJAPCFZ system cuts rocks of the Arai, Paranoá, and Bambuí groups and can be delineated from Cormari (small village south of the city of Nova Roma) through the São Bartolomeu River Valley to Alto Paraíso city following the SSW direction to the São Jorge village. This shear zone is characterized by a subvertical foliation, dextral kinematics, and a meter-scaled width. The CTFZ system is characterized by nearly vertical, SW trending strike-slip faults forming a 5-km-wide zone, which affects the basement rocks and the Araí Group. This shear zone has dextral kinematics, prominent foliation with a subhorizontal lineation, metasomatism, and metamorphism, leading to the formation of a rock with quartz and sericite matrix.

Campos et al. (2012) describes two larger-scale shear zones clearly correlated with the two structural systems described by Fonseca et al. (1995): Ribeirão São Miguel River Shear Zone (RSMSZ) and Serra de Santana Shear Zone (SSSZ). The RSMSZ occurs along the homonymous valley, contact between the Araí and Paranoá groups. This structure exposes conglomerates of the Rio São Miguel Formation that may occur in deformed areas. The SSSZ is a

Fig. 20.4 Veadeiros Plateau aerial view of the Preto River floodplain (**a**) and highlights abandoned channels and oxbow lakes (**b**)

regional structure that occurs to the east of the CVNP, along the geologic contact between rocks of the Aurumina suite and basal sediments of the Araí Group. This shear zone has dextral kinematics and strong subvertical foliation with N40-45E direction. In the field structures such as deformed feldspar augen, mica *fish* and shear bands can be observed.

Mapping of these strike-slip fault zones reveals in plan view an elongated S-shaped feature (restraining bends), which dominates topographic attributes (positive structures) within the region (Fig. 20.2). A strain gradient along both fault zones shows several deformation mechanisms, such as folding, distributed shear, and normal faulting. The postulated faults coincide with the boundary of the plateau block, where deeply eroded bedrock exposures are observed. As described elsewhere, restraining bends are sites of topographic uplift, crustal shortening, and exhumation of crystalline basement (Mann and Gordon 1996; McClay and Bonora 2001). Within the bend, oblique deformation shows accommodation by oblique-slip faulting or is partitioned into variable components of strike-slip fault displacements.

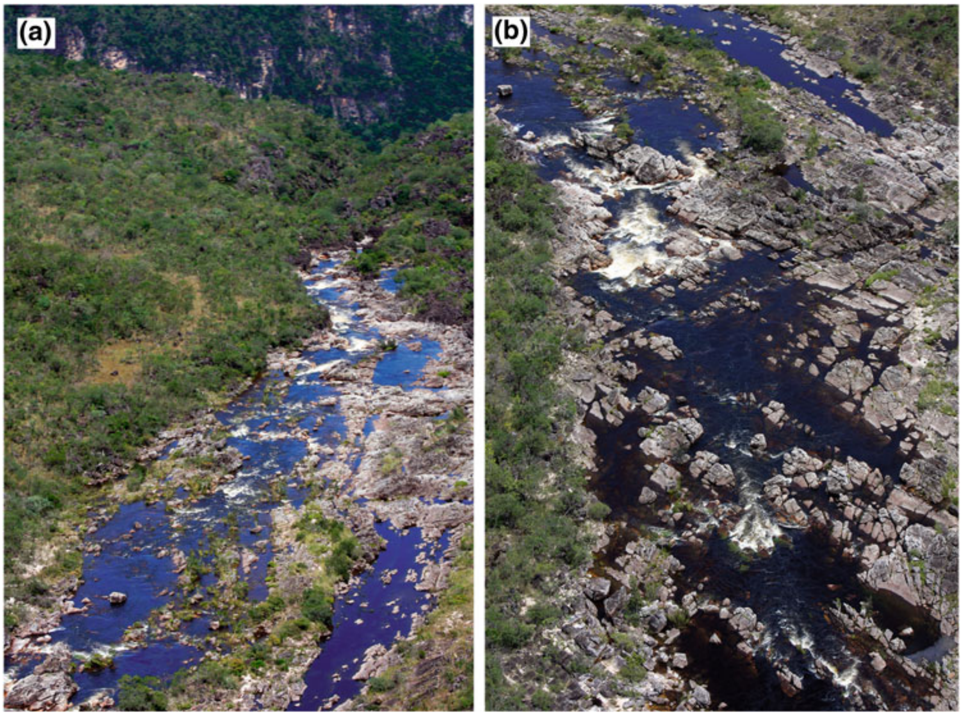

Fig. 20.5 Bedrock Preto River: waterfall (**a**) and rock exposure in channel bed showing joint and fracture systems (**b**)

The geometry of the fault systems has strong implications for the arrangement of basins and drainage patterns. The drainage density is directly related to the amount and orientation of deformation (or strain) occurring in the transpressive zone. Drainage pattern in fault zones is trellis, with high-density drainage, where the tributaries enter the main river at approximately 60-degree angles. In the central part of the bend, the drainage density is low and the relative shortening is expressed as synclinal and anticlinal open folds, parallel to the restraining bend. DEM provides a view of spatial variations in topographic relief along the faults zones.

In the region of the park, four landscapes are most visited due to its scenic beauty: (a) Veadeiros Plateau; (b) Preto River in the region controlled by faults; (c) Scarp; and (d) Moon Valley.

20.3 Landforms

20.3.1 Veadeiros Plateau

The plateau surface is characterized by subhorizontal strata that determine the presence of a wide area with the same type of rock and smooth topography. The geological structures are gentle folds of large extension. The bedrock consists mainly of quartzites and metasiltstones that exhibit high resistance to physical and chemical weathering, generating shallow soils with low fertility. Furthermore, the low permeability of bedrock causes hydromorphic environments with prolonged periods of intermittent or continuous saturation, where the flux of ground water occurs only laterally along fractures and bedding planes. The poor permeability maintains the high water table and leads to the formation of hydromorphic soils, depleted in oxygen and organic material accumulation. The open herbaceous vegetation (moist grass) grows on hydromorphic soils and is adapted to the conditions of soil saturation, favoring the accumulation and preservation of organic matter (Fig. 20.3a). In these water-saturated soils, the streams are bordered by grassy marshes containing "*buriti*" palms (known as "*veredas*") (Fig. 20.3b).

In the plateau, the Preto River shows meandering pattern where the Gleysol banks are cut and eroded forming abandoned channels. Figure 20.4 shows an oxbow lake (U-shape body of water) formed by rerouting of river course through neck cutoff from the main stream to create a lake. Although these characteristics typically occur when the river reaches a low-lying plain, in the CVPN, these fluvial features occur in elevated areas. An interesting feature of the Preto River is the dark color of water due to low concentrations of suspended matters and high content of organic acids.

The boundary between dry upland savanna and moist grasses is usually extremely sharp (Fig. 20.3b), but in some places, there are gradations. Vegetation associated with quartzite outcrops is known as "campos rupestres" and "cerrados rupestres" (from Latin *Rupestris* meaning "rocky") and derives from the shallow, acidic, nutrient-poor, well-drained sandy soils (litholic soil) and shares several (usually

Fig. 20.6 Panoramic photographs of the main attractions along the Preto River: Salto 1 (**a**) and Salto 2 (**b**) waterfalls

woody) plant species with the surrounding savannas. In areas with rock outcrops, shrubs and trees usually do not form a closed canopy. The relationship between vegetation, soil, and geomorphology is very striking in CVNP, where campo cerrado covers the level plateau with hydromorphic soils and gives way to savanna in the plateau upland and campos rupestres in the plateaus edges along the valleys dominated by rocky outcrops.

20.3.2 Preto River in Region Controlled by Faults

On the western edge of the park drainage, directions have a strong structural control corresponding to stress field from the Serra de Santana Shear Zone with N40-45E direction. Runoff takes place mainly along joint and fracture systems, forming a rectangular and trellis drainage pattern. High density of drainage is accompanied by steep slopes. In this highly fractured zone, bedrock rivers occur and are characterized by the lack of continuous cover of alluvial sediments, forming channels with long stretches of rock exposures in the bed and along the banks. Bedrock rivers are formed due to excess sediment transport capacity over the low rates of sediment supply from slow physical and chemical weathering (Fig. 20.5).

Along the river, geomorphological highlights are abundant such as waterfalls and canyons. The waterfalls are frequently controlled by the presence of intersections of fractures and faults. The geometry of these diverse landforms is largely attributed to tectonic features and erosion of the river along joints and major structural lineaments. In the wide waterfalls, large amphitheaters are formed, suggesting progressive lateral relocation of the river along the faults. Linear

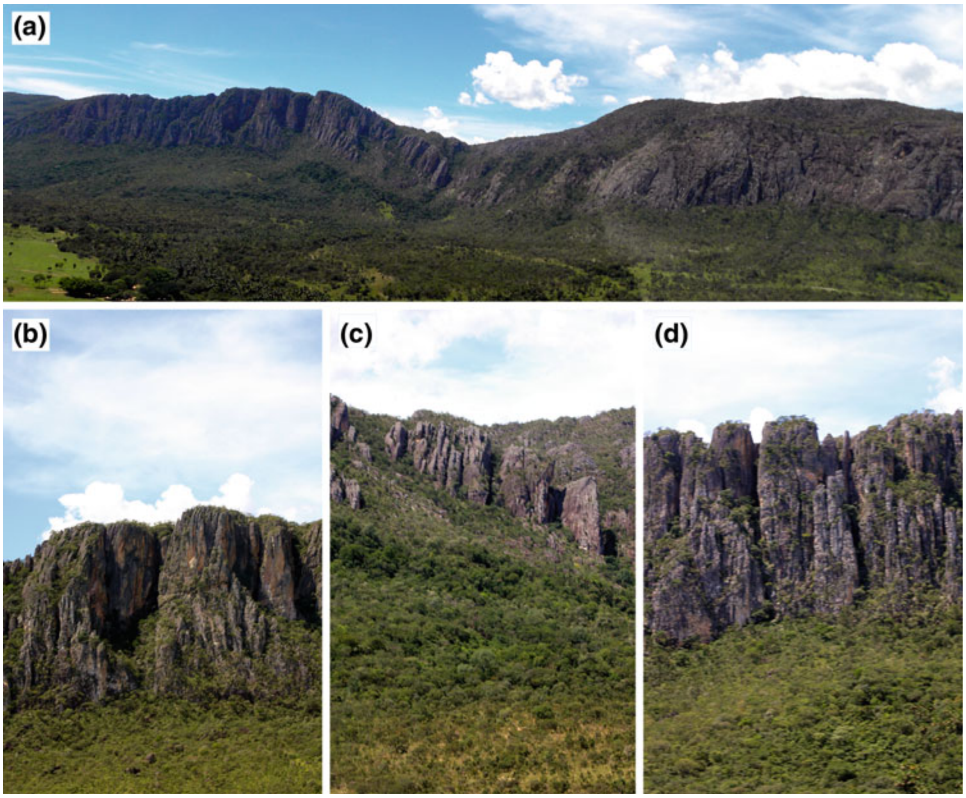

Fig. 20.7 Panoramic views of the escarpments in the Serra de Santana Shear Zone (**a**) and columnar pattern fashioned by vertical fractures (**b**–**d**)

flows create narrow and deep canyons along fractures in quartzite. Chaotic block accumulations are found at the foot of the waterfalls, in canyons, and in zones of steep slopes.

Strong seasonal rainfall on impermeable rock causes flash flooding marked by a greater quantity of surface runoff in a very short time. This extremely variable fluvial discharge commonly produces high-magnitude floods in the short term which are dangerous for tourists who are swimming or spend time near rivers. Generally, at the peak of the rainy season, the park closes because there is a risk flash flooding.

The most famous waterfalls along of the Preto River are Cariocas, Salto 1 and Salto 2. The Carioca falls are around 12 m high and erode the base by abrasion, creating a plunge pool. Salto 1 and Salto 2 are the highest falls in the Preto River with a vertical drop around of 80 and 120 m, respectively (Fig. 20.6). These waterfalls are the last steps of Preto River in the descent from the plateau toward the Tocantins basin floodplain. Another attraction are canyon 1 and canyon 2 separated by 15 m high waterfall where the Preto River carved a deep ravine between narrow cliffs.

20.3.3 Escarpment

The quartzite beds of the Traíras Formation can be clearly seen along a remarkable fault escarpment. The elevation of the scarps is of the order of hundreds of meters and with a length of above 60 km. The escarpment shows incipient piping from water infiltrating through the joint and bedding planes. Differential erosion along fractures and bedding planes in the scarp area creates walls separated by corridors and towers. The towers have different shapes and sizes, wherein the width is limited by the spatial distribution of the joints and height is dependent on lithological resistance of consecutive geological layers to erosion. Scarp retreat occurs by widening of fractures by chemical weathering of quartzite cement, accompanied by mechanical removal of rock fragments and grains, causing the collapse and fall of large blocks to the escarpment base. Toward the base, there are large accumulations of quartzite blocks (fallen from the top) and alluvial–colluvial fans due to the erosion of the upper parts of the scarp. The foothills are characterized by a dense savanna due to permanent humidity (Fig. 20.7).

20.3.4 Moon Valley (Vale da Lua)

On the eastern edge of the park, differential fluvial erosion in conglomeratic rocks from the São Miguel Unit has generated natural sculptures in the rock, which belong to the most remarkable natural features present in the CVNP. The São Miguel Unit is a guide basal layer of the Paranoá Group, which has an erosive contact with the top of the Araí Group. In the São Miguel River, bedrock is

Fig. 20.8 Photography of the Moon Valley showing natural sculptures from differential fluvial erosion in conglomeratic rocks of the São Miguel Unit

predominantly fresh to slightly weathered (gray color), composed of clasts and matrix. The clasts are composed of quartzite (white) and metasiltstone (greenish and brown). The dimensions of clasts range from millimeters to more than 50 cm, including a block with the major axis of approximately 1 m long (Campos et al. 2005). The basal conglomerate matrix was affected by advanced diagenetic processes, with recrystallization of the carbonate, which accounts for almost half of the rock composition.

The beautiful sculptural forms are derived from the dissolution of carbonate present in the matrix/cement of the conglomerate, creating well-polished pots, curved shapes, and smooth surfaces. The geologic layers are eroded in the direction of water movement; the forms often merge into one another and give rise to peculiar channels in the rock. It alludes to the lunar surface by local people who called the place the Moon Valley (Vale da Lua) (Fig. 20.8). The rocks positioned far from the riverbed have features indicative of oxidation, characterized by a dark coloration. The soils from these rocks are fertile and allow the development of dense vegetation.

20.4 Conclusion

The first economic exploitation of the São Jorge Region was the mining of quartz crystals in 1912. The main mining area was called Garimpão de São Jorge. Due to the fluctuation of crystal prices, there were periods of increased activity, such as in 1940/1944, which drew about 2,000 people, and in 1960, when several mines were exploited: Estiva, Vaginha, Pedrão, Areião, and again Garimpão. However, the significant decline in mining caused re-allocation of economic activities to tourism. The formation of the national park consolidated tourist potential for the region, and old miners have become economically dependent on tourism. Thus, conservation-based tourism is currently the main activity in the regional economic development.

Therefore, CVNP is one of the best preserved regions of the Brazilian savanna, consisting a wildlife sanctuary with numerous attractions: large plateaus, springs, bedrock rivers, canyons, towers, and waterfalls. The regional morphology has developed in the conditions of a strong tectonic control, responsible for major topographic variation and the presence of a landscape of great scenic beauty. For all these reasons, this natural area is one of the most popular and visited by tourists in the BCP.

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Chapada Do Araripe: A Highland Oasis Incrusted into the Semi-arid Region of Northeastern Brazil

21

Norberto Morales and Mario Luis Assine

Abstract

Located inside the Brazilian northeast, the Chapada do Araripe represents a prominent testimony of the regional evolution extending as a residual relief in the form of flat and elongated tableland with over 8,000 km^2 and an altitude close to 1,000 m, elevated up to 500 m from the Cariri Valley floor. Evolution by escarpment retreats influenced by gravitational processes developed piedmont deposits, marked by pediments and flat recessed areas, where urban centres have settled. Its sedimentary record includes Paleozoic and Mesozoic depositional sequences with exceptional fossil record. With high local rainfall and high permeability sandstones, the region is rich in water and lush natural vegetation and has a mild climate, characterised also as a regional centre of culture and economic development, begun in mid-eighteenth century and active to the present day. Those aspects that led the progress are assigned to miracles of Padre Cícero, patron saint of the region.

Keywords

Chapada do Araripe • Cariri Valley • Tableland • Piedmont deposit • Residual relief

21.1 Introduction

The Chapada do Araripe (Araripe Plateau) is a tableland located in the northeast of Brazil. This very flat plateau, elevated to over 1,000 m above sea level (Fig. 21.1a), preserves an impressive record of the geological and geomorphological history of the region. Its sedimentary rocks allow to recognise several environments through which the region passed during Cretaceous times. The landscape provides a testimony of a complex Cenozoic geomorphological evolution, beginning after the generation of the regional Sul-Americana planation surface.

Due to its unique features, the Chapada do Araripe became an area of environmental protection, housing the first Brazilian National Forest. Orographic rains result in higher precipitation, accumulation of groundwater and a number of springs, generating an interior oasis (Fig. 21.1b), a place of pioneer settlements that grew up around plenty of water, directly influencing the local cultural wealth. These features and the scenic beauty make the Chapada, which is a true oasis, embedded within the northeastern Brazilian semi-arid region, a paradise for ecotourism and environmental education.

The Chapada do Araripe is highlighted in the geomorphology of northeastern Brazil as a high, asymmetric tableland surface, elongated in the east–west direction with approximately 200 km of extension and altitudes over 1,000 m (Fig. 21.2). The plateau is located in the watershed of the great drainage basins of the São Francisco River (south), the eastern-northeastern Atlantic (north) and the Parnaíba River (west).

Located mostly in the southern portion of the state of Ceará (CE) and occupying parts of the Pernambuco (PE) and Paraíba (PB) states, the plateau is the geomorphological

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Fig. 21.1 Views of the Araripe Plateau: **a** the summit surface and the steep cornice in the region of Santana do Cariri; and **b** the forested cliffs facing the Cariri Valley, where convex forms on gravity flow deposits, are highlighted, upon which there is human occupation

expression of the upper stratigraphic units of a Cretaceous sedimentary basin, the Araripe Basin. This basin also extends to the east and northeast through the Cariri Valley, which is a peripheral depression with altitudes between 400 and 500 m a.s.l., where sediments of the lower stratigraphic units crop out.

The Cariri Valley develops from the eastern foothills of the Araripe Plateau and is a peculiar area in the interior of the region due to the wetter local climate (rainfall up to 1,200 mm/year) in comparison with the rest of the interior area of northeastern Brazil, where rainfall is from 300 to 800 mm/year, in which the Caatinga vegetation predominates. The caatinga is an exclusive biome of the Brazilian northeastern semi-arid region characterised by a rough and shrubby vegetation, like the savannah steppe, where most plants lose leaves and stems and become whitish and dry, making the landscape grey whitish. The orographic rainfall that occurs in the Cariri Valley and in the eastern portion of the plateau is responsible for recharging the aquifers, particularly those formed by the sandstones of the Exu Formation, whose waters emerge as many springs in the surroundings of the plateau. The rainfalls on the highest portion of the plateau, in its eastern and northeastern edge, also keep the enclave of lush woody savannah vegetation (‘Cerradão’) on top of the plateau; the area was preserved with the establishment of the Araripe National Forest.

In this chapter, the morphological characteristics of the plateau and the butte hills related to it are described and discussed. Additionally, we characterise the pediments formed in the surroundings of the plateau due to the evolution of its escarpments. An outline of the geomorphological evolution of the plateau is also introduced, recording the events of uplift and regional dissection that occurred during the Cenozoic. Because the geomorphology of the plateau is strongly conditioned by the geological evolution of the basin in whose strata the plateau is carved, a brief summary of its geological framework is first presented.

21.2 Geological Framework

The Araripe Basin is the most important and extensive one (approximately 9,000 km^2) among the inner basins of northeastern Brazil, located between the Potiguar Basin, the Parnaíba Basin and the Tucano-Jatobá Basin. The Araripe Basin is located between the Patos and Pernambuco lineaments. These two ancient geological features affect many of the inner basins of northeastern Brazil (Fig. 21.3).

The geological evolution of the Araripe Basin was strictly related to events from which the basins in the Atlantic continental margins originated in both Brazil and Africa. The geometry of the Araripe Basin is strongly controlled by

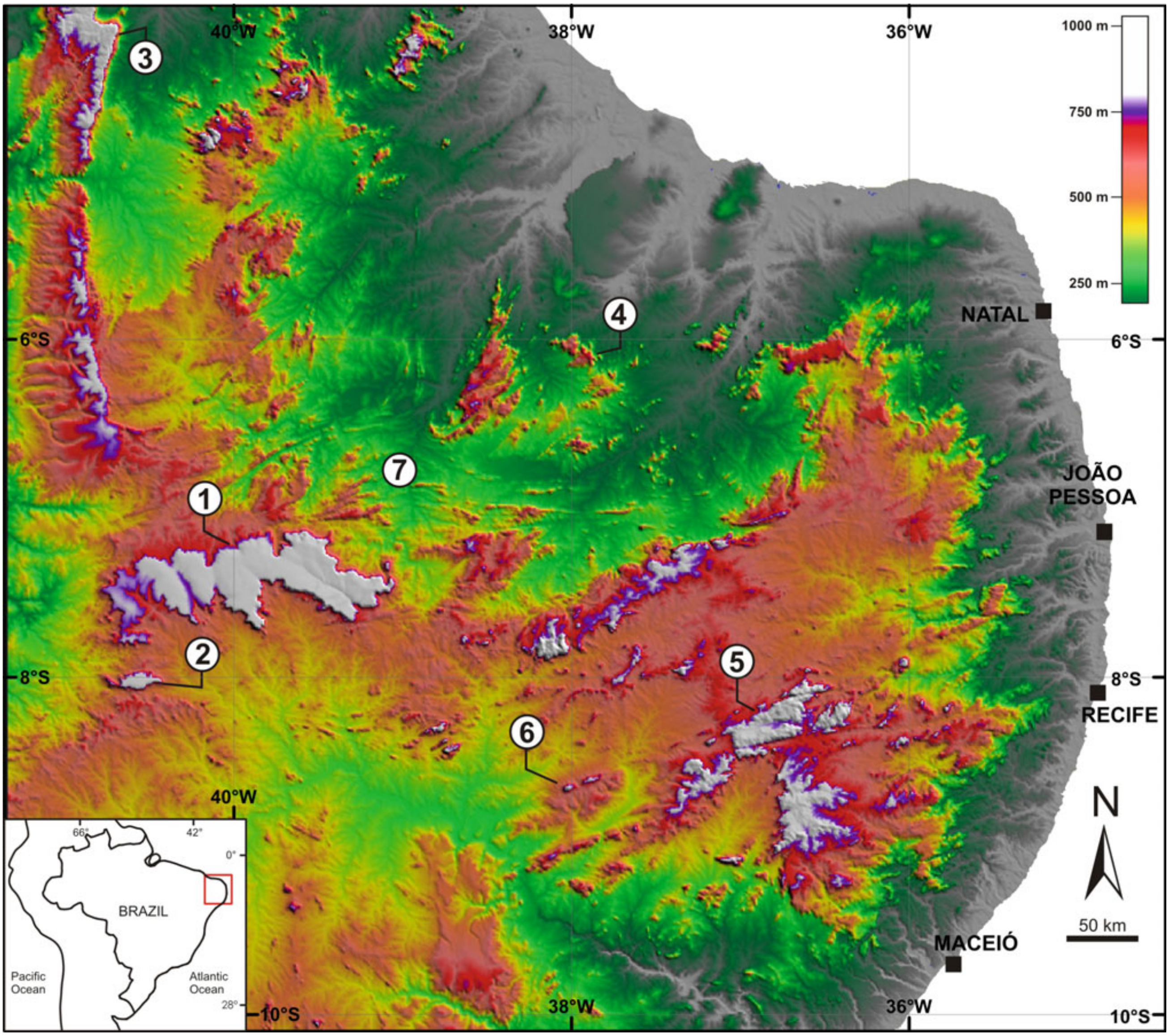

Fig. 21.2 The Araripe Plateau with respect to the physiography of northeastern Brazil. Flat-topped high relief constitutes the dissected remains of an elevated planation surface: *1* Chapada do Araripe; *2* Serra do Inácio; *3* Serra de Ibiapaba; *4* Serra dos Martins; *5* Borborema plateau; *6* Serra Negra; and *7* Cariri Valley (the digital model of elevation was built with altimetric data from the Shuttle Radar Topography Mission—SRTM/NASA 2000)

pre-Cambrian basement structures, which were reactivated during Mesozoic tectonic events that culminated with the Gondwana rifting, the opening of the South Atlantic in the Cretaceous, and the continental drift and individualisation of Africa and South America as new continents.

The continental rupture process that gave rise to the Brazilian marginal basins induced the formation of faults that spread inland, thereby originating the Potiguar and Recôncavo/Tucano basins, which protrude from the coast to the interior of the continent. The spreading into the interior of the northeast caused the movement of faults related to the pre-Cambrian lineaments of Patos and Pernambuco. The tectonic reactivation of these ancient shear zones led to the origin of small basins that are bordered by faults, such as those of Araripe, Iguatu and Rio do Peixe.

The stratigraphic record of the Araripe Basin is composed of five stratigraphic sequences, known as the (1) Palaeozoic (Cariri Formation), (2) pre-rift (Brejo Santo and Missão Velha formations), (3) rift (Abaiara Formation), (4) post-rift I (Barbalha and Santana formations) and (5) post-rift II (Araripina and Exu formations). The Araripe tableland is carved on the post-rift sequence of rocks, which unconformably overlie the units of the older sequences (Fig. 21.4).

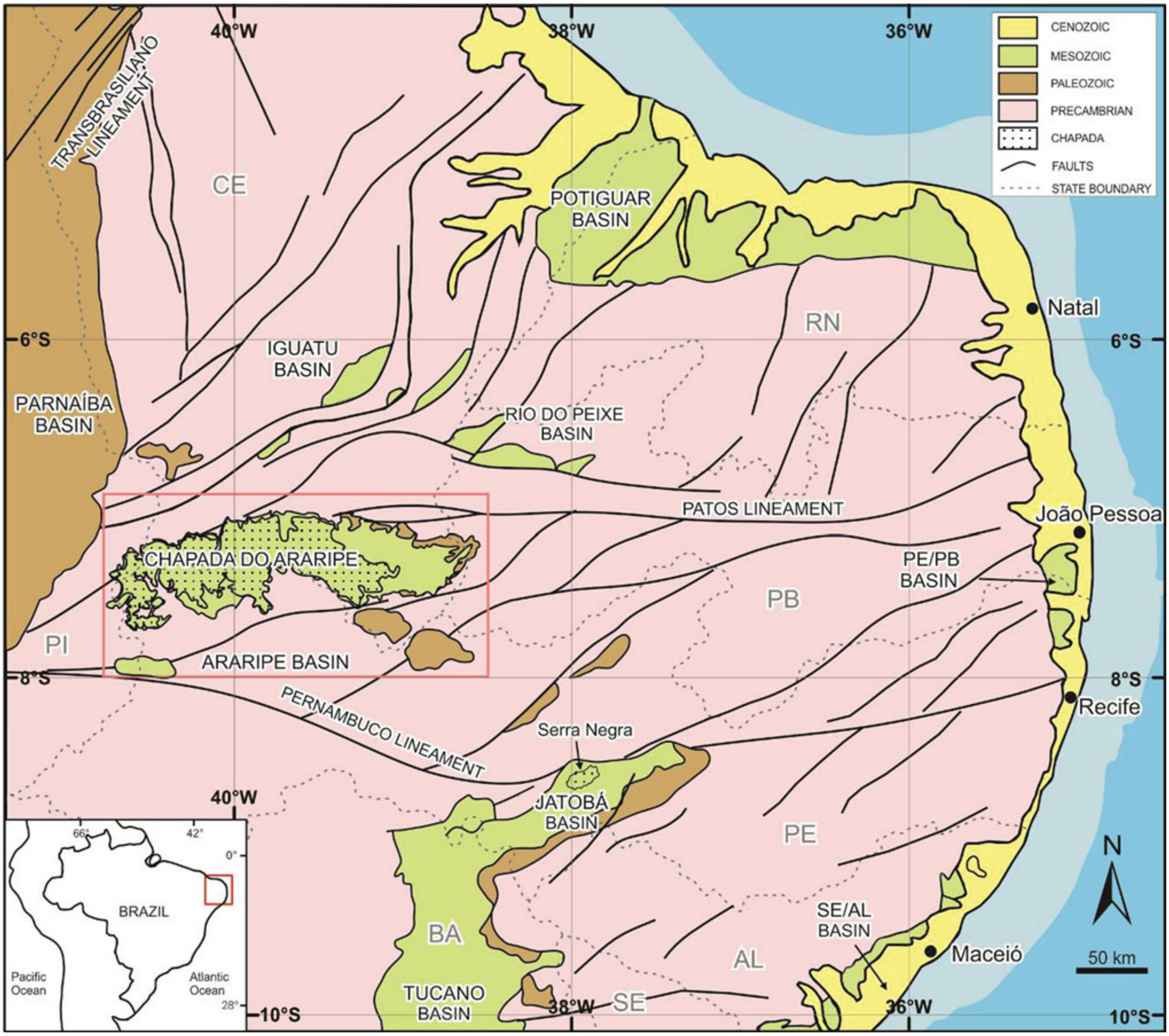

Fig. 21.3 The Araripe Plateau is modelled in Cretaceous sandstones of the Araripe Basin, which is located in the interior of the northeastern Brazil between two large pre-Cambrian lineaments that were reactivated in tectonic events in the Phanerozoic, known as Patos and Pernambuco. (States: *CE* Ceará, *RN* Rio Grande do Norte, *PB* Paraíba, *PI* Piauí, *PE* Pernambuco, *AL* Alagoas, *SE* Sergipe and *BA* Bahia)

The two post-rift sequences composing the plateau show a sub-horizontal attitude, while the three older sequences were faulted and moved tectonically with tilted fault blocks. This situation is particularly evident in the Cariri Valley, where units located below the unconformity are cut by several faults, structured in horsts and grabens, in opposite to the sub-horizontal layers of the Plateau. In the western portion of the basin, where the older formations are absent, the post-rift sequences lie on a pre-Cambrian crystalline basement without sedimentary units of the older stratigraphic sequences (see the geological section of Fig. 21.4).

The post-rift sequence I (Upper Aptian) is composed of the Barbalha and Santana formations and has a stratigraphic arrangement and palaeoenvironmental succession that is similar to the Brazilian marginal basins (Assine 2007). The Santana Formation is the most studied unit in the basin due to deposits of gypsum and because it is the main fossiliferous deposit in Brazil; additionally, the formation is famous worldwide (Santos and Valença 1968; Mabesoone and Tinoco 1973; Maisey 1991; Coimbra et al. 2002; Campos and Kellner 1985; Martill et al. 2007). Discontinuous gypsum layers are present on the laminated limestone with a maximum

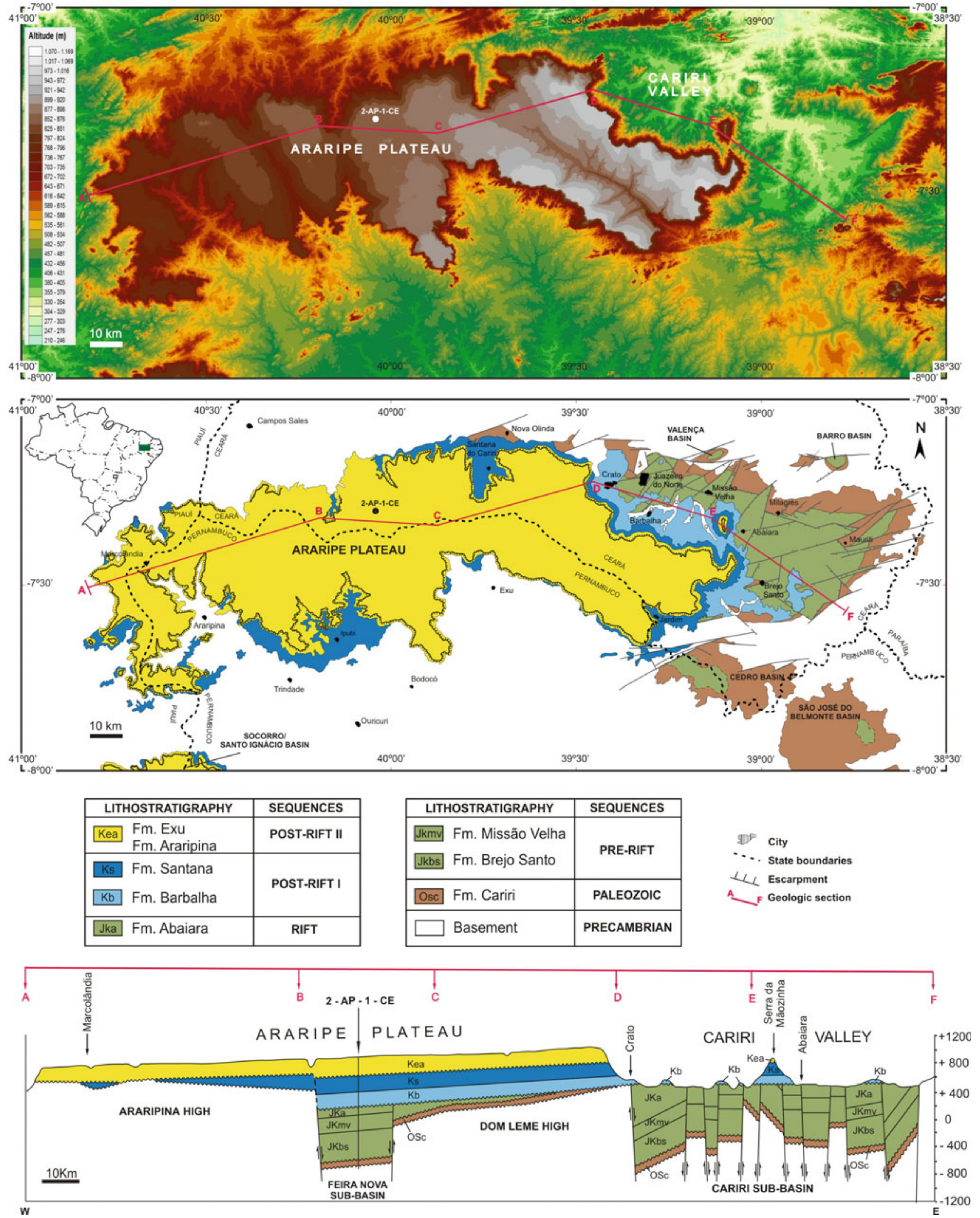

Fig. 21.4 The Araripe Plateau is carved on post-rift sandstones from the Upper Cretaceous (Exu Formation) of the Araripe sedimentary basin, whereas the Cariri Valley, located to the east of the plateau, is related mostly to the pre- and sin-rift formations from the bottom of the sedimentary pile (a digital model of elevation was built with altimetric data from the SRTM/NASA mission, 2000; the map and geological section from Assine 2007)

thickness of 30 m, forming extensive deposits in the western portion of the basin, which is the main producer of gypsum in Brazil. The section is transgressive in evaporites, culminating with black shales containing fossiliferous concretions and coquinas with marine fossils. Because of this fossil content, the region is the main Brazilian palaeontological site, with very well-preserved records of Cretaceous fauna and flora.

The post-rift sequence II marks an important change in the regional geology, resulting from the return to essentially continental conditions with the deposition of fluvial sandstones of the Exu Formation. The return to the conditions of continental sedimentation in the Araripe Basin occurred due to epeirogenic uplift of the Brazilian northeast since the Albian stage, thereby resulting in the restructuring of the continental palaeodrainage in the interior of northeastern Brazil (Assine 1994).

Fission track data of the Araripe Basin samples record uplift in the Late Cretaceous, beginning approximately 100 Ma (Morais Neto et al. 2005). Subsequently, there was an extensive period of tectonic quiescence until the end of the Cretaceous, combined with warmer and wetter climate, which resulted in peneplanation of the region and formation of ferricretes and silcretes in the upper portion of the Exu Formation. The ferricretes and silcretes are currently found underneath the summit surface. The current relief configuration is due to denudation processes that dominated during the Cenozoic and most likely were accelerated by cooling events after 40 Ma, according to additional fission track data from the Araripe Basin samples (Morais Neto et al. 2005).

21.3 Geomorphological Evolution

The sedimentary and morphological characteristics of the Araripe Plateau evolution show the importance of the process of sedimentary basin formation in distensive tectonic regime. It has followed an inversion process that led to regional uplift after the Albian stage (Assine 1990, 1992, 1994), which was also demonstrated by data on fission tracks that indicated cooling beginning between 100 and 90 Ma (Morais Neto et al. 2005).

The Araripe Plateau summit is the relict of an old planation surface (Ab'Sáber 2000; Maia et al. 2010), considered to be an extension towards the north of the Sul-Americana surface defined by King (1956) in eastern Brazil. The final modelling of this surface occurred in the time lapse from the Late Cretaceous to Early Palaeogene. This planation surface was created by widespread erosion, which planed off rocks of different ages, degrading the relief and transforming the landscape into a wide plain with altitudes lower than the present plateau summit.

During the peneplain generation, sedimentation occurred simultaneously in distal lower lands, with the formation of sandy, sandy clayey and conglomeratic alluvial covers, such as that of the Serra dos Martins Formation. The alluvial coverage, a thin unit that occurs directly on the pre-Cambrian terrains, was preserved from the posterior erosion in high reliefs, particularly in the Serra dos Martins in the Rio Grande do Norte state (RN) (Menezes 1999).

Once formed, the Sul-Americana surface was raised to different elevations, which surpassed 1,000 m in many areas. With the uplift that affected a large portion of the interior of northeastern Brazil, denudation processes increased in intensity and the surface was quickly dissected, resulting in residual relief, such as that of the Araripe Plateau. Once more, the data on the fission tracks indicate a cooling phase from 30 Ma (Morais Neto et al. 2005), and gravimetric geophysical data also have indicated the activity of epeirogenesis processes in the Borborema Province since 30 Ma (Oliveira and Medeiros 2012). The Macau volcanism recorded in the central portion of RN (Silveira 2006) is integrated in this context due to the regional uplift.

Buttes and mesas, such as the Serra do Ignacio, located to the southwest of the plateau, also serve as testimonies of the greater extension of the plateau towards the southwest (Fig. 21.2). However, the most striking testimony of the extension of both the sedimentary sequence of the Araripe Plateau and the Sul-Americana surface is given by the sole existence of the Serra Negra, which is a butte existing in the Jatobá Basin (Bacia do Jatobá) in the state of Pernambuco (PE), approximately 200 km south-east away from the Plateau (Fig. 21.2). It is worth noting that the Serra Negra, whose summit reaches 1,000 m, have sedimentary succession identical to the plateau, a fact that led Braun (1966) to recognise the Santana and Exu formations in the Jatobá Basin. Other remnants of this surface are found in the Serra dos Martins, but they can be also identified in other areas in the interior of northeastern Brazil, such as the Borborema Plateau and the Serra do Ibiapaba (Fig. 21.2).

A new event of erosion and planation was responsible for the formation of the Sertaneja surface during the Miocene, which evolved from the valleys incised into the Sul-Americana surface. The Sertaneja surface extends over a large area, with decreasing altitudes from the interior to the coast, but occupies a smaller area than the area originally occupied by the Sul-Americana surface. The surface disappears with inland progression near the current watersheds, such as the Araripe Plateau, where it is tentatively correlated to the surface that levels the hilltops of the Cariri Valley with altitudes between 400 and 500 m.

The retreat of the escarpments of the Araripe Plateau is a geomorphological phenomenon that remains active even today, with distinct processes of block falling and accumulation of talus deposits in the foothills, landslides and debris flows. As a result, a diversified range of alluvial fan deposits has formed, however, dominated by gravity flows. The deposits of these lobules are continually dissected by rivers that have their springs at the base of the escarpment and are preserved in a discontinuously and fragmented form in the upper piedmont areas and in the summit of the hills of the Cariri Valley.

In the Cariri Valley, drainage courses form a parallel and sub-parallel pattern, with interfluves aligned in the predominant north-northeast direction. The Batateira River, which runs parallel to the fault traces that delimit the Mesozoic sediments of the pre-Cambrian basement, forms the main drainage line that carves the piedmont deposits, thus allowing for direct observation of these deposits. The phenomenon of headwater capture is recognised, forming local areas of confluence, and the alignment of these areas can be related to fault traces, constitution or reactivation of ancient faults in early stages of regional geological evolution, within a neotectonic regime acting in the area.

21.4 Plateau Morphology

The plateau is an impressive residual relief. It is flat-topped, with predominantly sandy soils and poor superficial drainage. The escarpments that surround the plateau are very steep with sub-vertical cornices of tens of metres; they are a product of headward erosion and progressive retreat of its edges.

The summit surface has altitudes that exceed 1,000 m at the eastern edge and decline to approximately 800 m in the western portion, thereby resulting in a low topographic gradient of approximately 1 m/km. Although it has an attitude that is similar to the layers of the Exu Formation, the summit surface is not adjusted to the sedimentary bedding. The summit surface is an erosional one, related to deep laterization. Ferricrete and silcrete levels at the summit surface or immediately below it are common throughout the plateau. Sandstone cementation by iron oxide and silica in the upper portion of the Exu Formation, with duricrust formation, makes the rocks from the top more resistant to erosion and is the main cause of relief support (Fig. 21.5).

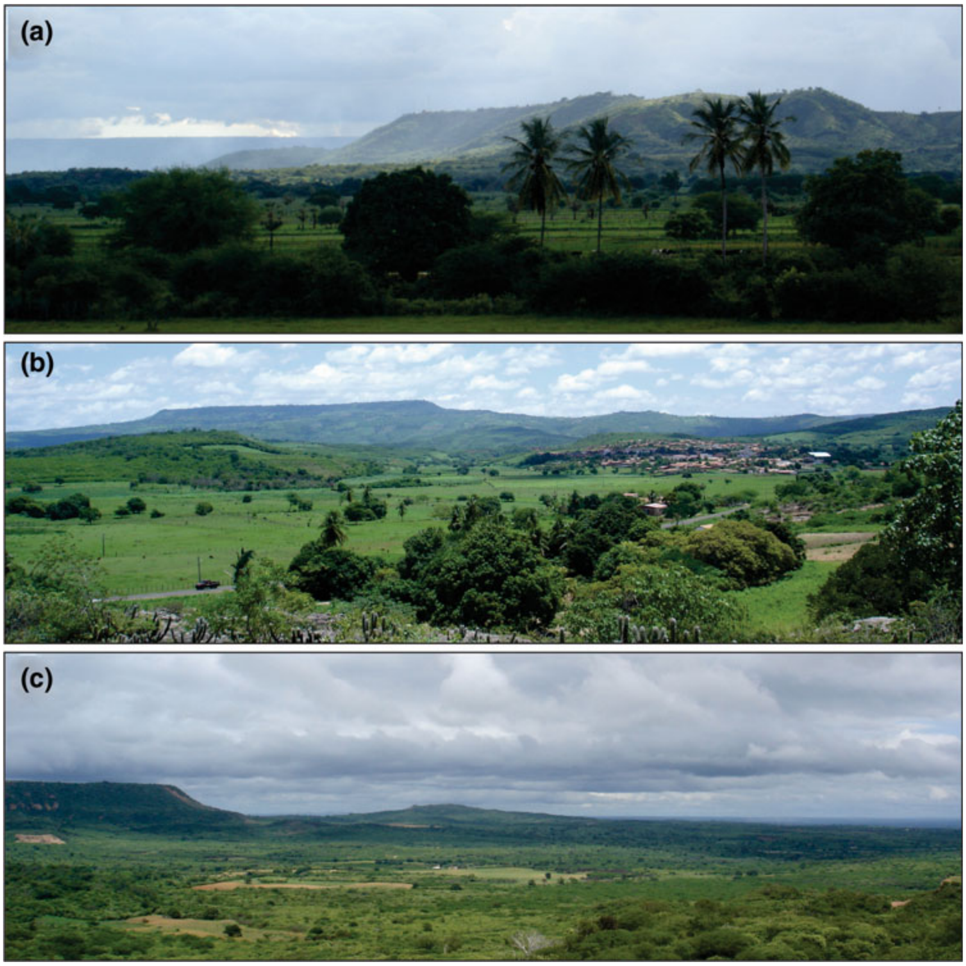

Fig. 21.5 Different morphologies around the Cariri Valley: **a** a lush vegetation on a plain flat-bottomed grassland of Cariri Valley and Morro do Horto at the background, supported by rocks of Precambrian basement, trace of relief due to rift tectonics; **b** cityscape of Abaiara with part of the escarpment of the Araripe Plateau in the background; and **c** Araripe tableland, steep escarpment and Cariri Valley viewed from Serra da Mãozinha looking towards west

21.4.1 Structural Control of the Plateau

The discovery that the rift section of the Araripe Basin is segmented by faults with large offsets, including under the plateau, was initially reported in geological mapping and in seismic reflection sections (Assine 1990; Ponte and Ponte Filho 1996). The style and spatial arrangement of the rift phase faults can be noted in the Cariri Valley, where Mesozoic units emerge from below the plateau forming units. Bordering the valley, pre-Cambrian rocks crop out in fault contacts with Mesozoic rocks, like in the Morro do Horto in the city of Juazeiro do Norte (CE).

The Cariri Valley is delimited by two sets of faults (Morales et al. 2011), where the oldest one is represented mainly by two normal faults of predominantly northeast–southwest direction, forming alternating horsts and grabens. They are responsible for rift sedimentation and deformation of the pre-rift layers. The second set, related to transtensive regime linked with the evolution of the basins of the Brazilian equatorial margin, is composed of faults with dominant WNW-ESE directions of great importance in the regional morphotectonic compartmentalisation. These faults also control the major structural directions of the plateau.

The two sets of rift phase faults were reactivated in the Cenozoic such that faults and fractures of similar directions determined the shape of the plateau. Despite the grooves and sinuous outline of the escarpment segment, the contours of the cornice line and the route of the drainage superimposed on the summit surface of the Araripe Plateau are controlled by extensive structural lineaments, which show the structural control on the retreat of the escarpments. Rectilinear escarpment fronts are traits of tectonic landforms, resembling fault-generated escarpments that have retreated by headward erosion. Fractures and faults of WNW-ESE direction control the major rectilinear segments of the escarpments. These structures, combined with others in the northeast–southwest direction, form straight and angled corners, giving rise to an approximately rectangular plateau on its eastern portion, which is clear in the digital model of elevation illustrated in Fig. 21.4.

21.4.2 Piedmont Deposits

The erosive retreat of the escarpments is the result of a broad spectrum of slope failure and gravity flow processes, from rockfalls to mudflows. In the northeastern portion of the plateau, in front of the Cariri Valley, C-shaped indentations carve the escarpment and form large erosive amphitheatres, being related to the retreat of the escarpment by gravitational processes of great magnitude (Peulvast et al. 2011).

In addition to the topographic unevenness, the above-mentioned processes are strongly influenced by water availability at the contact of Exu sandstones with the underlying shales of the Santana Formation. Rainwater infiltrates the sub-vertical fractures in the sandstones of the Exu Formation, then flows horizontally above the contact with the clayey section below and emerges in many springs at the base of the escarpments in the upper piedmont areas. These types of springs form the hydrographic network of the Cariri Valley, which is an area of greater demographic concentration, highlighting the hubs represented by the cities of Juazeiro do Norte, Crato and Barbalha (CE). During heavy rain periods, the underground waters trigger mass movements that displace great amounts of rock and debris towards the lower areas surrounding the plateau.

Mass movement events related to periods of great rainfall formed a wide range of gravity deposits in piedmont areas, which originated by dismantling of the summit surface. The piedmont areas surrounding the Araripe Plateau in all their extension are characterised by the presence of pediments, which decrease its inclination from the base of the escarpments to adjacent lower areas.

The piedmont area is wider in the Cariri Valley where old gravity flow deposits are found on the interfluve hills elongated in the north–south direction (Fig. 21.6). The deposits are constituted by clastic material with sandy to clayey matrix, rich in gravel and boulders, and often affected by recent faults (Fig. 21.7). Whole blocks of tens of metres are found rotated, most likely due to semicircular ruptures of large dimensions. Elongated forms resemble lobules of alluvial fan, but they are dissected by the current drainage and obliterated by superficial erosion; therefore, it is not possible to reconstitute the original geometry. In the most distal and smooth portions of the pediments, the surface is characterised by gravel pavements, which have originated from differential erosion of debris deposits by surface waters and wind. Silicified/ferricretised sandstone boulders derived from the erosion of the Exu Formation are distinctive amidst the gravel.

21.4.3 Mesas and Buttes

The Araripe Plateau is a dissected relief, dominated by headward erosion with progressive retreat of its escarpments, forming flat-top residual relief of different dimensions, such as mesas and buttes (Fig. 21.8).

Pinnacles that are supported by hardened sandstones of the Exu Formation, with steep and sub-vertical slopes, form features measuring tens to hundreds of metres high, bordered by a fringe of gravity deposits (talus and flows of debris lobules) in its middle slopes. The main example is the Serra da Mãozinha (Fig. 21.6), which is located in the northern portion of the main escarpment, with an extensive fringe of

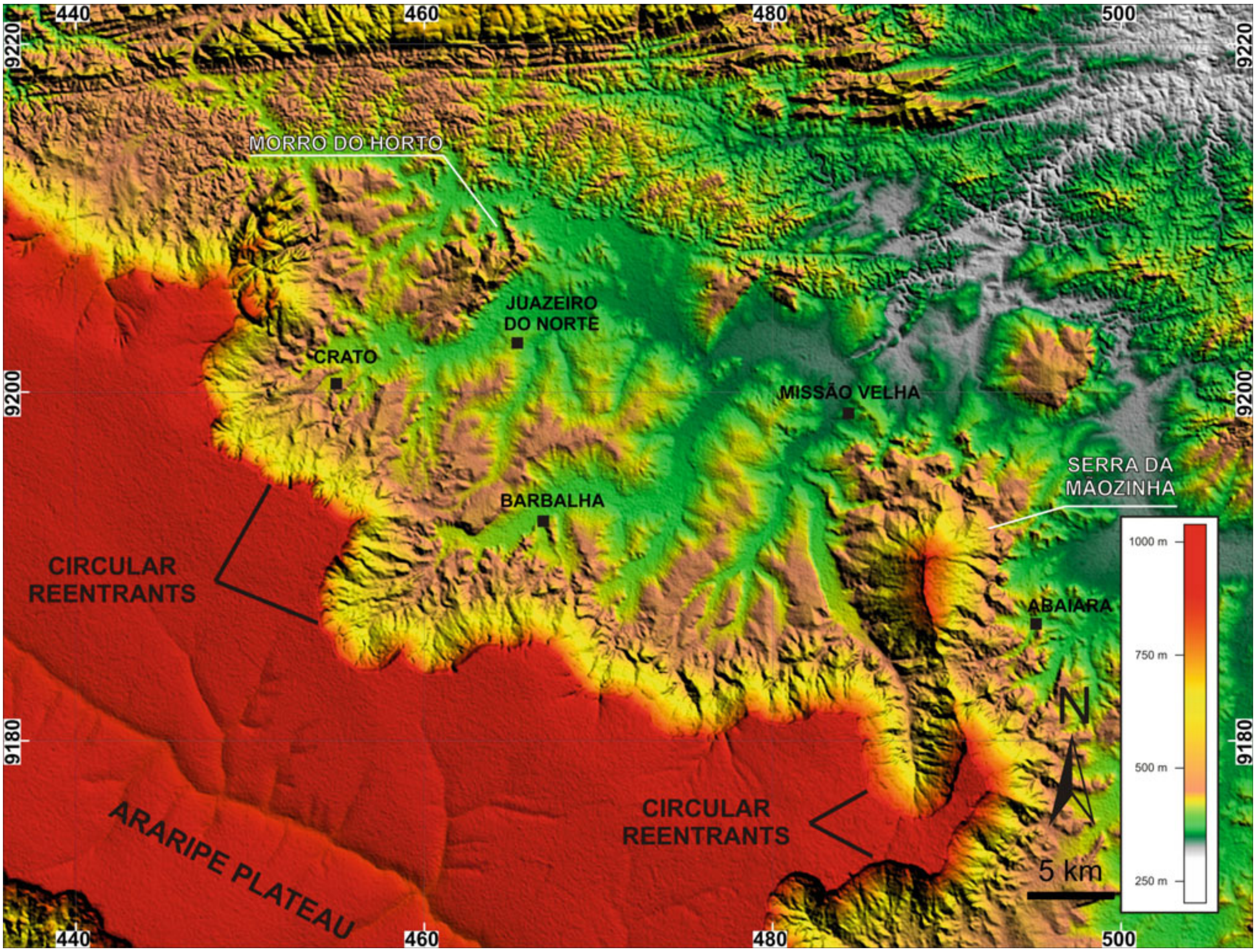

Fig. 21.6 The northeastern flank of the Araripe Plateau, facing the Cariri Valley, where the structural predisposition of the escarpment towards the west-northwest direction and the existence of semicircular grooves showing the retreat of the escarpments due to mass movements down the slope are highlighted. Piedmont deposits are continually reworked by the current drainage, which has its springs in the contact zone between the escarpments and the piedmont area, resulting in deposit preservation at the top of the hills in the valley. The Serra da Mãozinha provides the residual relief with the same stratigraphy as the plateau, constituting an example of a butte resulting from plateau retreat (the digital model of the terrain was built with data from SRTM/NASA)

debris flow deposits in its surroundings, in addition to very deep drainage incisions in the middle slope.

The most evident example of the plateau as a residual relief is the existence of the Serra do Inácio, a mesa located at the southwestern portion of the Plateau, which has the same geomorphological configuration and occurrence of duricrusts in the summit surface and is level with the western portion of the plateau (Figs. 21.1 and 21.3). Moreover, the Serra do Inácio features the same stratigraphic succession consisting of sandstones of the Exu Formation in the summit part and shales of the Santana Formation in the foothills. It is worth noting that the post-rift section sets directly on the pre-Cambrian crystalline basement in the western portion of the basin, with extensive layers of gypsum in the basal portion of its Cretaceous section, constituting the main gypsum outcrop area in the country.

21.5 Historical and Social Aspects

The occupation of the region began with the penetration of Portuguese people into the Indian territory of Cariri tribe in the early eighteenth century. The region flourished due to abundance of water resources, soil fertility and economic growth, especially with cultivation of sugar cane, cassava and cereals. After decades of prosperity, the poverty has increased since the mid-nineteenth century as a consequence of great droughts in the entire Northeast region. The lack of rains declining agricultural production and often calamitous situations produced increased religiosity, a fertile ground to the appearance of a religious and political leader, the Catholic father Padre Cicero (Della Cava 1970). Since then, Padre Cícero has been considered a saint and every year

Fig. 21.7 Examples of piedmont deposits: **a** a silty sandy colluvium matrix in which the silicified sandstone boulders of the Exu Formation over the Cretaceous sandstones predominate; **b** clast-supported conglomerates coexist with facies in which clasts fluctuate in the matrix, denoting processes of cohesive debris flow; and **c** small faults affect the piedmont deposits, showing the role of neotectonic activity in relief formation

people pilgrimage to Juazeiro do Norte from everywhere in the northeast region, and these events are very important to the commerce and local economy.

On top of the plateau, the presence of native vegetation represented by lush vegetation led the government to create the Araripe National Forest in the year of 1946, the first in Brazil. It is characterised by an Atlantic Forest biome, represented by semi-perinifolia rainforest with transition to savannah, with preservation of a large number of native species. It is, after all, an important haven for wildlife in the region, including animals threatened by extinction. It represents an element of great importance in maintaining hydrological, climatic and ecological balances of the region.

Richness of water is due to the role played by the regional aquifer of the Araripe Plateau, which acts as a huge reservoir that distributes the waters along the fringes of its cliffs into numerous sources that feed the local rivers. Groundwater remains a vital aquifer, depending on and controlled by the regional geological rift sedimentary basin, preserved and covered by the pile of sedimentary rocks that build the tabular region of the Araripe. Absorbed rainwater returns to the surface on the sides facing the Cariri Valley, developing lush greenery (wet forest) and making the local climate very pleasant. The presence of the sources becomes an important tourist attraction, mainly represented by the presence of mineral waters and thermal spas and parks.

The scientific importance of the region has been recognised since the mid-nineteenth century, due to the great number of well-preserved fossil deposits (especially in the Santana Formation), dating from the Early Cretaceous (Aptian–Albian). Early research conducted in the region dates back to 1840 when the Araripe was characterised as the first area of the Brazilian territory having its dating determined based on palaeontological records, based on studies of fossil fishes conducted by Louis Agassiz in 1844. Since then, the region has attracted many researchers, leading to the recognition of enormous biodiversity (Maisey 1991; Martill et al. 2007) that includes, besides fishes, reptiles as crocodilians, turtles and snakes, molluscs and echinoids, insects, arthropods, plants in the form of stems, leaves

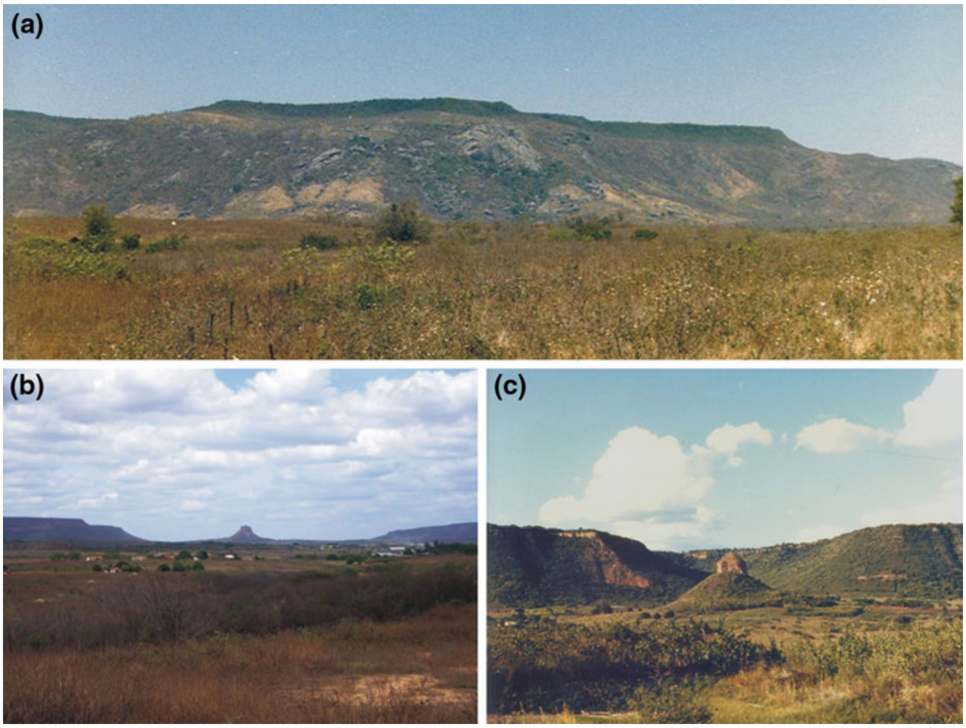

Fig. 21.8 Retreated escarpments expose irregular palaeorelief, which exists under the sedimentary rocks, such as the granite massifs in the southern side of the Araripe Plateau (**a**), and form beautiful buttes, which attest to the greater extension of the plateau and the Cretaceous rocks on which it was carved (**b** and **c**)

and pollen, and the pterosaur fossils that have received great international prominence. This importance has led to an international recognition, culminating with the creation of the Araripe Geopark, the first global geopark established in Brazil. Colleting thousands of specimens of fossils and exposing them to all visitors, two museums add importance to the region, the Museum of Paleontology of the URCA, Regional University of the Cariri Valley, located in the city of Santana do Cariri, and the Museum of Crato, sited at the city of Crato, belonging to the Paleontological Research Center of DNPM, National Department of Mineral Production.

The above characteristics have consolidated regional prosperity, which started in the early nineteenth century, and cultural growth achieved by household wealth resulting in an urban core of large population growth, marked mainly by the municipalities of Crato, Juazeiro and Barbalha. The region now employs a population of over 500,000 inhabitants, with great economic and social growth.

21.6 Conclusions

The Araripe Plateau is a clear testimony of the marine retreat event that occurred in the interior of northeastern Brazil during the Cretaceous, approximately 100 Ma ago. This plateau has rich and abundant Aptian fossil records that are famous worldwide and are spectacularly preserved. The sedimentary succession records continental sedimentation controlled by regional uplift since the beginning of the Late Cretaceous.

The summit surface of the plateau, at approximately 1,000 m a.s.l., is a remnant and main representative of the Sul-Americana surface, indicating posterior epeirogenic movement, which intensified after 30 Ma, as indicated by fission tracks and gravimetry data and Macau volcanism data.

Due to the aforementioned uplift, a drainage system started to develop, promoting progressive retreat of the escarpments. The Araripe Plateau survived as a great regional watershed, a remaining testimony of this local evolutionary relief formation. Structural features of both the escarpments and the superimposed drainage coincide largely with the fault lines that delineate the sedimentary packages of the rift sequence of the basin, indicating pulses of reactivation of older faults during the Cenozoic. Some of those faults still preserve the tectonic landscape as in the Morro do Horto where people built the monuments to Padre Cícero.

The summit surface is the record of a significantly broader flattish surface, which once stretched for much of the inland northeastern Brazil and of which the high flat-topped residual landforms are remnants. These landforms invariably exhibit ferricretes and/or silcretes, such as in the sectors of the Borborema Plateau, the Serra dos Martins and the Serra do Ibiapaba.

The duricrusts (ferricretes and silcretes) that cover the plateau give support to the relief, making the eastern edge of the plateau a screen for the orographic rains, which create wetter microclimate and contribute to the origin of an enclave of savannah vegetation (Cerrado Biome) within the Caatinga domain. Water that percolates through the sandstones and emerges at the base of the escarpments supplies the surrounding areas, especially the Cariri Valley. These conditions are responsible for the high demographic concentration in the developing pole represented by the cities of Juazeiro do Norte, Crato and Barbalha.

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Stone and Sand Ruins in the Drylands of Brazil: The Rustic Landscapes of Catimbau National Park

22

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and Daniel Rodrigues de Lira

Abstract

Catimbau National Park (CNP) is the only one in Brazil entirely circumscribed by the semi-arid climate and the Caatinga biome of the Northeast region of the country. It is situated in the state of Pernambuco and comprises a set of sandstone landscapes of unique scenic beauty as well as holds important records of archaeological, biogeographical and geomorphological history of the central drylands of the country. The area displays a mosaic of natural landscapes developed on sand covers of the borders of Jatobá sedimentary basin, an important regional geologic feature that was severely deformed by post-Cretaceous tectonic movements following the break-up of Gondwana continent and the final opening of the South Atlantic Ocean. The occurrence of table-like buttes and uplifted homoclines, some in excess of 1,000 m in elevation, favours the development of moister and cooler environmental conditions, which are reflected in the local ecology by means of vegetation refuges and enclaves that differ significantly from the prevailing thorn-scrub xerophytic formations of the Caatinga. Concentration of drainage network towards the base and knick-points at the abrupt sandstone escarpments favours the formation of seasonal swampy areas and lagoons, which are rare natural features within this dryland region of the eastern seaboard of South America.

Keywords

Sandstone landscapes • Brazilian drylands • Catimbau National Park

22.1 Introduction

Within the core of the drylands of north-eastern Brazil, a chimeric landscape emerges in sight of the travellers that follow State Road PE-270, heading from the town of Arcoverde to the municipality of Buique, in the central region of the State of Pernambuco (Fig. 22.1). Displaying a type of rustic and rugged beauty, Catimbau National Park (CNP) holds mysteries, some of which only recently have begun to be revealed by science… Mysteries that are hidden amidst the extensive sand covers and stone ruins.

The area of the Park shelters important prehistoric rock paintings that exhibit a style marked by both pure abstract artwork and anthropo-, phyto- and zoomorphic representations, such as those portrayed in the Alcobaça archaeological site rock art panel, the second largest of its kind in Brazil. Pollen grain analysis and radiocarbon dating point to a steady increase of human presence in the region since at least 4,500 years. BP, as suggested by the appearance of *Orbygnia* pollen grains in organic sediment cores recovered from the swampy areas situated on the footsteps of major escarpments (Nascimento 2008). *Orbygnia* is an exotic species in this region, and its presence in the geological

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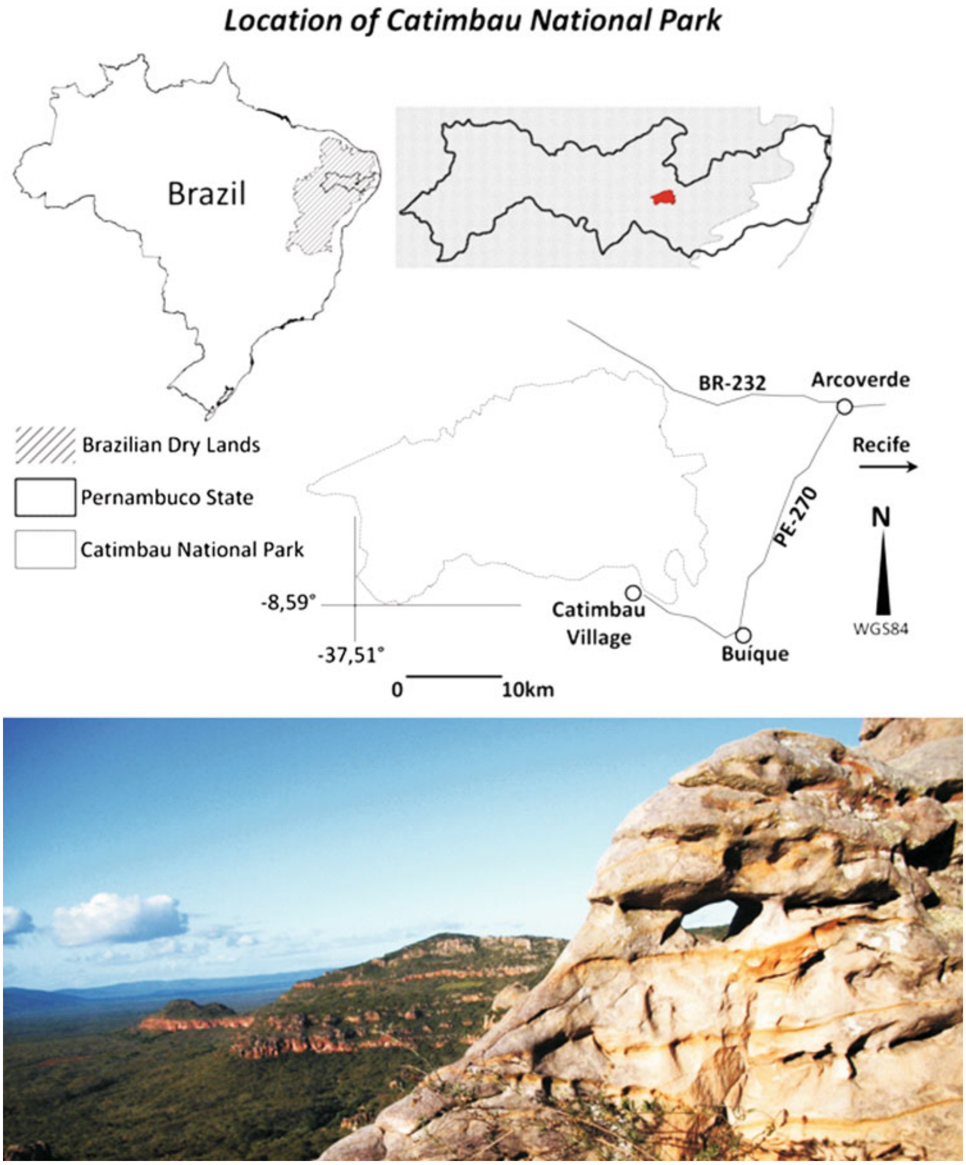

Fig. 22.1 Location of CNP, state of Pernambuco (north-east Brazil) and its eroded sandstone landscapes (*Photo*). *Source* Lucas Costa de Souza Cavalcanti

record is probably related to the migration of human groups from the west towards the coastal zone.

The assemblage of fauna and flora in the Catimbau exhibits quite distinctive species, such as the tree *Jacarandá rugosa* and the endemic lizard *Scriptosaura catimbau*. Among the uncommon occurrences in the region, attention is drawn to the composite *Paralychnophora reflexoauriculata*, which is indigenous to the rocky elevated grasslands of Chapada Diamantina, situated more than 800 km to the south-west of CNP. Furthermore, Brazil's largest diversity of bats is found within the caves of the Park. Such ecological singularities are the product of the distinctiveness of the region's geomorphological units that control the spatial distribution of precipitation within the Park limits, ranging from a meagre 600 mm/year in the lowlands to more than 1,200 mm/year on the elevated summit surfaces along its south-east border (Fig. 22.2).

Transformed into a Conservation Unit by a Federal Decree in 2002, the region of Catimbau valley was deemed of extreme biological and archaeological importance to the country. The set of physical, geographical and ecological elements, coupled with the area's peculiar geological history, cooperated towards the development of the region's spectacular landscapes. Despite its natural potential for tourism, the area where the CNP was created is at a high risk of human induced and climatic desertification (SNE 2002; MMA 2007), thus demanding cautious land management approaches.

Fig. 22.2 Remarkable natural features of CNP. **a** Impressive sandstone escarpments; **b** Rock art panels (e.g.: Alcobaça Archaeological Site); **c** Uncommon plant and animal species (e.g.: *Paralychnophora reflexoauriculata* (GM Barroso) MacLeish). *Photo* Lucas Costa de Souza Cavalcanti

Notwithstanding the prehistorical occupation and its ecological singularities, the building of the cultural landscapes of this sector of the State of Pernambuco results from a special miscegenation between indigenous and exotic cultural elements, as can be seen from the main agricultural products cultivated on small scale by local farmers (manioc, sweet potato, beans, maize, tomato, cashew, guava, orange and cotton), and livestock, specially bovine cattle, sheep, goats and chicken. Exotic, drought resistant species such as *Prosopis juliflora* have been introduced to provide extra forage for the cattle.

22.2 A History Written in Sand

The rare set of landforms of the Park embodies a history that dates back to ca.100 million years, to the time of break-up of the Gondwana supercontinent and the opening of the South Atlantic Ocean. At that time, a large Palaeozoic intra-continental basin, characterized by the an extensive, quartz rich, sandstone cover (Tacaratu Formation) was submitted to uplift and dismantlement as a consequence of continental rifting, resulting in the development of a series of step-like tectonic grabens and horsts (Carvalho 2010).

Subsidence processes, also related to continental rifting, created topographic depressions in which the Palaeozoic sandstone layers of the Tacaratu Formation received protection from erosion advancing from the newly formed Atlantic Ocean. In the surrounding uplifted terrains, sedimentary covers have been completely stripped away, revealing the underlying crystalline basement. The trapping originated as a result of the continental rift that separated Africa from South America. However, due to the extremely resistant basement rocks of the Pernambuco-Alagoas Massif lying to the north of the CNP, the rifting process was locally interrupted. This geological obstacle forced the continental rift to open along another direction, further to the east, thus creating the contemporary seaboard of the northeastern bulge of Brazil, located 200 km to the east of the first rifting. To this date, the tectonic, sediment filled depressions and plateaus south of the Pernambuco-Alagoas Massif remain in the landscape as silent witnesses of this “aborted rift”, also known as an aulacogen (Fig. 22.3) (Barbosa 2006; Lima Filho et al. 2011).

The aborted rift imprisoned several Palaeozoic and Mesozoic sedimentary formations that integrate the Reconcavo-Tucano-Jatobá basin. CNP is located in the north-easternmost corner of this morphostructure, on the outer limits of Jatobá

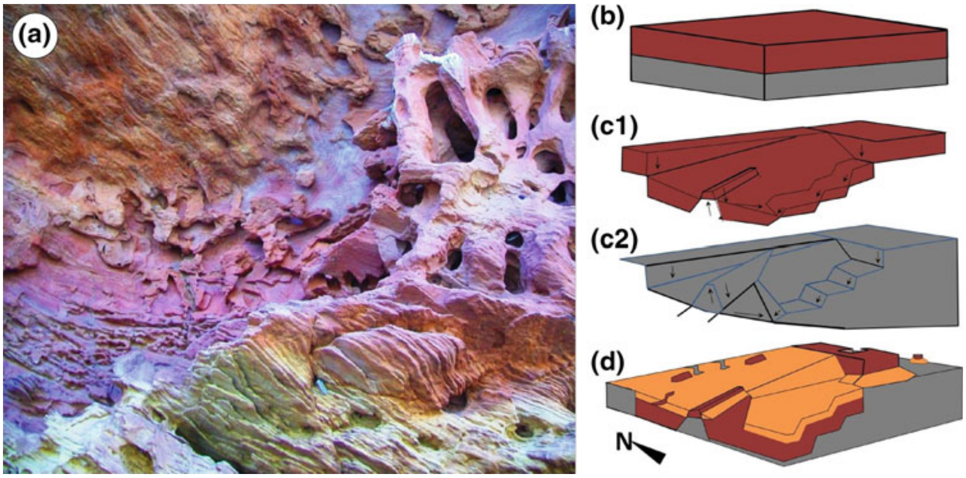

Fig. 22.3 Landscape evolution of CNP. **a** Tacaratú Formation (sandstone); **b** Hypothetical pre-rift phase (*red* sedimentary rocks; *grey* crystalline rocks); **c** Rift phase (**c1** sedimentary response–**c2** crystalline subsidence). **d** Resulting of weathering and long-term erosion (*Orange*). *Source* Lucas Costa de Souza Cavalcanti

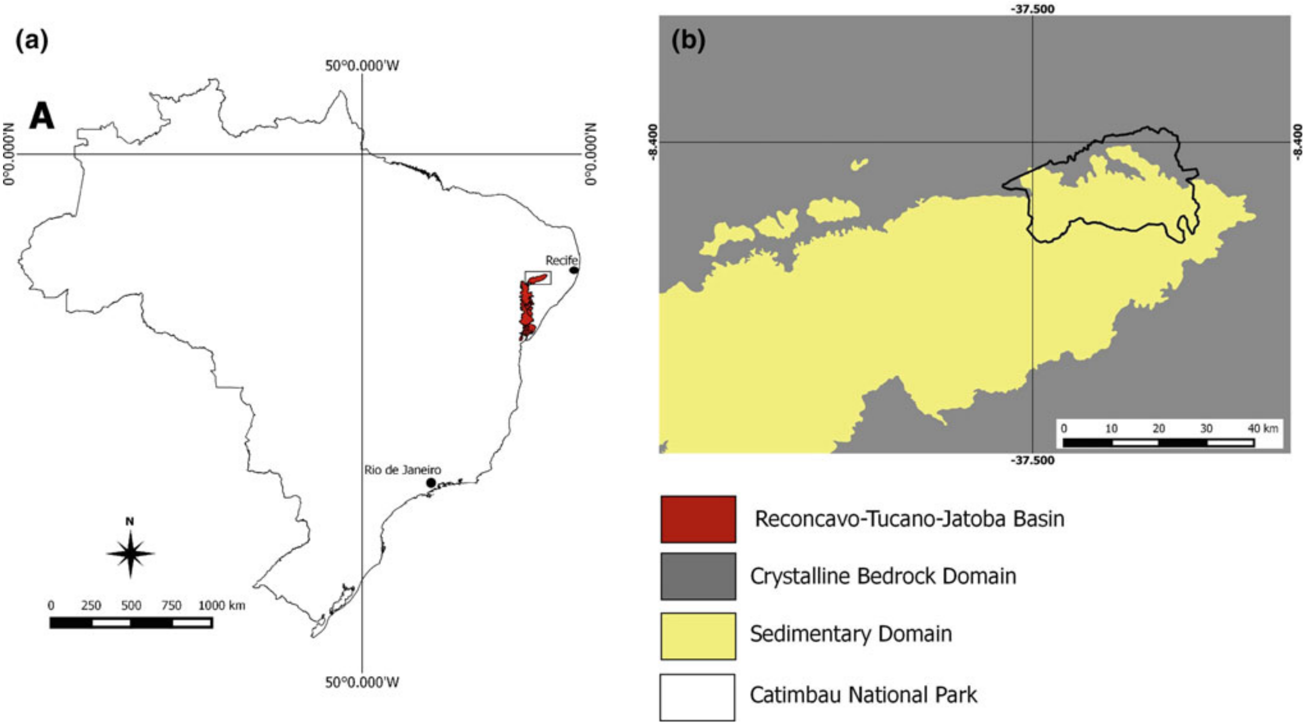

Fig. 22.4 **a** Reconcavo-Tucano-Jatoba sedimentary basin; **b** Geological context of CNP. *Source* CPRM. *Source* Lucas Costa de Souza Cavalcanti

sedimentary basin and the surrounding crystalline basement of the Borborema Highlands (Fig. 22.4).

Progressive erosion of Tacaratu Formation led to the carving of a series of dazzling sandstone geomorphic features, whose effects upon the local climate contributed to the establishment of a distinctive environmental scenery, sheltering both animal and vegetation rarities, as well as providing extremely favourable conditions for the first human settlers of the area throughout the mid-Holocene. This peculiar climatic dynamics derives from a local type of "valley-mountain" circulation, notably wherever sandstone remnants lie atop structural highs (e.g. Buique horst), thus favouring the occurrence of orographic rains, especially on south-east facing escarpments in excess of 400 m of total relief.

The south-eastern border of the Park is exposed to moisture-laden winds that generate higher precipitation along the E–SE facing slopes, resulting on a remarkably complex landscape, even more so wherever the outcropping sandstone layers are exposed to a much more humid climate. This environmental arrangement is reflected in thick, well-developed soil mantles, and in unusual biota that differ significantly from their counterparts in the drier areas of continental north-eastern Brazil. Moreover, this elevated section along the border of CNP, which forms an important regional drainage divide, separating the drainage basins of the Ipanema and Moxotó rivers, traps enough orographic precipitation to influence the distribution of more humid ecosystems along the exudation line at the base of the escarpment, such as the semi-permanent Puiu lagoon.

Almost 25 % of the Park area is made up of rock outcrops associated with the Silurian coarse-grained Tacaratu Formation, whilst the other areas show an extensive cover of unconsolidated sand and, to a lesser extent, layers of pelitic Cretaceous sediments and outcrops of crystalline rocks, mostly orthogneiss. The latter are more common along the northern and eastern borders of the Park. Amidst the large sandy covers and ruiniform relief on sandstone remnants, one finds a landscape of exceptional diversity, derived both from mechanical and geochemical processes, harbouring caverns, swampy areas, buttes, pediments and escarpments that witnessed a long-lasting and dramatic geological history.

22.3 Amidst Sandstone Ruins and Sand Covers

In order to understand geomorphic diversity of the Park, one must go beyond what eyes can behold. It is necessary to turn to other sets of rather elusive data, such as those contained in rock layers or derived from the construction of digital terrain models and an in-depth analysis of the Quaternary sediment record, derived from either outcrop data or borehole stratigraphic information. The combination of those varied sources was used to divide the Park area into geomorphological units that correspond to groups of landforms that share the same evolutionary history.

Alongside the geomorphological units, a landscape transect is presented, illustrating the most significant environmental contrasts of Catimbau (Fig. 22.5). Based on the observation of these illustrations, one can readily grasp the origin of contrasting landscapes and alternation of terrains with quite distinct geomorphic characteristics. These main units are sandstone ruiniform staircase-like plateaus, extensive sand covers resulting from the weathering of Tacaratu Formation, further dissected by ephemeral drainage, and vast low-lying rock *glacis* or pediments.

The geomorphological units of the Park correspond with seven large morphostructural sets which comprise a sequence of tectonically controlled lowlands (grabens and half-grabens) and/or structural highs (horsts) that make up the north-easternmost section of the Reconcavo-Tucano-Jatoba basin. The transect X–Y on Fig. 22.5 presents the sequence of units as they have been presented in regional geological literature: Frutuoso graben and Quiridalho horst (Santos 2012); O Puiu graben and the Half-grabens systems of Cumbe-Ponta da Várzea-Catimbau (Costa Filho et al. 2001) and; the Buique horst.

According to the above, the landscapes of CNP are primarily conditioned by the pattern of regional morphostructures that decline in elevation from east to west, following the original trend of the Mesozoic “aborted rift” or aulacogen. In spite of long-term weathering that led to the disaggregation of sandstone layers and soil formation, landforms at Catimbau largely observe the controls and limitations imposed by structure and lithology (cf. Fig. 22.3).

The eastern and south-eastern borders of the Park display a set of structural step-like levels (plateaus), whose escarpments are limited by wide low-lying *glacis* (gently inclined ramps carved on soft sedimentary rocks), dotted with residual butte hills that attest to the role of long-term denudation operating along the borders of an uplifted sedimentary basin (Fig. 22.6). Despite being partly eroded, these landforms still display a step-like arrangement that is very well marked in the landscape by vertical or sub-vertical sandstone walls separating levelled plateau surfaces. Some local escarpments exceed 200 m high.

The base of the escarpments is covered in toppled sandstone blocks which attest to geomorphic evolution controlled by gravitational processes, primarily rockfall. In other sectors, massive rock walls are subject to seepage erosion. The latter is a consequence of water infiltration on the top of the adjacent structural levels. Groundwater finds its way into the pervious coarse-grained sandstone, through ubiquitous fracture networks and the horizontal strata that intersect with the steep rock escarpments. The flow of water converges towards the base of the slope, thus gradually eroding the underlying layers and undermining the prominent buttresses. This process results in further slope collapse by the toppling of large boulders along the exudation lines (Fig. 22.7).

Furthermore, the dissection of escarpments footslopes often generates intricate sandstone pseudokarst forms (cf. Fig. 22.3a) and results in the elaboration of cave-like rock shelters, where the outpouring groundwater forms a series of springs that attract animals and promote right ecological and microclimatic conditions for the development of a very particular flora, of which the hydrophyle *Typha angustifólia* is an example. Thecaves formed at the base of the escarpments shelter several impressive prehistorical rock painting panels, like the one at Alcobaça archaeological site (Fig. 22.2b).

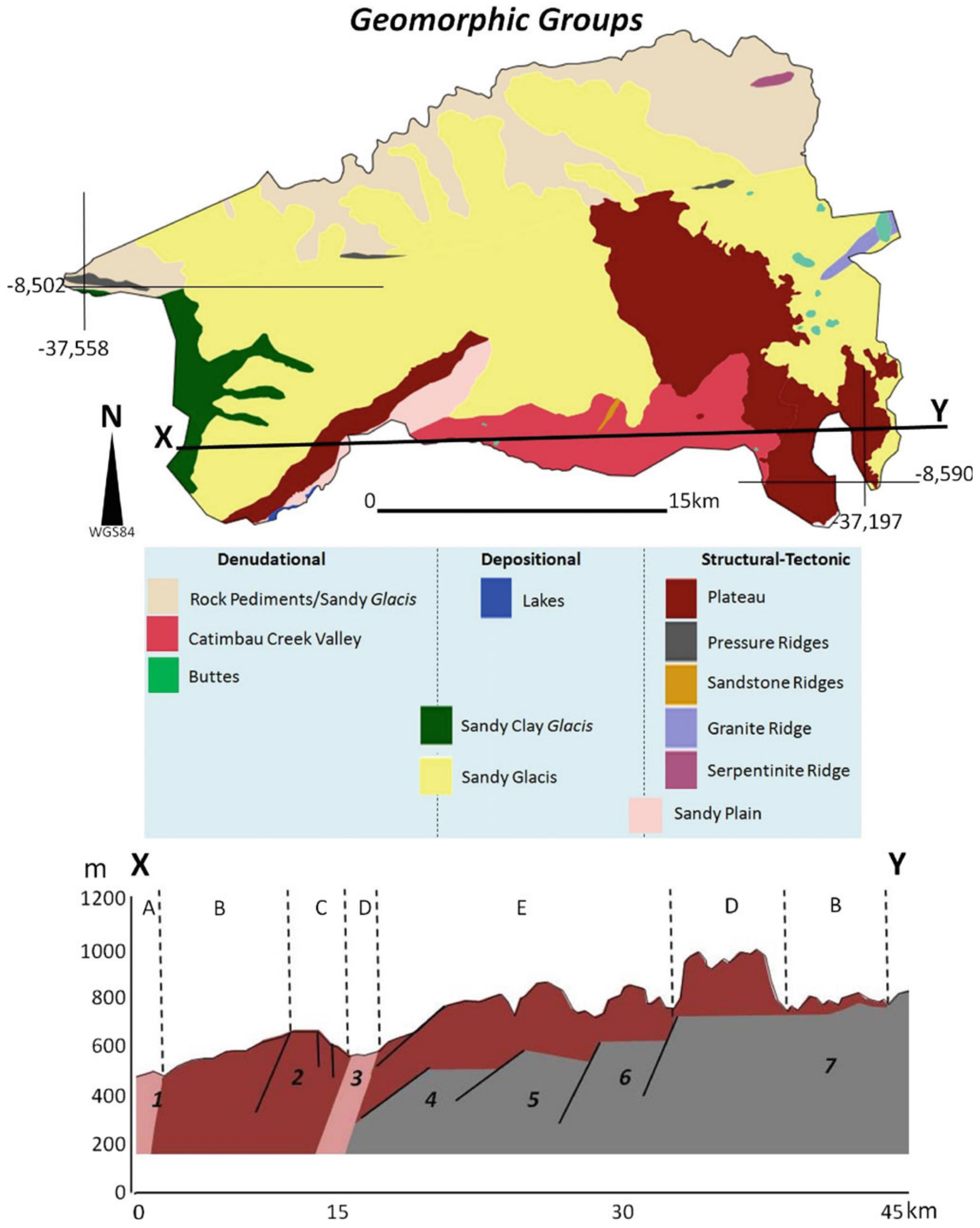

Fig. 22.5 Geomorphic units of CNP. On profile: *1* Frutuoso graben; *2* Quiridalho horst; *3* Puiú graben; *4* Cumbe half graben; *5* Ponta da Várzea half graben; *6* Catimbau half graben; *7* Buíque horst. **a** Sandy clay glacis; **b** Sandy glacis; **c** Plateau; **d** Sandy plains; **e** Catimbau Creek Valley. *Red* and *Pink* sedimentary rocks; *Grey* crystalline rocks. *Source* Lucas Costa de Souza Cavalcanti

Fig. 22.6 *Glacis*, residual buttes and step-like structural levels along the eastern border of CNP. *Photo* Lucas Costa de Souza Cavalcanti

Fig. 22.7 **a** Base of a sandstone escarpment displays fallen rocks and pipes created by seepage erosion; **b** Open cleft and tilted outer block at the base of an escarpment; **c** Fallen rock column. *Photo* Lucas Costa de Souza Cavalcanti

Along the clefts that cut across the steep rock walls, caves are formed and these provide a perfect habitat for several nocturnal species of birds and chiroptera, as well as hide ancient legends of the first human dwellers in these lands. On the rocky summits of the higher structural levels, one may contemplate the most spectacular vistas of the area, whose scenic grandeur provides a small glimpse of the long-lasting denudation history of the border of Jatobá sedimentary basin.

In contrast, the northern sector of the Park is marked by the presence of crystalline rocks, especially metamorphic, with concurrent gradual thinning of the conspicuous sand covers. In this area, soft rock glacis give way to extensive rock and detrital pediments cut across the Precambrian metamorphic complexes, which are the most characteristic landform units of the Brazilian semi-arid realm. These landscapes display soil covers and flora well adjusted to the severity of the hot and dry climate.

At this sector, the thinning sand cover becomes mildly clayey as a result of weathering of the underlying metamorphic rocks. Wherever the sand cover is lacking, the relief becomes remarkably level, and very clayey and saline soil pockets develop (Planosols). In other areas, rock outcrops and gravelly desert pavements devoid of any significant soil cover prevail. In both cases, the landscape is covered by the typical vegetation assemblage of the Caatinga biome, as attested by the presence of the genus *Schinopsis*, *Poincianella* and *Commiphora* and cacti of the genus *Pilosocereus*.

This domain of crystalline rocks displays very well-defined limits that coincide with an important regional geologic structure of the Pernambuco shear zone. It cuts across the entire length of the state of Pernambuco (over 800 km) into west Africa, which testifies to its ancient age, predating the opening of the South Atlanticocean. To the north of this structure, metamorphic rocks occur, mostly orthogneiss, whereas to the south of it, sand covers and the ruiniform relief characteristic of the long-term erosion of the Tacaratu Formation are predominant.

South of the Pernambuco Shear Zone, along the gently westward tilting surface of the Jatobá sedimentary basin, and below the higher structural levels, the sand covers become thicker, the soil is very porous, prone to drying, and acidic, and the vegetation is dominated by thorn-scrub and several

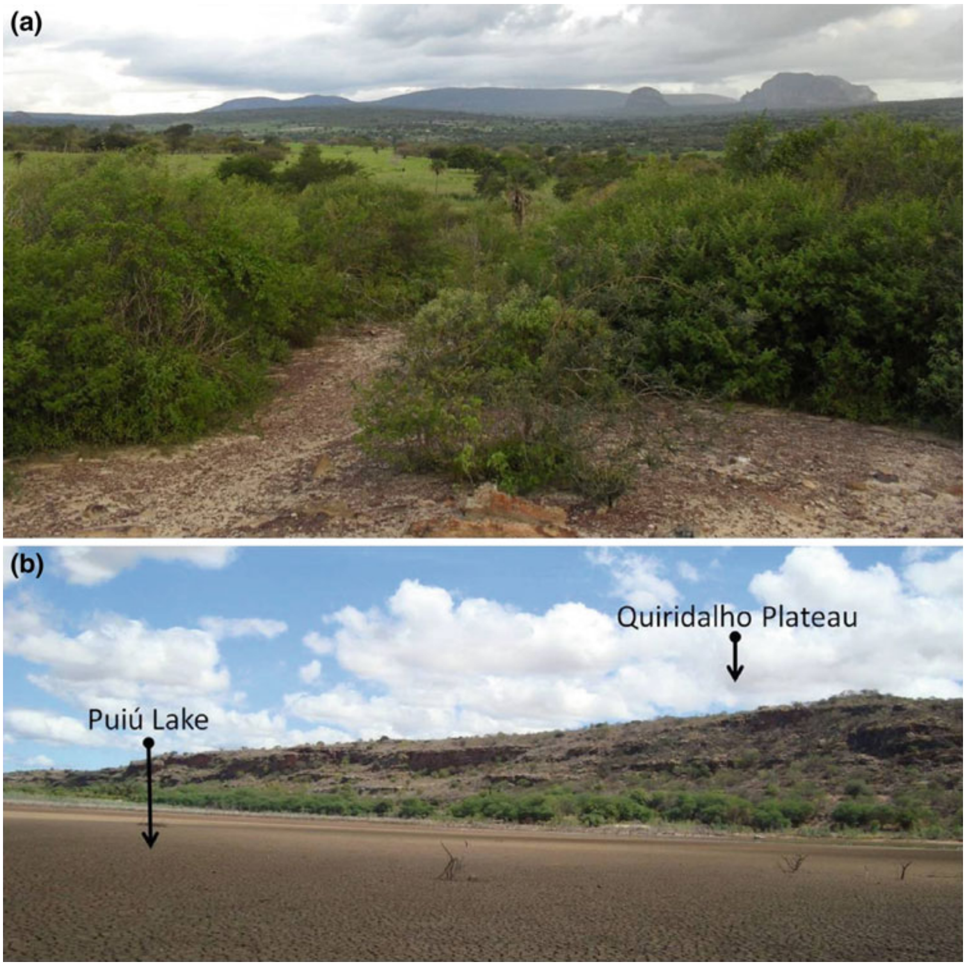

Fig. 22.8 **a** Sandy glacis on the sedimentary basin; **b** Quiridalho Plateau (horst) and Puiú lagoon (graben). View from Puiú lagoon (dry season). *Photo* Lucas Costa de Souza Cavalcanti

stinging species. Nonetheless, amidst this inhospitable scenery, a true oasis-like landscape emerges, the Puiu graben, a tectonically controlled depression, dominated by the homonymous lagoon (Fig. 22.8).

Lying at the base of the Quiridalho structural high (horst), the Puiu lagoon provides the adequate environmental conditions to sustain a 200-year-old settlement. The Puiu Village, as testified by its old chapel, has been successfully thriving on the seasonally flooded fertile soils that surround the lagoon. Yet, moisture levels rely almost exclusively on the emergent groundwater along the base of the Quiridalho horst escarpment. This reliable water supply is maintained by the infiltration of the Catimbau creek into the pervious Tacaratu Formation sandstone, the creek headwaters lying on the higher and wetter surfaces to the east of Puiu Lagoon.

22.4 Concluding Remarks

In this brief account on the geomorphology of the only National Park established in a sedimentary basin within the drylands of north-east Brazil, one is confronted with a landscape of exceptions. Lying in the distant and lonely tracts of land that border the Reconcavo-Tucano-Jatobá sedimentary basin, the CNP represents a true geomorphological and ecological heritage, a mosaic of extraordinary landscapes, protected by law.

With a geological past linked to the opening of the South Atlantic Ocean and the long-term and gradual erosion of the ancient sedimentary covers of the north-east bulge of Brazil, the Park inherited a set of diverse landforms, comprising caves and vast plateaus, residual buttes and extensive sand covers. Such landscapes, whose contrasts and singularities have resulted from the exposure to shifting climatic patterns and tectonic forcing, are of rare and extraordinary beauty.

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Serra Da Capivara National Park: Ruinform Landscapes on The Parnaiba *Cuesta*

23

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Abstract

Serra da Capivara National Park (SCNP), situated in the south-east corner of the State of Piaui, north-east of Brazil, harbours one of the most expressive sets of ruinform landscapes carved on sandstone. Its geomorphological uniqueness arises from the combination of geological and climatic factors. The area is located next to the edge of the Parnaiba sedimentary basin of Paleozoic age, where it meets a Neoproterozoic fold belt and an Archean craton. SCNP lies in an ecotone between the caatinga and Cerrado biomes. Adding to its geomorphological singularity, the dramatic landscapes of the Park are overlapped by one of the most important prehistorical heritages of South America. Human presence on this remote tract of the Brazilian savannas dates back to the Late Pleistocene and is singled out by the exuberant collection of prehistoric rock painting and engravings. The relief of the SCNP is characterized by steep sandstone cliffs cut through by narrow valleys that form gorges and water gaps. The relief of the Park comprises three geomorphological units: the escarpment, the dip-slope and the longitudinal depression. Whereas along the escarpment one finds the most remarkable landmarks of the Park such as prominent cliffs and rock arches, gorges and canyons along the dip-slope also reveal an impressively dramatic scenery.

Keywords

Parnaiba Basin • Homocline structure • Ruinform relief • North-east of Brazil

23.1 Introduction

Serra da Capivara National Park (SCNP) was created by Federal decree in 1979. It is located in the south-east of the state of Piaui, north-east region of Brazil (Fig. 23.1). The area lies on the westernmost fringes of the caatinga biome, in the transitional zone to the Cerrado biome, thus along the boundary of the semi-arid and subhumid wet/dry tropical climates, constituting a unique biogeographical ecotone. In 1991, the SCNP was inscribed on the UNESCO list of world's natural and cultural heritage.

The SCNP includes a unique group of landforms associated with the geomorphological context of the border of a sedimentary plateau in homocline structure (*cuesta*). This morphostructure was subjected to several uplifts, fracturing and exhumation episodes that helped to shape escarpments, canyons, gorges and water gaps of remarkable beauty (Fig. 23.2), whose oldest evidence of human occupation constitutes one of the largest and most important collections of archaeological sites of South America.

The uniqueness of the early human presence in the area of the SCNP derives from the fact that it dates back to the Late Pleistocene (Guidon and Arnaud 1991; Parenti 2001),

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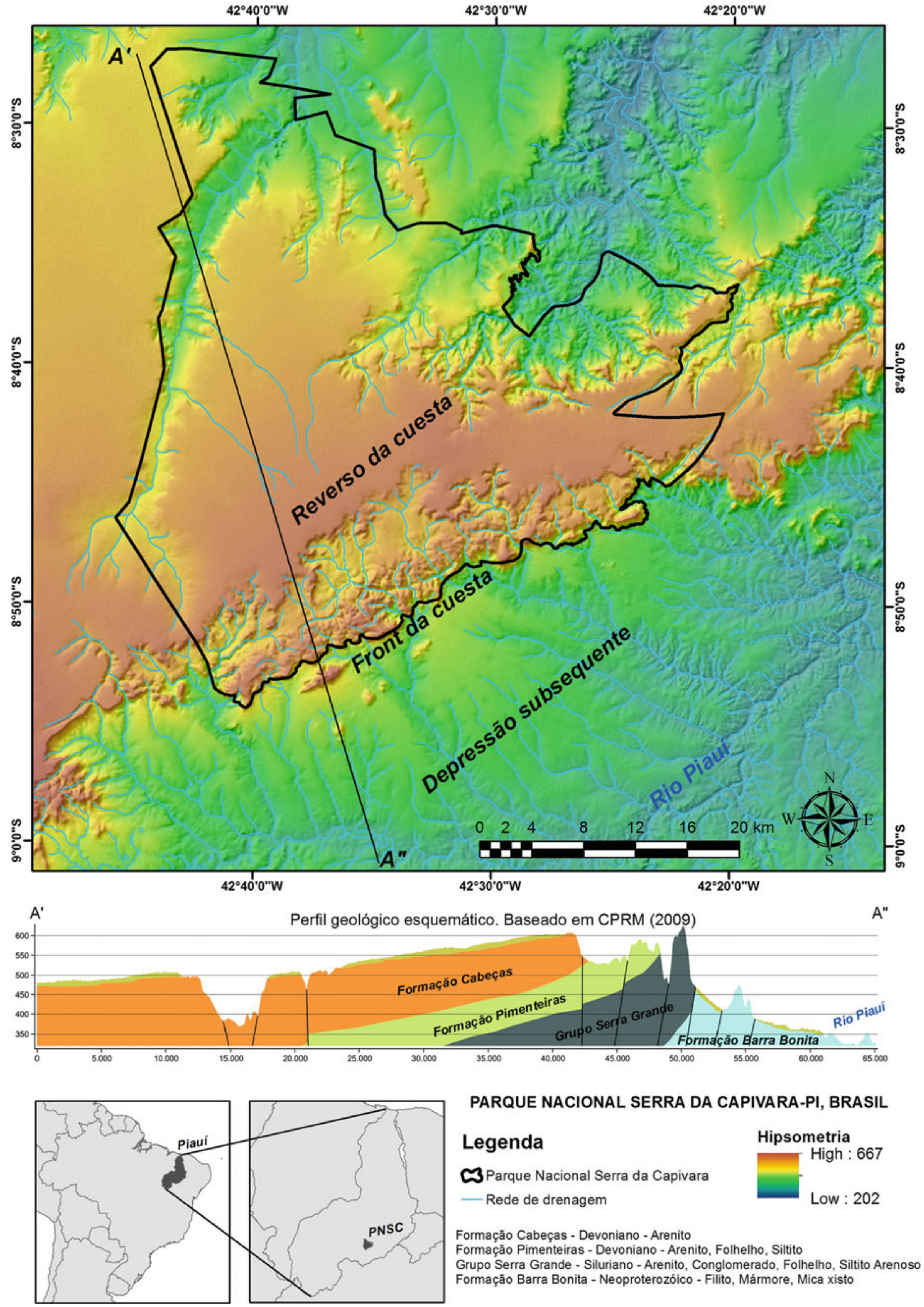

Fig. 23.1 Location of the Serra da Capivara National Park (SCNP), State of Piauí, north-east of Brazil. Shaded relief and schematic geologic transect

Fig. 23.2 Overview of the south-east border of Serra da Capivara National Park (SCNP), Baixão da Esperança site. The area synthetizes the singular landscape domains that integrate the Park. *Photograph* Luiz F.G.L. Katz

thus being one of the oldest in the continent and so confronting some of the current mainstream paradigms regarding the arrival of man in the Americas (Meltzer 2009). The area also stands out for the ubiquitous occurrence of rock paintings and engravings that make up one of the world's largest collections of their kind. The historical occupation of the area was characterized by displacement, extermination and acculturation of indigenous peoples, aiming at the establishment of cattle ranches at the onset of the seventeenth century. Such spatial transformation took place as an economically subsidiary activity to the European colonization process along the eastern coast of the north-east of Brazil, where sugar cane plantations thrived.

Due to the uniqueness of its geographical situation, in the transition between the semi-arid and wet/dry tropical climates where two of Brazil's large biomes merge, and at the junction of three geological provinces, the SCNP exhibits an extreme diversity of geomorphological landscapes. These comprise vast regional planar surfaces, sharp knickpoints along the cliffs, canyonlike entrenched drainages, residual buttes and mesas, as well as small-scale landforms shaped by differential erosion and weathering on different types of sedimentary and crystalline lithology.

23.2 Geology, Structures and Landscape Diversity

The SCNP is situated at the junction of three major continental geological provinces: São Francisco Province, Borborema Province and Parnaíba Province. The oldest of the three, the São Francisco Province, is formed by an Archean craton that integrates the basement of the South American platform (Trompette et al. 1992). This province outcrops to the south of the SCNP and contains mainly high-grade metamorphic rocks such as gneisses and migmatites, shaped into elongated hills in accordance with the axis of N–S-oriented folds.

The Borborema Province consists of a complex core of folded crystalline rocks whose origins date back to the Archean, when the basement suffered an initial tectonic deformation as a response to the Transamazonica Orogeny in the Paleoproterozoic (Mabessone 2002). Longitudinally, the Brasiliano Orogeny, from the Neoproterozoic onwards, affected thoroughly the structural framework of the province, leading to the establishment of shear zones and strike-slip faults of E–W and NE–SW directions. The Brasiliano

Orogeny triggered an intense granitic plutonic activity, regional metamorphism and reworking of older supracrustal belts.

Within the boundaries of the SCNP, the south-west sector of the Borborema Province crops out, marked by the presence of the Riacho do Pontal fold belt. This structure overlaps the São Francisco craton to the south and underlies the sedimentary deposits of the Parnaíba Basin to the west. In the area, it is still possible to identify evidence of the compressive ductile deformation that forced the Riacho do Pontal fold belt over the much older structures of the São Francisco craton. Locally, these structures were cut through by granitic plutons resulting from the Brasiliano Orogeny.

The Parnaiba Province comprises four sedimentary basins, one of them being the Parnaíba Basin, atop of which most of the SCNP lies, right next to the eastern and south-eastern borders of the basin. This intracratonic basin has a circular to elliptic outline, symmetrical profile and low subsidence rate. Lying above a large continental syneclise which later was subject to uplift, the basin was originally placed along Eo-Paleozoic rifts of NE–SW trend, in structural accordance with the Transbrasiliano lineament that cuts across a large portion of the eastern South American platform (Chamani 2011). Locally, this mega-structure separates the Borborema from the Parnaiba Province, displacing and uplifting the SE border of the basin, in the area of the SCNP. de Góes et al. (1993) believe these rifts were formed during the early breakup of the Gondwana supercontinent in the Eo-Paleozoic, when a vast network of fractures developed, thus creating an original intracratonic depression where the Parnaíba Basin is located. Later, continental rifting process from the Early Jurassic to the Late Cretaceous led to reactivation of Neoproterozoic shear zones. Reactivation of these shear zones, coupled with the opening of the Atlantic Ocean, resulted in the general uplift of the Borborema Province, the São Francisco craton and the Parnaiba Province alike.

In spite of the South America–Africa separation and the uplifting of old faulted structures initiated during the Mesozoic, the current intraplate tectonics is still in operation in several sectors of the Borborema, São Francisco and Parnaíba provinces (Hasui 1990; Saadi 1993). The Cenozoic reactivation of the shear zones played an important role in the dynamics and individualization of geomorphic compartments in the region, defining crystalline highlands, rejuvenated structural massifs and sedimentary plateaus structured on uplifted basins and syneclises (Brown et al. 2000; Bezerra et al. 2008, 2011; Chamani 2011). Within this context, the infilling of the syneclise occurred, with the deposition of five sedimentary sequences, correlated with global tectonic cycles (Soares et al. 1978; de Góes et al. 1992). Structural elements that are present in the basin are also strongly related to fault-line reactivations throughout the Phanerozoic.

In the SCNP, the outcropping rocks are related to Siluro-Devonian deposition and form the basal sequences of the Parnaíba Basin, corresponding to the Serra Grande and Canindé Groups, respectively. The Serra Grande Group comprises the Ipu, Tianguá and Jaicós Formation (da Cunha 1986), whereas the Canindé Group comprises the Itaim, Pimenteiras, Cabeças, Longá and Poti Formations (de Góes and Feijó 1994).

In the Park, Ipu Formation rocks (Serra Grande Group) are, in general, sandstones and conglomerates. The exposure of sedimentary structures along the scarps attests to various high-energy cycles within an alluvial fan system. These deposits have also been interpreted as fluvioglacial fans by Caputo and Lima (1984).

Pimenteiras Formation (Canindé Group) is lithologically represented by a predominance of finely laminated shale (CPRM 2009). Schobbenhaus (1984) suggests that these lithological and sedimentary characteristics point out to an infraneritic to coastal environment.

Cabeças Formation (Canindé Group) overlies the pelitic rocks of Pimenteiras Formation. The rocks of this Formation are predominantly layered and well-stratified sandstones. They are indicators of proximal tidal lobes transiting into tempestites and mudstones in distal sections (Santos and Carvalho 2009). The occurrence of striated rock pavements and faceted cobbles points to glacial influence (Caputo 1984).

Longá Formation (Canindé Group) is largely characterized by a pelitic section of shales interspersed with a package of sandstones and siltstones (de Lima and Leite 1978). The observed sedimentary structures are parallel laminations, cross-stratification, low-angle ondulations and ripple marks. According to de Lima and Leite (1978), the lithological, sedimentary and fossiliferous traits of Longá Formation suggest a regressive depositional environment.

23.3 Remarkable Ruinform Landscapes in a Homocline Structure

The distribution of landforms in the SCNP is directly linked to structural controls upon the hierarchy of geomorphological units. In fact, in the Park, combined lithological, structural and morphoclimatic controls operate at several scales to produce peculiar sets of morphologies. Regionally, the area can be described as the edge of an intracratonic basin with a homocline gently dipping towards NW. Starting with the structural context, it is possible to subdivide the SCNP into three large morphological domains of remarkable scenic appeal: the longitudinal depression, the cuesta escarpment and the dip-slope. Nested on those larger landform units, lithological controls and weathering play an important role in the evolution of smaller-scale landforms such as buttes,

Fig. 23.3 **a** Landform domains of the Parnaiba at the SCNP. *I* Escarpment, *II* dip-slope and *III* longitudinal depression. **b** Pedra Furada. Ruinform morphology developed along the crossing of fracture lines and the sedimentary bedding along an obsequent drainage gorge. *Photographs* Luiz F.G.L. Katz

rock arches, canyons, inselbergs and even karstic microforms (Fig. 23.3).

23.3.1 The Role of Structure

The reactivation of the South American platform since the Late Mesozoic, reinforced by the cyclic events of landform rejuvenation throughout the Cenozoic, emphasized the dipping of the homocline structures along the eastern border of the Parnaíba Basin, close to the deformational stress focal areas. These are located along the main fault and deep shear zones whose kinematic responses resumed during the reactivation of the platform. Thus, a sequence of structural landforms, typical of a reactivated basin edge, was created, with uplifted, tilted and subsided blocks. Within this context, the cuesta main escarpment can be described as a retreating fault scarp. However, at a more detailed scale of observation, the morphology of the escarpment is disrupted by a sequence of half-grabens and horsts that demonstrates the role played by shallow brittle tectonics on the spatial distribution of landforms and their geometry. The action of tectonics promoted uneven uplift of the border of the basin in the area of the SCNP, with a notable inflection of the faulted blocks from NE to SW. Tectonic deformation elevated the contact between the underlying metasediments of Riacho do Pontal fold belt and the basal siliciclasts of Serra Grande Group. In certain areas, such as to the SE of the Park, the uplift of the surrounding metamorphic fold belt has brought the area to elevations similar to those of the summit of the cuesta itself. The activity of normal faults, in shallow brittle regime, favoured the appearance of fault breccias along fault planes, formed between the metasediments and the overlying coarse sandstones of the Basin (Fig. 23.4).

The shear zones and subordinate brittle structures of NE–SW trend provide the limit for the cuesta escarpment, as well as control the entrenchment of the main water course of the region, the Piaui River, thus establishing a longitudinal drainage pattern as well as a local base level that lies up to 60 m below the surrounding pedimented surfaces. Shear zones and fault lines with an N–S and NW–SE trend act as secondary structural elements that command the distribution of the tributary drainage, which is equally adjusted to the prevailing structural controls. The role of the structural trends is particularly relevant in controlling spatial distribution of the obsequent drainage that carves its way through the cuesta main escarpment. The same is valid for the main consequent drainage that runs on the dip-slope of the

Fig. 23.4 **a** Faulted blocks along the escarpment of the cuesta. *I* Tilted block and *II* subsided block. **b** Uplifted geologic contact between the Riacho do Pontal fold belt (*base*) and Paleozoic siliciclastic sediments of the Parnaíba Basin (*top*). Normal fault with fault breccia accumulation along the displacement plane (*right corner*). *Photographs* Luiz F.G.L. Katz

homocline plateau within the area of the SCNP, the Serra Branca Valley (Fig. 23.5).

The geometry of the half-grabens, also tilted to NW, directly influences entrenching and direction of the drainage network. The major drainage lines are adapted to the limits between faulted and fractured blocks, so creating a repetitive pattern of fault-line and flexural slopes. In between the slopes, drainage courses and their corresponding Quaternary floodplain deposits are nested. The organization of the fluvial hierarchy within the drainage basins rigidly obeys the patterns of fracture distribution. As a consequence, headwater catchments are structurally adjusted to fracture planes that intersect the land surface. The low inclination of the summit and dip-slope lead to the evolution of solution microforms (honeycomb weathering), widely spread throughout the area, and scenic values of the rocky interfluves in the vicinities of major slope breaks (Fig. 23.6).

The backwearing of the cuesta escarpment is primarily subordinate to fault and fracture lines of NE–SW trend and, secondarily, to headward erosion promoted by the obsequent drainages, which are also controlled by brittle structures and the sedimentary bedding. Those drainages actively strip the planar stratification of the homocline structure, halting at the more resistant silicified or less pervious layers, thus initiating an exhumation process that creates structural and lithological levels that are very characteristic of low-dipping sedimentary plateaus. Gravitational faults along the major breaks of slopes and cliffs also collaborate to haste the pace of the retreat of the cuesta's escarpment. In certain areas, such as the Pedra Furada water gap, fluvial dissection along structural weakness lines resulted in the development of canyons, narrow gorges and other erosive landforms of great scenic beauty. In fact, the physiognomy of the subvertical rock cliffs that integrate the plateau escarpment, marked by texture, dip and colours of alternating sandstone and coarse conglomerate strata, superimposed on the differential erosion forms, constitutes the principal landmark of SCNP, synthetizing the rugged scenic appeal of this landscape.

The occurrence of residual buttes in front of the main escarpment, and aligned in the same NE–SW direction, reinforces the idea of the action of headward erosion in shaping this major landform, as obsequent rivers worked their way through the less resistant rock strata and more fractured areas (Fig. 23.7).

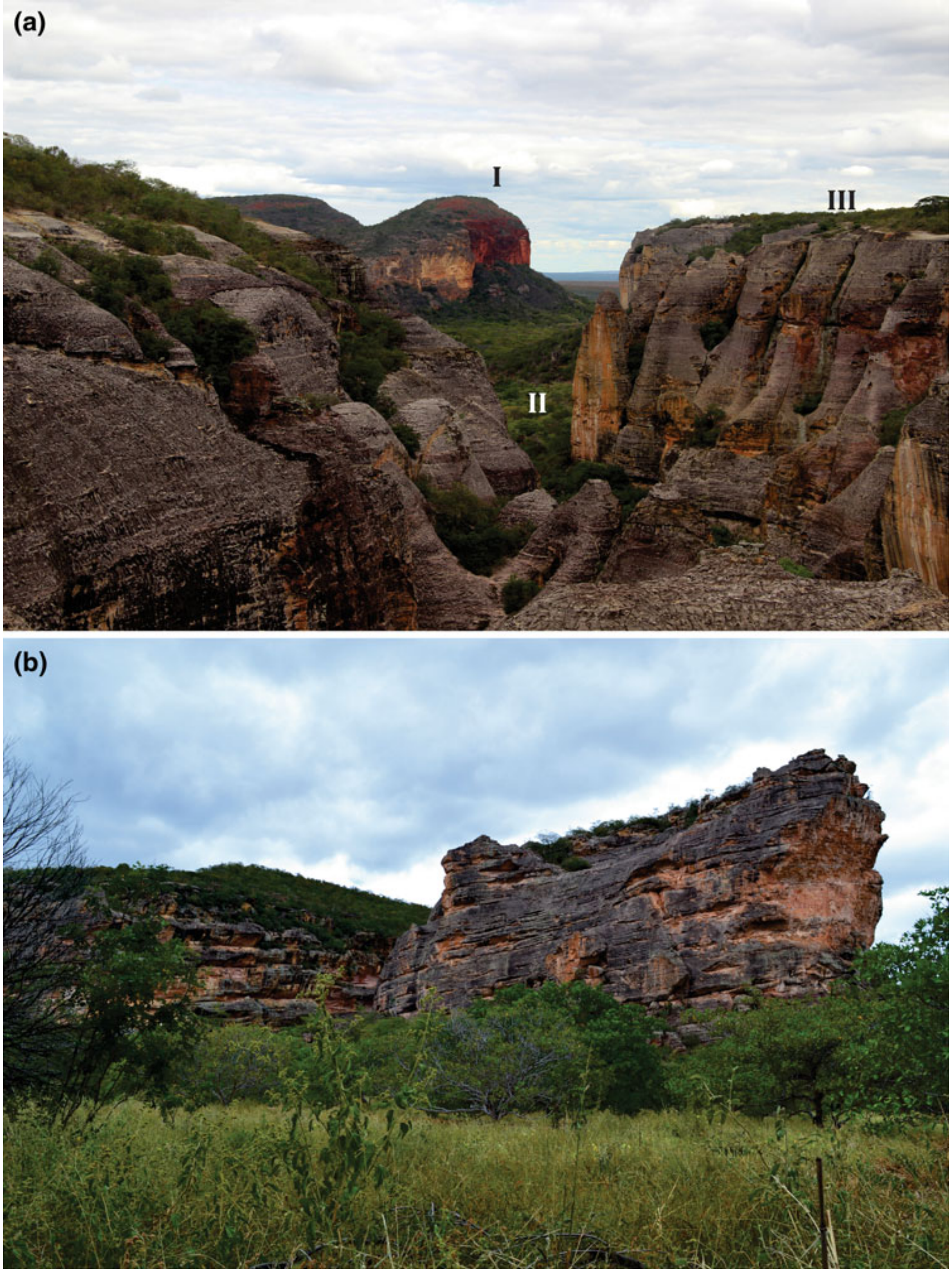

Fig. 23.5 **a** Obsequent drainage controlled by the structure at Baixão das Andorinhas. *I* Cuesta escarpment, *II* drainage axis and *III* subvertical fracture network. **b** Serra Vermelha butte at the cuesta escarpment. North-west dipping layers, to the south-west of SCNP. *Photographs* Luiz F.G.L. Katz

23.3.2 Weathering and Drainage

On the cuesta dip-slope, the predominance of sandstone lithology and the low inclination of the layers towards the Parnaíba Basin depocenter favoured the formation of deep weathering mantles that have evolved into quartz-rich soils. However, above the clay-rich substrate, such as mudstone or siltstone, oxisols and iron duricrusts have evolved. The loose and highly pervious soils explain low drainage density and the conservation of large tablelike interfluves along the dip-slope. Nonetheless, in the areas of intersecting structural lineaments, mostly the NNE–SSW trending with those of NE–SW direction, large topographical hollows have evolved in which soils and sediments have been eroded and the underlying Paleozoic strata exhumed. These processes have collaborated with the opening of entrenched elongated depressions below the top of the dip-slope. Those valleylike landforms display flat shallow bottoms preserved by the underlying impermeable layers. Along the neighbouring slopes, the contact of geological materials of contrasting perviousness facilitates the origin of the exudation line and the appearance of several springs that could have evolved into first-order tributaries by headward erosion. Drainage hierarchy and density depend on the exposure of the

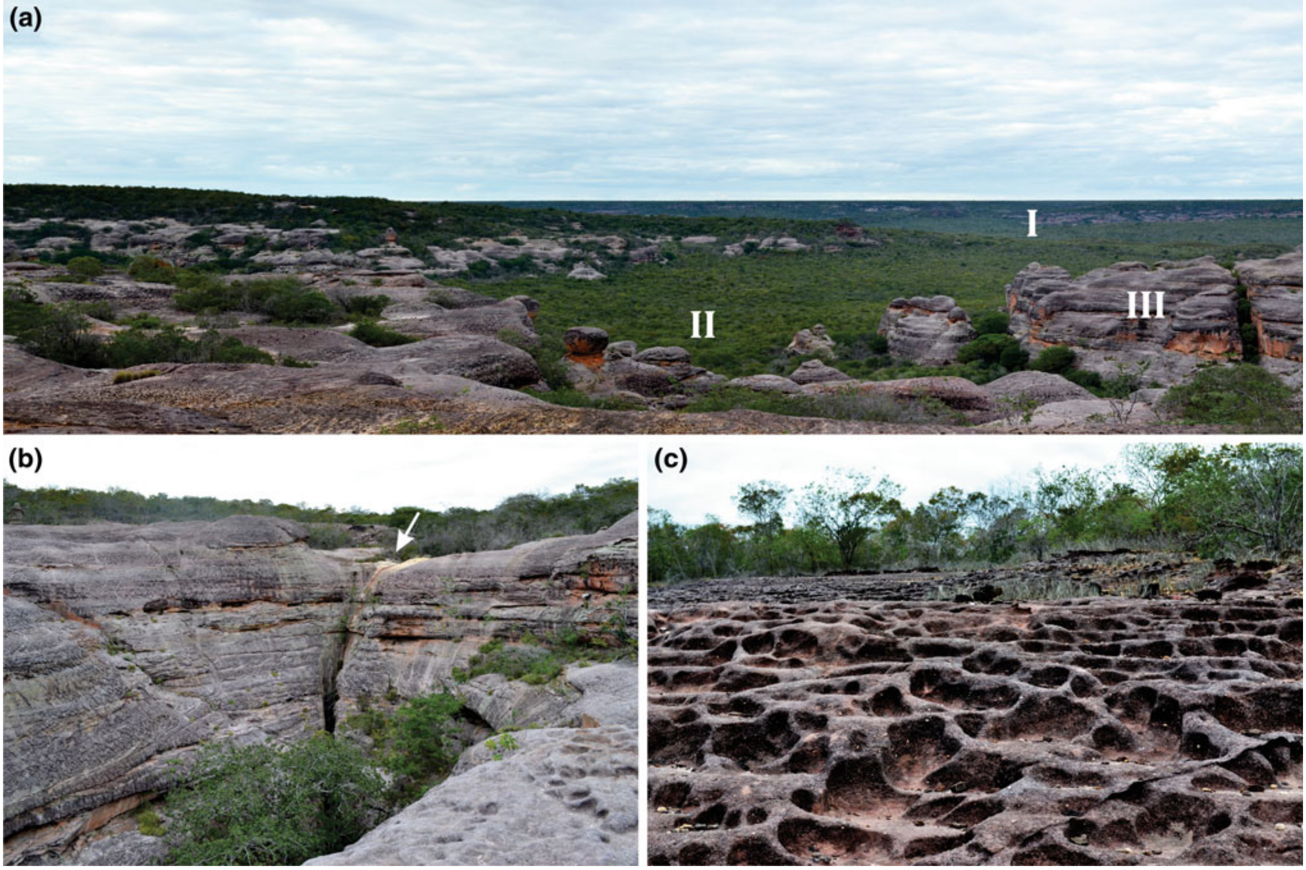

Fig. 23.6 **a** Consequent drainage of Serra Branca, western sector of SCNP. *I* Serra Branca canyon, *II* elevated catchment and *III* fractured blocks. **b** Consequent catchment controlled by fractures. **c** Honeycomb weathering on the rocky summits of Serra Branca Valley. *Photographs* Luiz F.G.L. Katz

underlying exhumed layers, as well as on the uplift of faulted blocks in the vicinity of the cuesta escarpment, accentuating the inclination of the homocline structure that dips towards the basin interior. The striking tectonic control on the summit of the plateau, at the transition area from the face of the escarpment to the dip-slope ramp, generates a landscape of *horsts* and *grabens*, mainly on the south-east border of the SCNP.

The consequent drainage basins on the dip-slope can be split into two distinct groups. Both are strongly controlled by fault-line systems that propagate all the way from the underlying metamorphic basement to the top of the thick sedimentary cover that overlies it. However, lithological differences and base-level control act differently upon the two units, thus leading to the elaboration of distinctive drainage patterns and corresponding dissected landscapes. Along the Serra Branca Valley, drainage is entrenched on subvertical cliffs, forming a straight and elongated canyon that cuts through the sandstones and conglomerates of Cabeças Formation of Devonian age. Unable to actively dissect the side slopes of the canyon, lower-order channels merely concentrate the overland flow into the network of fractures that cuts the valley transversally. In the north-east sector of the Park, the presence of pelitic rocks of Pimenteiras Formation (Devonian) and the occurrence of a large subsided fault block placed between the plateau summit and the regional base level to the east—the floodplain of the Piaui River—have resulted in the origin of a much more dissected landscape and therefore exhibiting a lower degree of fluvial entrenching due to the general lowering of the interfluves. From this difference in structural behaviour and lithological controls, two sets of landscapes arise, displaying varying degrees of scenic interest. In this context, the Serra Branca Valley distinguishes itself as more striking landscape feature as a consequence of deeper entrenchment and steepness of the slopes. The occurrence of gorges and water gaps along the valley contributes to the damming of sandy sediments that are washed away from the slopes, thus generating a flat-bottomed valley, veneered by a continuous sheet of whitish quartz sands.

The regional contact between the uplifted sedimentary basin to the west and the denuded Proterozoic fold belt to the

Fig. 23.7 **a** Obsequent drainage forming a gorge. Pedra Furada water gap, south sector of the SCNP. *I* fractured blocks, *II* valley bottom infilled by alluvium–colluvium fans and *III* strata tilted towards the depocenter of the Parnaíba Basin. **b** Obsequent drainage adapted to a fracture network. Capivara cliff, south sector of SCNP. **c** Residual butte parallel to the cuesta escarpment. Serra Grande Group. Jurubeba Hill, south sector of the SCNP. *Photographs* Luiz F.G.L. Katz

east, under the influence of harsh semi-arid climate, has resulted in two distinct scenarios of Neocenozoic unconsolidated sediment yield. Along the cuesta escarpment, the collapse of rocks of the Serra Grande Group led to accumulation of significant coarse-grained hill slope deposits, talus aprons and colluvial fans. The geographical distribution of steeper slopes and their basal knickpoints provides adequate accumulation space for Quaternary sedimentation derived from the overall erosion of the escarpment. To the east of the basin, lower rates of chemical weathering create a landscape mosaic dominated by pediments, displaying varying degrees of dissection, either mantled by thin residual soils or gravelly desert pavements.

The pedimented surfaces situated to the south-east of the escarpment are dotted with structural landforms, shaped in different rock types and subjected to the deformational regime that induced the rise of the basin edge. These landforms constitute ridgelike inselbergs, related to the outcrops of steeply dipping metamorphic limestone layers of the Riacho do Pontal fold belt. Over these ridges, some karstic features have developed, such as karren and caves. These testify to the occurrence of moister paleoclimates in the region, thus permitting the development of noteworthy limestone solution features.

Dome-shaped isolated inselbergs occur in Neoproterozoic granitic intrusions related to the Brasiliano Orogeny that cut discordantly the fold belts to the south-east of the SCNP. In the outcropping area of the Sobradinho–Remanso Complex (São Francisco craton), lithology is dominated by intrusive rocks that were affected by regional metamorphism during the Transamazonica Orogeny (Paleoproterozoic). These bedrock types do not result in particularly remarkable landforms, albeit elongated hills display a concordant alignment with the axial planes of the Archean folds.

The hierarchic distribution of erosive landforms related to the cuesta retreat has exerted an important control upon the choices and deliberations of early human groups that occupied the landscape of the SCNP. Thus, geomorphology studies complement those aimed at the reconstruction of the archaeological landscape of the area since the beginning of its prehistoric settlement. The antiquity of the peopling of the SCNP escarpment provides evidence that it occurred in synchronicity with the most dramatic paleoclimatic changes of the Late Pleistocene and Holocene that commanded the evolution of hill slope and fluvial accumulation landforms. Climate shifts during the Late Pleistocene and Holocene triggered the origin of landscapes ecologically quite distinct from the contemporary ones. The climatic cycles, with alternating moister and drier spells, some quite unlike the contemporary phase, have certainly influenced not only the operation rate of erosional and depositional processes, but certainly the availability of natural resources and the possibilities of landscape use for the first human dwellers of the area (Fig. 23.8).

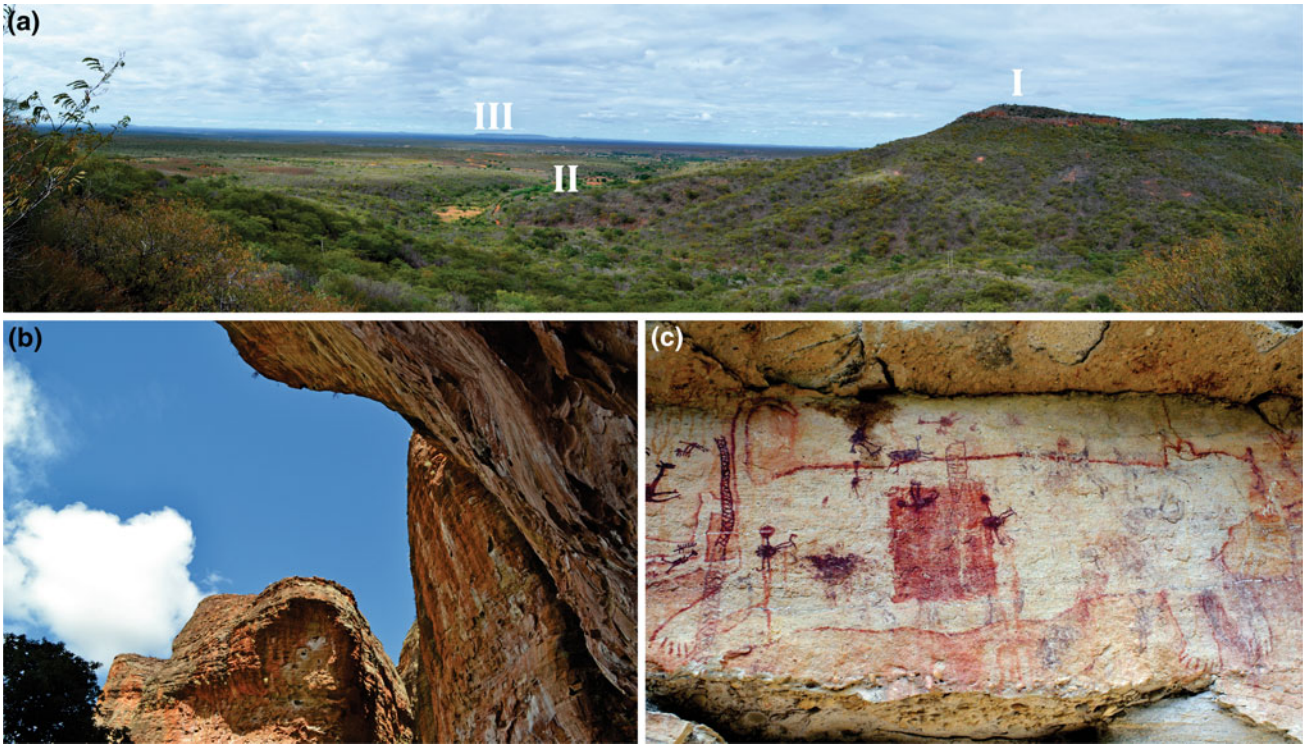

Fig. 23.8 **a** Panoramic view of the longitudinal depression to the south-east of the SCNP. *I* Escarpment, *II* longitudinal depression and *III* ridgelike inselberg. **b** Rock shelter Pedra Furada water gap rock shelter, southern sector of the SCNP. **c** Rock painting at Estevão III rock shelter, north-east sector of the SCNP. *Photographs* Luiz F.G.L. Katz

23.4 Epilogue

Landforms of the SCNP constitute three remarkable landscape units: the cuesta escarpment, the dip-slope and the longitudinal depression. Each of these units has a particular scenic beauty created by the overlapping of the exuberant ruinform morphologies and ecological singularities of the transition zone between two of Brazil's largest biomes, the caatinga to the east and the cerrado to the west.

The exuberance of geomorphic features of the SCNP can be appreciated at several scales of observation that range from the larger regional units, shaped at the convergence of three continental geological provinces, to the subtleties of erosional features and microforms that emerge over different rock types. The magnificence of this assembly of landforms of continental Brazil, coupled with one of the world's largest occurrence of archaeological sites, justifies the preservation of the SCNP as one of the globally most spectacular natural and cultural heritages.

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24 Tepequém Mountains: A Relict Landscape in the Northern Amazon

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and Marcondes Lima da Costa

Abstract

The Tepequém Mountains, located in the northern portion of the state of Roraima, represent a relict contoured steep scarps developed in Paleoproterozoic sandstones, surrounded by hills and flat surfaces to smoothly wavy. The morphology of the relief is the result of interactions of paleoclimatic and structural–tectonic processes. This chapter discusses the processes responsible for structuring various forms of relief at the top of the mountain range. In addition, these landscape features reveal anthropogenic activities related to diamond mining and have recently attracted the interest of tourists.

Keywords

Sandstone • Intermontane plains • Residual relief • Amazon landscape

24.1 Introduction

The Roraima State is the northernmost federal unit of Brazil. Its northern portion presents a diversity of geomorphological features, which contribute to a distinct and almost unique landscape in the Brazilian Amazon. The landscape is marked by dissected plateaus (known as *tepuis*) and bordered by intermontane pediplains as well as residual elevations rising above extensive plains vegetated by grassy steppe savannas. This landscape reflects the complexity of structural–tectonic and paleoclimatic history, which have led to the formation of the contemporary Roraima lands and contributed to the development of different soils.

Within this landscape lie the Tepequém Mountains, which are grand geomorphological features. They stand out in the regional landscape (Fig. 24.1), with their characteristic morphology of steep scarps and beautiful waterfalls. The landforms found at the top represented by intermontane plains and valleys dissecting residual elevations follow the direction of faults and fractures, preferentially NE–SW and E–W, consistent with the large regional structural lineaments.

The natural resources present in the landscape of the Tepequém Mountains have encouraged its occupation since the mid-1930s, initially for the gold and diamond mining that attracted many people from the farthest regions of Brazil. With the ban on mining in the early 1990s, the region has undergone a sudden abandonment. Families who remained in the community are today living on incipient economic activities such as fish farming, tourism, and soapstone crafts.

24.2 Geological Context

The territory of the state of Roraima is a part of the northernmost portion of the Amazonian Craton, reported by Amaral (1984) as the Guyana Shield. Lithologically, this craton consists of Archean–Neoproterozoic rocks (Cordani et al. 2010), comprising one of the most extensive ancient cratonic regions of the world. The Brazilian part of the Guyana Shield corresponds to the geochronological

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World Geomorphological Landscapes, DOI 10.1007/978-94-017-8023-0_24,

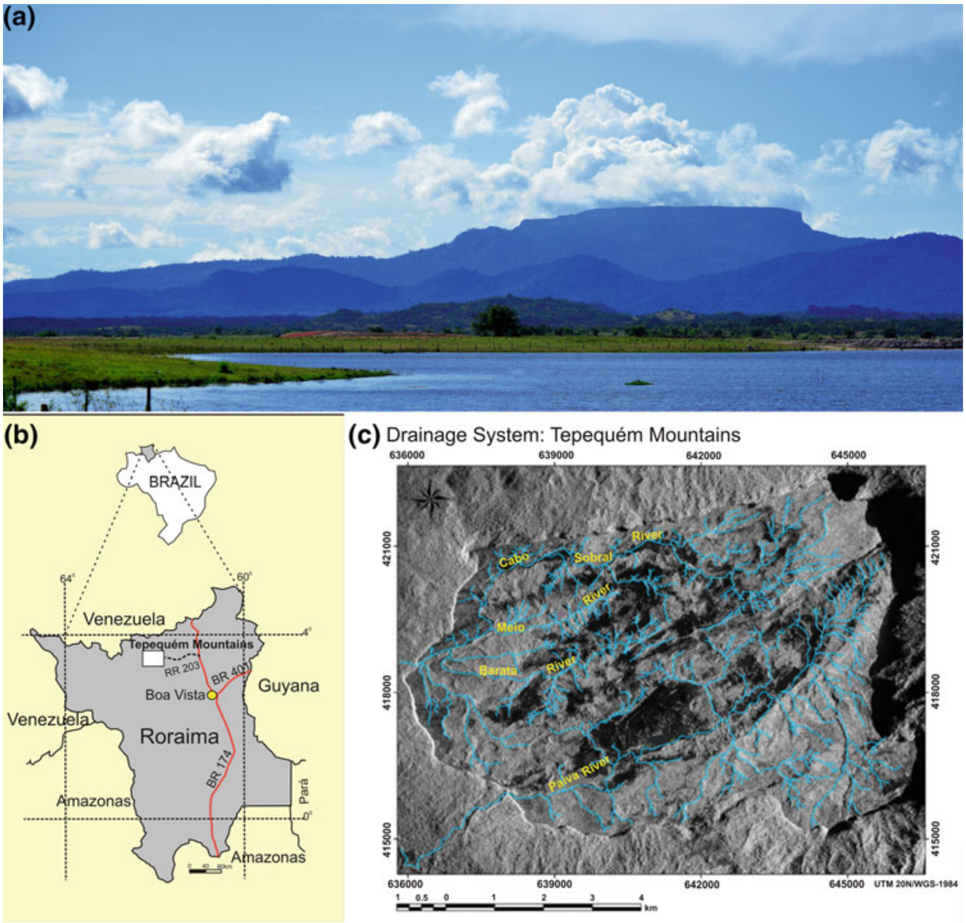

Fig. 24.1 **a** Landscape of the Tepequém Mountains, showing their grandiosity among the mountains, hills, and plains. **b** Geographic location of the Tepequém Mountains in the far north of Roraima, in the northern portion of the Brazilian Amazon. **c** Synthetic aperture radar (SAR) image by the airborne L band, highlighting the drainage system. (*Photograph* Jorge Macêdo)

provinces of Central Amazonia (>2.5 Ga), Maron-IItacaiunas (2.2–1.95 Ga), and Venturari–Tapajós (1.95–1.8 Ga) (Macambira et al. 2009).

Reis et al. (2003) subdivided the state of Roraima into different lithostructural areas: Urariqüera, Central Guyana, Parima, and Anauá-Jatapu. According to these authors, the Urariqüera area occupies the northeast quadrant of Roraima, with the major arrangement of lineaments structured from E–W to WNW–ESE and to NW–SE, where predominating granites and volcanites are present in elongated bodies together with an extensive sedimentary cover.

The Tepequém Mountains are built of this sedimentary cover. They display a rhomboidal geometry, with an area of approximately 70 km^2. The top surface has altimetric variation between 560 and 1,100 m a.s.l., and the mountains are bordered by steep scarps. In addition, the substrate of the Tepequém Mountains consists of volcanic rock series that occur in bands extending from WSW–ENE to WNW–ESE. These include dacites, rhyolites, and esites and ignimbrites (Fig. 24.2).

Overlapping this volcanic basement, the Tepequém Mountains are carved in a sequence of siliciclastic Paleoproterozoic rocks that, according to Fernandes Filho et al. (2012), constitute two decreasing upward megacycles of fluvial and coastal clastic deposits. These deposits are represented by sandstones, conglomerates, mudstones, and rhythmites (sandstone/pelite). At a more detailed scale, a nearly rhombic perimeter of the Tepequém Mountains is apparent. It has strongly pointed edges and concave, abrupt cliffs, with a rough surface on top. These features are not compatible with the tabular relief.

The geometric arrangement of the mountains, in general, involves a synclinal fold of kilometric magnitude, with an axis toward the ENE–WSW, showing a light trim on WSW. The inner flank of the fold is defined by a set of synform and antiform folds of faint expression, with axes directed NE–SW. In the western and southwestern portions, lineaments are observed, configuring folds with the vertical axis outlining an asymmetric "M" on the map. In the inner mountains, sigmoidal structures indicate conditioning with dextral kinematic motion (Fig. 24.3).

According to Tavares Jr. (2004), in the Paleoproterozoic, the transtensive tectonic regime trending NE–SW, with its dextral component, affected the preexisting structures and resulted in the development of compressional and extensional fields. The latter, defined as transtensive efforts,

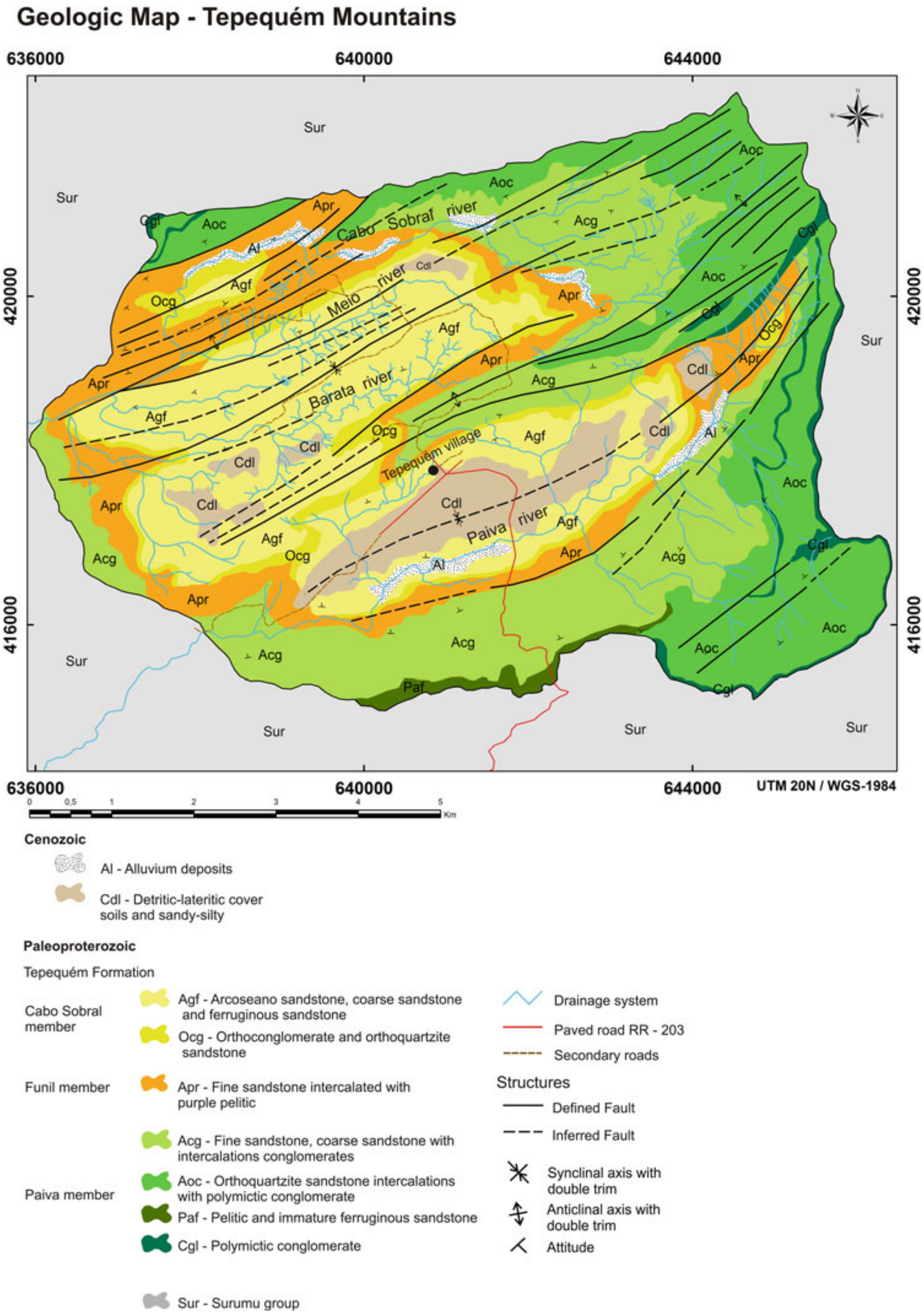

Fig. 24.2 Geologic map of the Tepequém Mountains, highlighting the directions of dips of bedding planes and showing the synform shape. Adapted from Fernandes Filho (2010)

yielded structures such as releasing bends that led to the inception of the Tepequém sedimentary basin. According to Fraga et al. (1994), the inversion process in the basin may have been related to basement reactivation during the deformational episode of K'Mudku (~1.2 Ga). The interpreted structural features characterize K'Mudku a transpressive structural regime with NE–SW dextral kinematics, configuring the rhombohedral geometry of the Tepequém sedimentary basin.

The period of extensional tectonics in the Guyana Shield, associated with defragmentation of Pangaea, is represented in the Tepequém sedimentary basin through normal fault systems oriented in the direction of N60°–90°E. The roughness of the relief at the top of the hills, reflecting successive anticlines and synclines, is related to this system of normal faults, which causes anticlockwise and clockwise rotations in the bedding to form chevron folds. Lineaments in the direction of N10°W–10°E, suggesting dextral

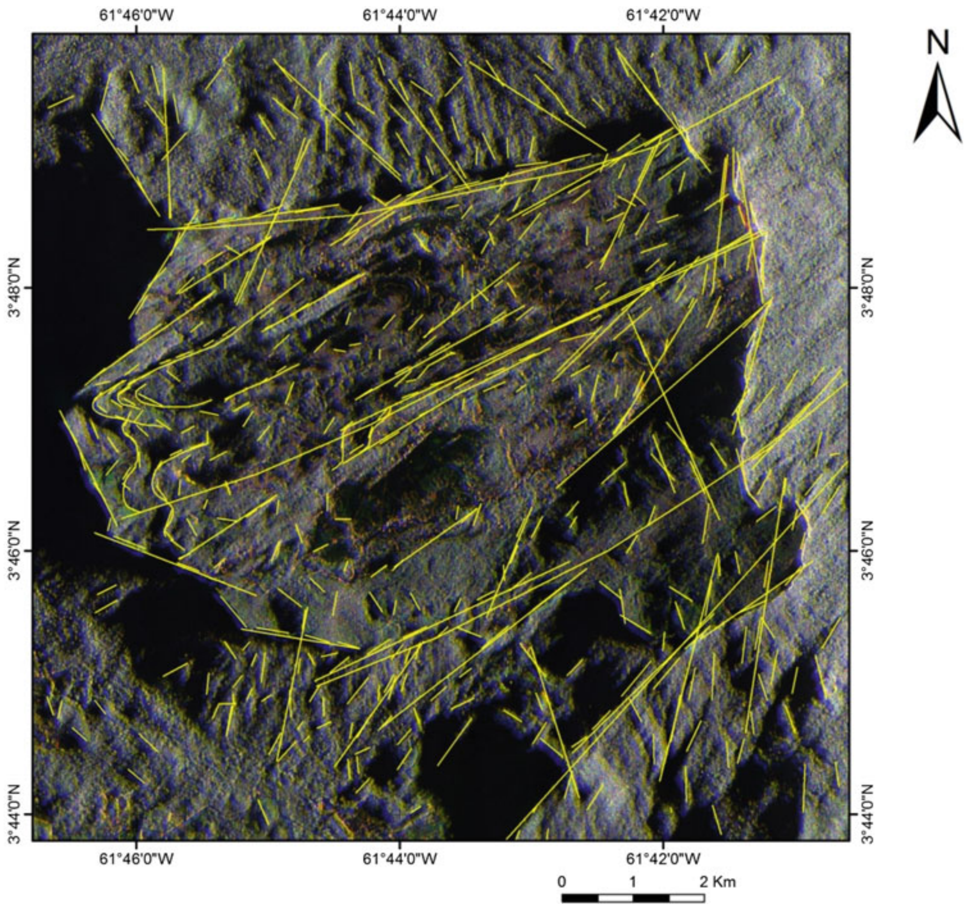

Fig. 24.3 Radar image in L band, SAR/SIPAM (Amazon protection system), highlighting the structural lineaments of the main orientation (NE–SW)

strike-slip movements, interrupt the system failures in the N60°–90°E orientation. This arrangement implies a possible correlation with neotectonic activities.

24.3 Geomorphological Compartmentalization

The Tepequém Mountains, which have a surface area of approximately 70 km^2, present a clear morphological contrast with the surrounding terrain (Fig. 24.4). Their geomorphic structure consists of a rough mountain top surface, with altitudes ranging between 575 and 1,100 m a.s.l., truncated by abrupt erosional scarps with declivity greater than 30°. These are limited in the footslope zone by extensive pediments with ravines. Therefore, this patterned excels at regional landscape consisting of hills lined with altitudes of up to 900 m a.s.l. The area is surrounded by an extensive smoothly flattened surface with altitudes not exceeding 250 m.

These morphological traits of the regional landscape show notable differences in altitude and slope, and they contribute to establish a distinct landscape in the northern Brazilian Amazon. The configuration of natural elements of the landscape of the Tepequém Mountains and the surrounding region define subjection to lithology and structural setting as evidenced by the topography and the organization of the drainage systems.

24.4 The Shape of the Tepequém Mountains

The Tepequém Mountains have the morphology of a summit surface with differences in altitude of up to 500 m at the top, differing from the geomorphological features of tabular surfaces that are known as *tepuis* (a Taurepang Indian word that indicates flattop mountains), such as Mount Roraima (Briceño and Schubert 1990). While analyzing the landscape of the Tepequém Mountains, Beserra Neta (2008) and Nascimento (2013) recognized patterned dissection, which is identified by dip-slip fault scarps, steep slopes, and valleys dissecting residual elevations. Accumulation has occured in intermontane plains (Figs. 24.5 and 24.6).

The morphological boundaries of the Tepequém Mountains are emphasized by escarpments. They are steeper than 30° and represent the dip-slip scarps of normal faults. The outline of the cliffs follows E–W (in the north), NE–SW (in the north, east and south), and NW–SE alignments (in the

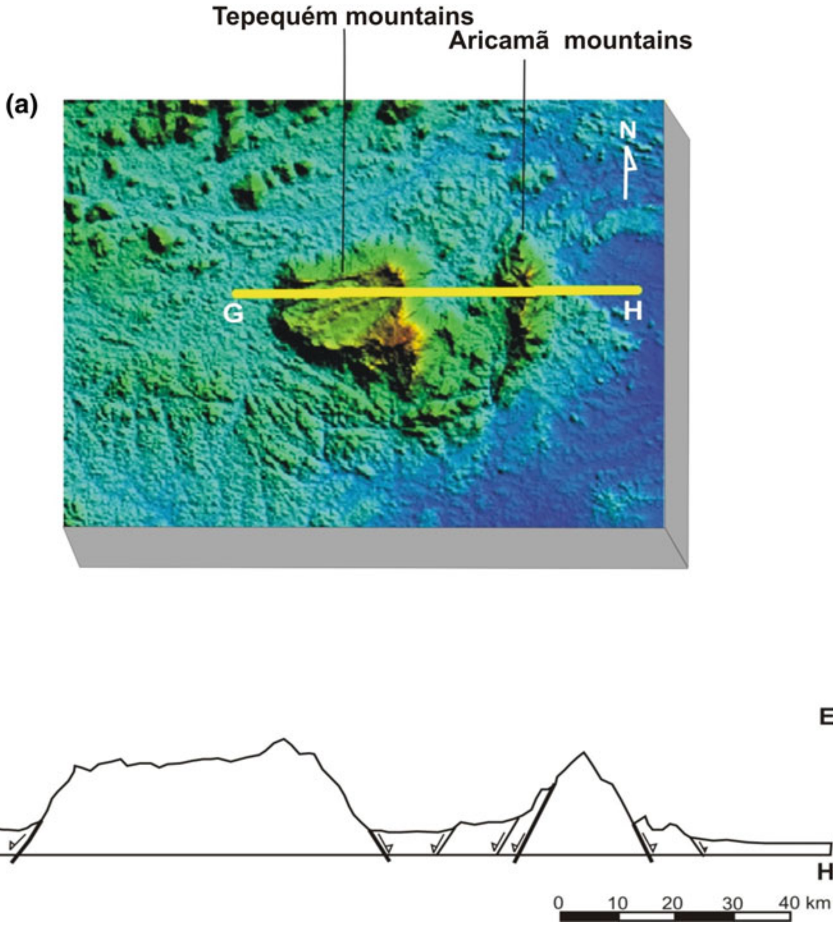

Fig. 24.4 **a** Digital elevation model (SRTM) of the Tepequém Mountains and the surrounding region. **b** E–W profile showing how the geometry of the blocks is related to the reactivated normal faults and dextral strike-slip shearing zones oriented in the NE–SW direction. Note that between Tepequém and the Aricamã Mountains, there are low areas with altitudes not exceeding 250 m a.s.l

Fig. 24.5 In the forefront, the erosional escarpment (in the south-southeast edge) is covered with dense forest. In the background (*right*), the southwest slope directed toward the Paiva River Valley and the flattened surface (the intermontane plain of Tepequém) can be identified. (*Photograph* Jorge Macedo)

west and southwest). These orientations correspond to the Precambrian regional structure related to the preferred areas of normal and strike-slip faults. At the top, the scarps exhibit sandstone walls and steep slopes, but in the lower slope cut across the basement, pedogenic colluviums are covered by dense rain forest.

According to Almeida (2012), the differences in the topography of the scarps surrounding the mountains result from both normal and strike-slip faults, which favor the formation of beautiful waterfalls, such as those of the Paiva (Fig. 24.7) and Cabo Sobral rivers. Steep slopes, formed predominantly in sandstones, have a linear concave shape

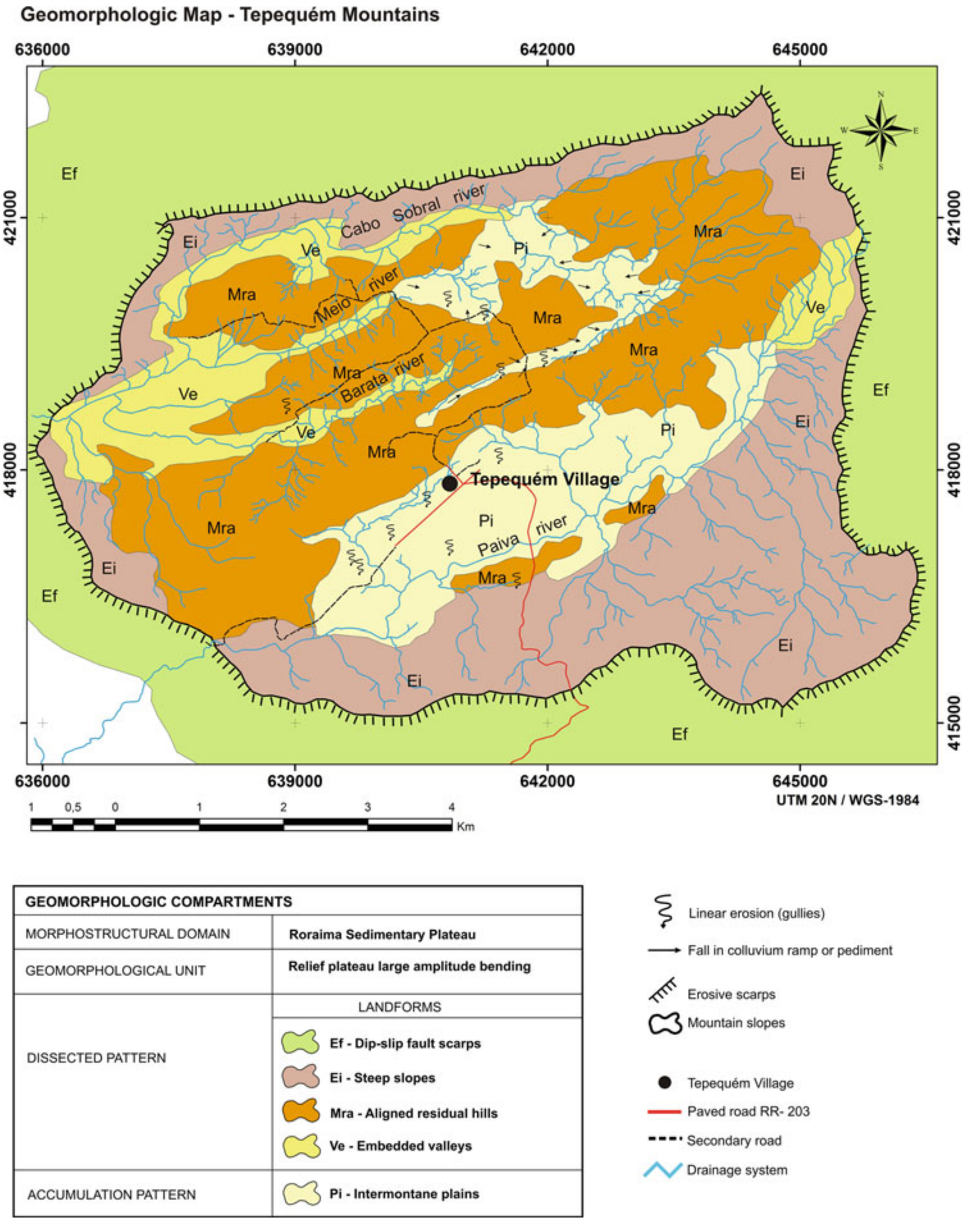

Fig. 24.6 Geomorphologic map with compartments identified in the Tepequém Mountains. *Source* Nascimento (2013)

ranging between 20° and 25° at the top (Fig. 24.8), with uplifted edges that rise between 750 and 1,100 m a.s.l. This uplift is due to the tilting of blocks generated by normal faulting.

The residual hills, with elevations reaching 744 m, are structurally aligned in NE–SW direction. They have convex–rectilinear elongated ridges with trapezoidal faces with concave–convex dissected slopes that sometimes host accumulation of colluvium at the foot. They are connected to open flat-bottomed valleys. These hills have developed in coarse and ferruginous sandstones with interbedded conglomerates, exposed in the form of large blocks, which top a surface covered by vegetation of the open savannah shrub type.

The flattened surfaces lie along the valleys of the Cabo Sobral and Paiva rivers, between the aligned hills. They are slightly inclined to the WSW, with a tilt angle ranging from 3° to 5°, at an altitude of 575–670 m a.s.l. These plains have been developed on sandy well-drained sediments, locally classified as Podzols. They are structurally bounded by faults and fractures with ENE–WSW orientation.

The plains are covered with vegetation of the grass–shrub savannah type. Therefore, they have a low density of ground cover, favoring rain erosion. On these surfaces, linear erosion traits in the form of ravines are carved in the remobilized material. Linear erosion was intensified due to diamond mining, which has take place since 1937 and operates in the colluvium and especially in the alluvium of the major rivers

Fig. 24.7 The Paiva waterfall located in the southwestern scarp of the Tepequém Mountains-RR, highlighting levels corresponding to the fault planes. (*Photograph* Jorge Macêdo)

Fig. 24.8 **a** Steep slope located to the southeast of the Tepequém Mountains, highlighting the uplift of the edges that rise up to 1,100 m. The uplifted edges are a result of the tilting of blocks in the fault plan. (*Photograph* Jorge Macêdo)

draining the Tepequém Mountains. The natural beauty of these geomorphological features has piqued the interest of tourism, establishing a new economic alternative to region.

24.5 Final Considerations

The landforms present on top of the mountain of Tepequém show evidence of tectonic events and paleoclimatic effects from the Paleoproterozoic to the present. The distinct landforms making up the top of the mountain of Tepequém, steep slopes, structurally aligned hills, embedded valleys, and intermontane plains, implying an unsupported modeled with tabular morphology, which has been found in the *tepuis* located in the Venezuelan savannah, i.e., at Mount Roraima.

This diverse landscape has been subject to uncontrolled exploitation of its natural resources since the 1930s, mainly gold and diamond mining. More recently, the cultural and economic potential of ecotourism related to the lush geological and geomorphological features has been explored.

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Carajás National Forest: Iron Ore Plateaus and Caves in Southeastern Amazon

25

Luis B. Piló, Augusto S. Auler, and Frederico Martins

Abstract

The Carajás National Forest in the Amazon is an outstanding area of conservation. The occurrence of mafic and felsic volcanic (Neoarchean) rocks is associated with banded iron formation (BIF) lenses, including jaspilites. Particularly on the BIF, there is the occurrence of ferruginous breccia which supports the tops of several mountain plateaus, generally referred to as the Carajás Ridge. Hills, drainage channels, and a number of closed depressions are commonly found on the surface, in addition to savannah surrounded by a luxuriant tropical forest. Subsurface rainwater drainage (throughflow) occurs via a network of small conduits on the tops of the mountain ranges, in addition to rainwater draining superficially in channels that are directed to closed depressions or to drainage headwaters. Several rocky scarps exist on the edges of the mountain ranges, in addition to talus deposits. Over 1,000 caves have been recorded in the area, and shallow, short-length (about 30 m) caves are predominant in this region. Longer caves, which may reach over 300 m, are normally present as single semicircular, funnelled, or straight chambers and are comprised of very irregular interconnecting passages in various sizes. Within the caves, clastic deposits are predominantly autogenic and originate from collapsed parts of the ceilings and walls. Chemical deposits are generally made up of small-sized features with a diverse mineralogy. Crusts and coralloids predominate in addition to draperies and micro-rimstone dams, and irregular pendulous forms known as *pingentes* hang from the ceilings, and are similar to stalactites. Speleothems are composed mostly of iron oxide–hydroxide and phosphates. The Carajás National Forest is a protected federal area that is used for different purposes, including the operation of the world's largest iron ore mines. The savannah environment which is embedded amidst the tropical forest must be protected as conservation areas to represent the most expressive remnants of the original context. In addition, environmental compensation areas contiguous to the National Forest are being purchased, and these will become part of the Carajás protected area.

Keywords

Amazon region • Serra dos Carajás • Caves • Archaeology

25.1 Introduction

The Carajás National Forest covers an area of 411,949 ha and is located in the southeastern Brazilian Amazon (Fig. 25.1), approximately 540 km south of Belém, the capital city of the state of Pará. The region experiences two types of climates: The continental equatorial climate corresponds to an extensive region of hilly lowland areas [below

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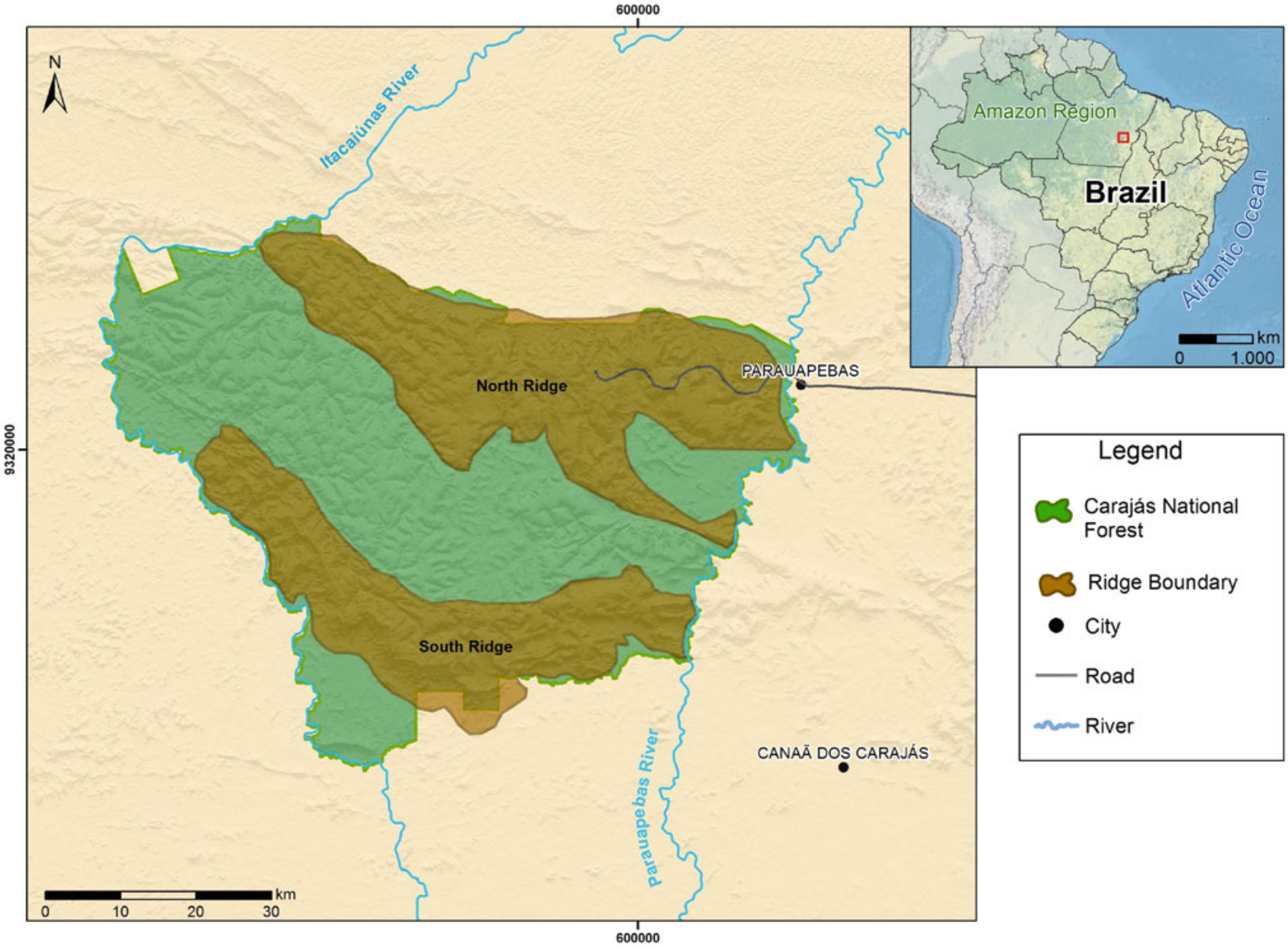

Fig. 25.1 Location of Carajás national forest in southeastern Amazonia

350 m above sea level (a.s.l.)] and is characterized by an average temperature of 25 °C and annual rainfall between 1,900 and 2,000 mm; and at higher altitudes of the Carajás Ridge (above 700 m a.s.l.), the climate is mesothermal equatorial, with an average temperature of 23 °C, and annual rainfall reaching 2,400 mm (ICMBIO 2003). The region also shows two contrasting seasons: a dry five-month period, from June to October, and a very rainy period, from December to April.

Geologically, the so-called Carajás Formation, located in the Neoarchean metavolcanosedimentary sequence within the Grão Pará Group is noteworthy. It is composed of banded iron formations (BIF) represented by jaspilites, with mafic rocks situated above and beneath it (the latter belonging to the Parauapebas Formation). Andesites, basalts, volcaniclastic materials, and gabbro are also present. The jaspilites show an intercalation of light and dark bands of iron oxide and silica (jasper and chert) of millimetric to centimetric thickness. High-content iron ore bodies (>64 % Fe) are encased in the jaspilite layers and were generated by enrichment of the jaspilites through chemical processes involving hydrothermal fluids (Lobato et al. 2005). The Xingu Complex is located below the metavolcanosedimentary sequence and is composed of granite and gneiss rocks.

Structurally, the Carajás Ridge is represented by an S-shaped synform–antiform pair known as the Carajás Fold (Lobato et al. 2005), which is broken by the Carajás transcurrent system (Pinheiro 1997) dividing the region into the north and south ridges. This transcurrent system is composed of a group of interrupted lineations situated in a general E–W direction. The Carajás Fault represents the main structure in this system, and this influences the course of rivers, scarps, and cave passages.

Over the iron formation, there are wide covers of iron breccia of two main origins that are generically known as *canga* and which act as caprock on some plateau tops regionally represented by the Carajás Ridge, and which Maurity and Kotschoubey (2005) named hematite breccias. The first origin is as a product of the fragmentation and gravitational collapse of the top of the iron formation due to geochemical leaching of the silica and later cementation of the clasts (gravel and pebbles) of the BIF. In this case, transport of the clasts is rather reduced. This type of *canga* may contain over 85 % Fe_2O_3, in addition to SiO_2, Al_2O_3, and P_2O_5 (Piló and Auler 2011). The second origin is related to typical colluvial covers in which the percentage of the iron matrix is increased, and the transport of the clasts on slopes occurred over a longer period of time. In these iron breccias, which are normally situated on medium and low slopes, there is an increase in the percentage of silica, phosphorus, and aluminum, and a depletion of iron. The savannah has evolved on these iron crusts and particularly on the top of the ranges, and is surrounded by Ombrophilous Forest (Fig. 25.2). This forest represents the largest preserved area of tropical forest in the southeast Amazon. The xerophytic savannah vegetation represents a singular ecosystem in the Amazon and has renowned endemism (Campos and Castilho 2012).

Currently, the region of the Carajás Ridge is one of the most important Brazilian speleological regions, and it shows the considerable (and previously unknown) potential of the iron formation and the *canga* covers in generating caves. The area has therefore recently received considerable research attention and has allowed for new discoveries in Brazilian speleology (Piló and Auler 2009).

25.2 Surface Forms

The Carajás National Forest includes two geomorphologic units on a regional scale: A dissected plateau and the peripheral depression both located to the south of Pará (Boaventura 1974). Valentim and Olivito (2011) named these compartments the residual plateaus of the southern Amazon and the interplateau depression of the southern Amazon, respectively.

According to Boaventura (1974), the dissected plateau is represented by the Carajás Ridge, which is formed by a complex of folded and faulted Precambrian rocks. Its northern and southern sectors, represented by the north and south ridges, are locally suspended synclines. These features are generally truncated by deep valleys, with extensive, well-preserved fault scarps.

Fig. 25.2 Tropical forest inside the Carajás National Forest: In the background, the plateau is cut into several ridges by fluvial downcutting (photograph by João Marcos Rosa)

On the north and south ridges inserted within the Carajás National Forest, one may initially point out the top compartment of the ridges, supported by the BIF and *canga* covers (Fig. 25.3). This undulating surface (located above 700 m a.s.l., and which may reach up to 800 m) is comprised of hills, closed depressions, valleys, and gullies, and such features are particularly well-developed on the iron-rich rocky substrates (either on the BIF or on *canga*). Minor hills may show elongated interfluves, or may have convex crests, and such features are often surrounded by closed depressions, which are the main morphological features along the crests of the south and north ridges. These depressions measure tens to hundreds of meters long and are generally circular or elongated. On the south ridge, a coalescence of depressions has been recorded, most of which contain temporary or perennial lakes that generate suspended aquifers, and whose bottom areas are covered by mafic rocks or clay sediments. In addition, small-scale collapse depressions are created due to the collapse of the roofs of small cavities in the *canga* cover.

Maurity and Kotschoubey (2005) named these depressions sinkholes (pseudokarst) due to the degradation of the *canga* (geochemical leaching), which generated an increase in porosity and hence low density areas. The origin of these features is associated with the collapse of the geochemically unstable breccia cover, which initially led to the creation of smaller depressions and eventually evolved into wider sinkholes. Campos and Castilho (2012) named these features doliniform depressions.

The main hydrological process acting on the ridge tops is infiltration, which is typical in an area of deep fractured aquifer recharge. Due to the lack of soils on the ridge tops, a part of the subsurface rainwater drainage (throughflow) is enabled via a network of small conduits. It is also necessary to highlight the wide network of surface channels draining toward the closed depressions, or feeding the fluvial headwaters at the margins of the ridge tops (Fig. 25.4). However, these channels are only active on a seasonal basis, and the production of sediments in this sector of the landscape is reduced.

Fig. 25.3 Top of the southeastern border of the south ridge. Note the hills and closed depressions occupied by lakes (photograph by João Marcos Rosa)

Fig. 25.4 Drainage channels on the top of the south ridge embedded in the iron breccia. Due to climate seasonality, these channels are active only during the rainy period from December to April (photograph by João Marcos Rosa)

In addition to the top surface, it is important to discuss the ridge borders. The *canga* is fragmented in this sector, and therefore, the soil conditions are improved because without the hard substrate the forest vegetation can fix itself on the soil, allowing for the advance of tropical forest over the savannah. A set of semicircular valley heads (amphitheaters) is also evident in sectors, where rocky scarps with strong structural control (NW–SE) occur, which can reach over 30 m in height (Fig. 25.5). Talus deposits involving boulders and pebbles from the *canga* and the BIF occur at the base of these scarps, which indicates mass movements related to rockfalls, and temporary water springs are also frequently found at the bottom, giving rise to channelized runoff. This is an extremely dynamic sector in the Carajás landscape and is the main zone of production and transport of sediments. Salgado et al. (2007) measured the production of the cosmogenic isotope ^{10}Be and demonstrated that the *canga* and BIF are extremely resistant to denudation, as in a similar landscape in southeastern Brazil, with erosion rates of 1.71 and 2.58 m per million years (m/My). However, they are more prone to scarp retreat (backwearing), with erosion rates of between 12.71 and 14.60 m/My.

Irregular morphology occurs below the upper reaches of the ridge slopes, extending to the foothills. In this area, there is a specific occurrence of small scarps or rocky pavements comprised of *canga*, BIF, or mafic rock. A cover of reddish gravel soil (oxi-soil) supports the Ombrophilous Forest, and temporary water springs are also found in this sector.

At the foot of the ridges (at about 350 m a.s.l.), it is important to highlight the presence of colluvial fans, represented by ferruginous breccias formed by lithologically diverse clasts (including volcanic rocks, meta-arenites, and quartz). These are terminal landforms of the hillslope sequence and are dominated by depositional processes.

In between the main ridges within the Carajás National Forest, there is also an impressive group of hills and slopes with peaks reaching between 500 and 600 m in altitude. The interfluves are elongated or convex and the mid-slopes are intensely gullied. A strong structural predisposition controls landscape downcutting in these areas. Rock diversity,

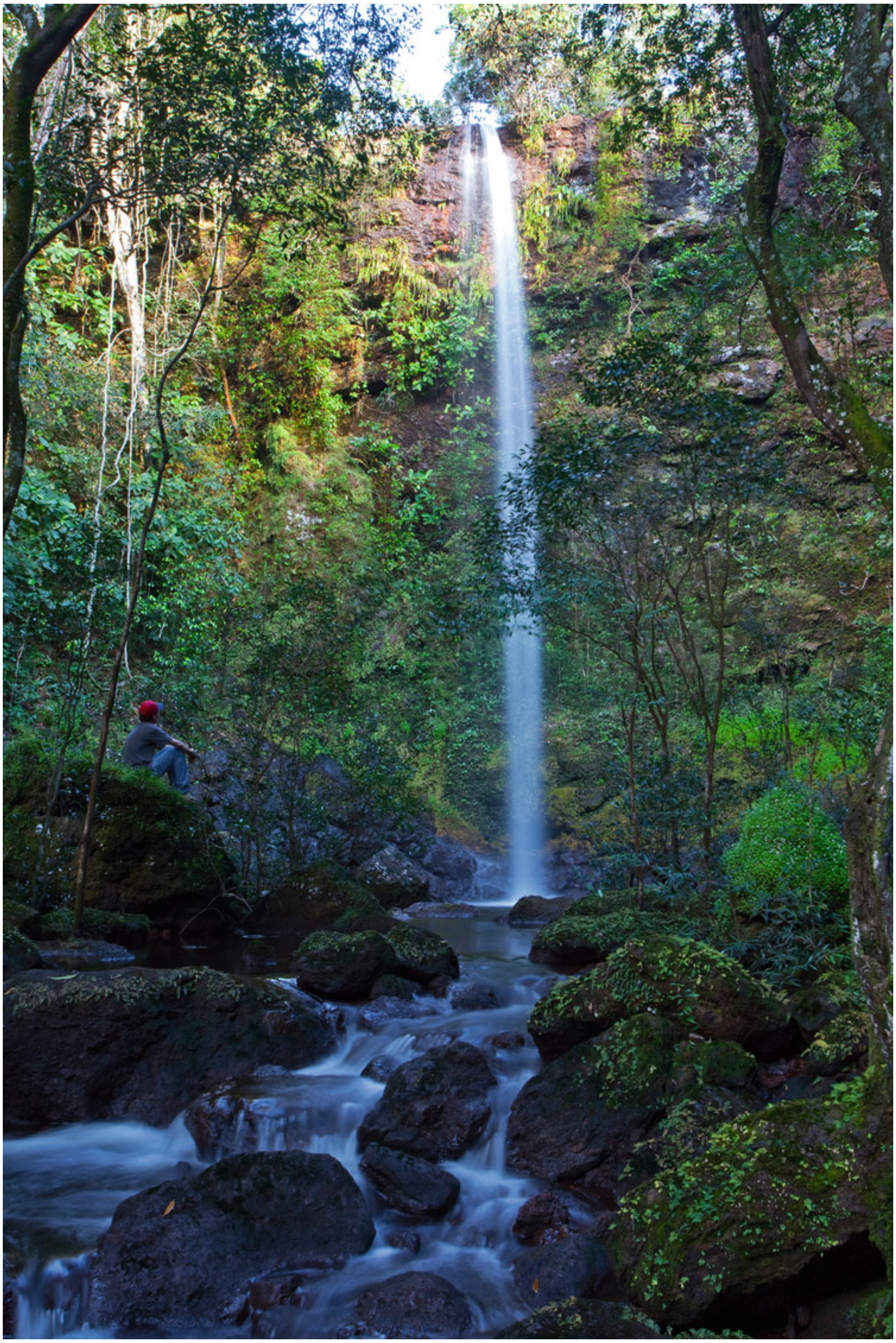

Fig. 25.5 Temporary runoff waterfall on the rocky rim of the south ridge; talus deposits are frequently found at the base of these scarps (photograph by João Marcos Rosa)

including granites, volcanic rocks, and meta-arenites, also influences morphological differences in this lower landscape.

25.3 Caves

Over 1,000 small caves have already been identified in the Carajás National Forest, which has one of the largest concentration of caves in Brazil. The caves are located at the foot of scarps situated in different landscape settings, including at the edges of ponds, on scarps at the top of the plateaus, as well as in the colluvial footslopes of ridges. The caves have developed in the inner part of the ferruginous breccias, within the BIF, and at contact points between them. Caves in meta-arenites and in altered volcanic rocks have also been identified, but only in small numbers.

In general, the caves are small and are on average 30 m long, although caves over 300 m have also been identified. One cave reached over 1.5 km in length. Many of these caves have only one small chamber, with annexes that narrow into narrow channels. Their outlines in plan are semicircular, tapered, funnelled, or straight. The longer caves feature very irregular passages of various sizes, which are interconnected with one another, and the larger chambers are often connected by narrow passages. The sections are very irregular (Fig. 25.6) with pillars, pendants, and skylights present. Structural control occurs, particularly in caves within the BIF.

Most caves are dry. Temporary water springs and drainage channels occur, resulting from dripping or percolating rainwater through small conduits or geological discontinuities. During the rainy season, dripping is significant inside the caves due to rock porosity and the proximity of these caves to the surface.

The clastic deposits found in the caves are predominantly autogenic, consisting of hematite clasts originating from the BIF, ferruginous breccias, and sometimes altered mafic rocks. Pebbles and boulders are mainly the result of gravitational

Fig. 25.6 Cave chamber in the ferruginous breccia at Serra Norte. Conduit sections are very irregular with pillars and pendants. The floor is typically flat or slightly sloped, according to the slope inclination. Photograph by Augusto Auler

Fig. 25.7 Cave chamber in the ferruginous breccia on the north ridge. Clastic deposits are predominantly autogenic, resulting from the collapse of part of the ceiling and walls. Photograph by Ataliba Coelho

processes, such as the collapse of portions of the ceiling and walls (Fig. 25.7). These deposits have a close connection with bedrock. However, the sediment transport is currently very limited inside the caves, and allogenic sediments are confined to entrance taluses and may be present under skylights.

In the ferriferous caves of Carajás, chemical sediments are generally comprised of small-sized deposits with diversified mineralogy. Crusts and coralloids predominate, in addition to draperies, micro-rimstone dams, and *pingentes*. Fracture filling crusts, wall dripping, and *pingentes* are composed of iron and aluminum oxide–hydroxides (hematite, goethite, and gibbsite), and it is important to emphasize that the solutes that form these speleothems originate from iron rock (breccia or BIF).

Coralloids and crusts situated on the floor (Fig. 25.8), walls, and over blocks are mainly comprised of iron oxide–hydroxides and phosphate (strengite, phosphosiderite, and leucophosphite), and the origins of the constituent minerals are associated with both bedrock and bat guano. Phosphate-formed stalactites, stalagmites, and certain types of coralloids are rare.

While working in the southeastern region of Brazil, Simmons (1963) was the first to attribute the genesis of iron ore caves to dissolution processes. He claimed that the dissolution of dolomite, and also quartz and hematite, leads to the formation of an altered iron ore zone with high porosity that reaches 50 % of the rock volume. In addition, Pinheiro and Maurity (1988) proposed two speleogenetic phases for Carajás. During the first phase, which occurred entirely in the groundwater zone, unstable alumino-ferrous and clay–mineral complexes of Fe, Al, and Si were formed, and these filled the empty spaces within breccias and the BIF. The removal of this unstable material then led to the formation of irregular holes that can be seen on cave walls (Pinheiro and Maurity 1988). The second phase, which also occurred in the phreatic zone, included erosive processes (piping), which basically expanded the cavities generated during the first phase. These erosive processes were then intensified when

Fig. 25.8 Crusts formed by iron oxide–hydroxides and phosphate covering the cave floor on the north ridge. Photograph by Augusto Auler

the cave was subjected to vadose processes, which resulted in the collapse of roofs and walls.

Some authors such as McFarlane and Twidale (1987) believe that for the formation of iron ore karst, the dissolution of not only silica and dolomite, but also iron oxides is essential. The creation of what McFarlane and Twidale (1987) labeled as "pale zones" in saprolite is dependent on iron leaching. Given the low soluble nature of iron oxides, these authors suggested the participation of microbiological agents. Parker et al. (2013) then investigated the involvement of microbial communities in the genesis of the Carajás caves and identified intense microbial and biofilm activity in irregular pendulous forms hanging from the ceiling (*snottites*), their genesis being attributed to iron reduction and oxidation processes. With the reduction of iron, the flow of groundwater is then able to move the mass of aqueous Fe (II), allowing for the expansion of voids and formation of caves. Piló and Auler (2009) have referred to the caves generated in the BIF as "minerogenic," in relation to their association with jaspilite mineralization.

According to Auler et al. (2014), the first stage of speleogenesis in iron ore caves bears similarities to hypogene processes, in that it develops at depths, away from surficial processes. The morphology at plan scale resembles slow-flow non-integrated hypogenic caves such as flank margin caves. Sluggish water flow environment, dominance of chemical and microbiological processes, and decoupling in relation to water flow routes are common features, although iron ore caves evolve through much longer timescales. Unlike hypogene settings, in which an active hypogene cave will eventually become detached from groundwater systems, the later evolution of iron ore caves results in a drastic transition between a sluggish phreatic deep environments toward a shallow vadose environment subject to hydrological slope processes.

Paleoburrows have also been identified in the Carajás region, denoting bio-erosional processes in the formation or expansion of caves in iron breccias. A network of circular passages is evident with claw marks on the walls and ceiling. It is considered that these cavities were used by extinct mega-mammals (particularly armadillos), which inhabited the region of Carajás during the Tertiary and Quaternary periods. The caves have also been occupied by ancient prehistorical groups, and various dates from the region already exceed 9,000 BP years. Dated Late Holocene materials are associated with ceramic and lithic materials, but older dates are associated only with traces of the lithic industry, including lithic flakes, chips, and some cores (Kipnis et al. 2005).

25.4 Conclusions

The Carajás National Forest presents a wide range of outstanding landforms and is one of the most important regions in the Brazilian Amazon. It is a unique landscape where the tops of ridges stand out and are formed by the BIF and *canga*. A large number of closed depressions, very similar to sinkholes, in addition to drainage channels, hills, and scarps are further characteristic landforms. Relevant discussions have been initiated on the genesis and active processes of these peculiar forms.

The savannah vegetation on the *canga* and BIF is nestled within the exuberant rainforest and deserves special attention since it is home to an extremely rich environment, including a large number of endemic species with specific metabolic and anatomical adaptations (Cleef and Silva 1994; Porto and Silva 1989).

The Carajás is of great speleological importance. Specific speleogenetic processes have been revealed, including biospeleogenesis. Minerals and speleothems not yet identified in any other caves in the world have been recorded, in addition to invertebrate fauna with new species (Pinto-da-Rocha and Andrade 2012) and troglobitic animals (Campos-Filho and Araujo 2011). The archaeological data from inside the caves have helped to recreate the history of human occupation in the Amazon. According to Knips et al. (2005), with obtained dates of more than 9,000 BP, Carajás is already included in discussions related to early human occupation in the Americas.

The Carajás National Forest integrates a federal preserved and protected area of 1.2 million h, which is referred to as the Carajás Mosaic (Fig. 25.1). The Mosaic also includes biological reserves, protected areas (APA, an acronym in Portuguese), and indigenous protected reserves. This region has experienced severe deforestation in recent years, which has left a legacy of unproductive pastures and anthropized areas.

The Forest allows for certain types of usage, including mining activities. Out of the 400,000 h of protected area, 3 % of the vegetation cover represents the *canga*/savannah ecosystem, coinciding with the iron ore deposits, and these are considered to be the largest in the world. The Chico Mendes Institute for Biodiversity Conservation (ICMBio), a Brazilian environmental agency, responsible for managing protected areas with support from researchers, seeks to establish a permanent preservation area for this ecosystem within the Carajás National Forest. This area should include all of the Forest's attributes, ensuring that all representative remnants of this geo- and biodiversity are fully protected (Martins et al. 2012). It is also important to emphasize that environmental compensation areas contiguous to the National Forest and intended for restoration are being purchased and will become a part of the Carajás protected area.

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Serra do Mar: The Most “Tormented” Relief in Brazil

26

Bianca Carvalho Vieira and Marcelo Fischer Gramani

Abstract

The Serra do Mar is a system of escarpments and mountains that stretch more than 1,500 km between the states of Santa Catarina and Rio de Janeiro with a general ENE orientation. It has high lithological and structural complexity along its entire length, with some stretches quite recessed from the coast and some very close to it. It caught the attention of explorers as early as the eighteenth century, and its origin and evolution have always intrigued researchers, particularly after the 1930s, when more systematic studies on the lithology and formation of the sedimentary basins that surround it were undertaken. With its wide variation in altitude, high slopes, and high rainfall volumes, as well as the fact that it includes, Brazil’s largest area of Atlantic Forest, the Serra do Mar has always been a “barrier” to be overcome, as it is situated between the country’s major urban centers and its main ports.

Keywords

Serra do Mar • Atlantic forest • Orographic barrier • Santos fault • Atlantic border

26.1 Introduction

Serra do Mar stands out due to its orographic distinctiveness, as a system of escarpments and mountains that span more than 1,500 km between the states of Santa Catarina and Rio de Janeiro, in accordance with a general ENE orientation of the structures of the Atlantic Shield (Fig. 26.1). Lithologically, the area is highly complex and includes migmatitic and metamorphic associations and igneous complexes, due primarily to events taking place in the Precambrian and Eopaleozoic eras.

Some geomorphological characteristics of this landscape draw particular attention. Some stretches are extremely steep and continuous (Fig. 26.2a), whereas others are more irregular and heterogeneous (Fig. 26.2b). Moreover, the range has a discontinuous outline, in some areas advancing toward the coast and in other sections retreating toward the interior of the Plateau. For some authors, this discontinuity is the result of lithological differences, such as the presence of complex fault systems and shear zones and morphotectonic events that formed the Atlantic Plateau during the Paleocene and Miocene.

Along with Serra da Mantiqueira, Serra do Mar constitutes the most outstanding orographic feature on the Atlantic edge of the South American continent (Almeida and Carneiro 1998), having been called, due to its escarpments, tectonic processes, faults, and marked folds, the “most tormented relief in the country” (Almeida 1953). It stands out in the Brazilian landscape because of both its impressive geomorphological features and its role in the human occupation of Brazil from the period of colonization to the present day.

As Zalán (2012) highlights, Serra do Mar has several local names as follows: Paranapiacaba, Paraty, Couto, dos Órgãos, and da Carioca, among others. In a way, these designations

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World Geomorphological Landscapes, DOI 10.1007/978-94-017-8023-0_26,

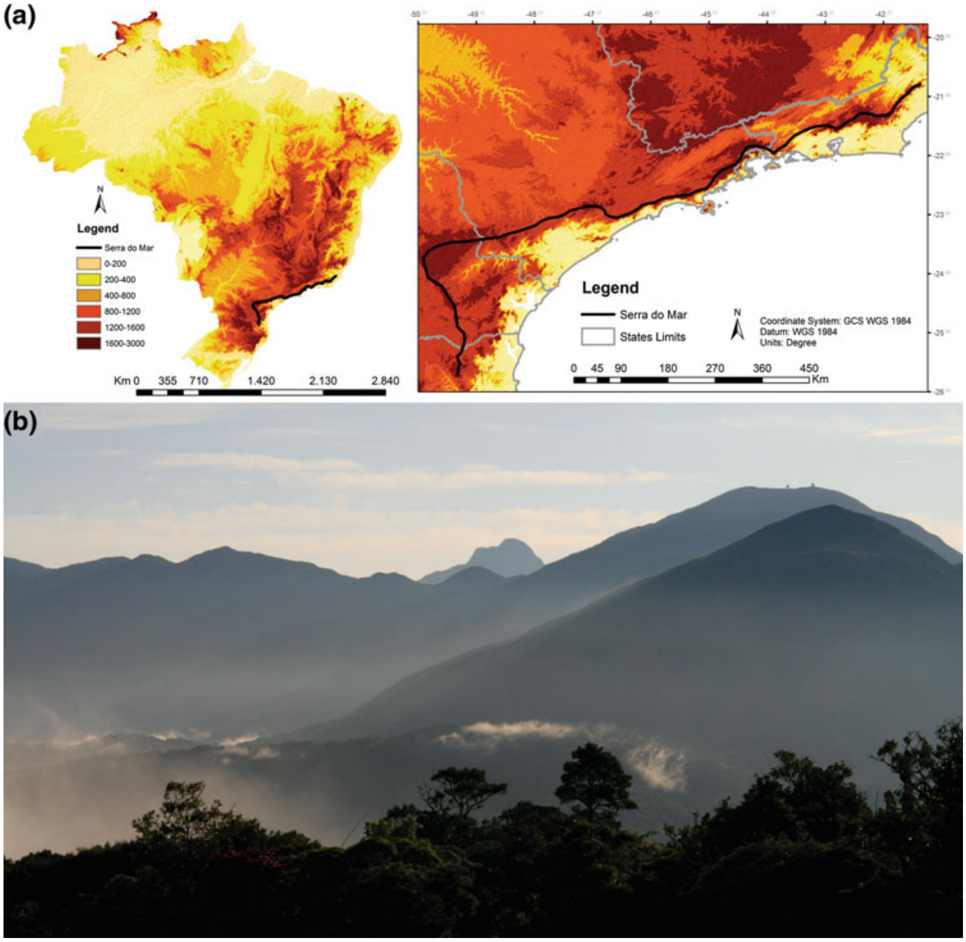

Fig. 26.1 **a** Location of the Serra do Mar in Brazil. **b** Serra do Mar, Paraná (*Source* **b** Tiago D. Martins)

reflect geomorphological characteristics of each local site, developed in response to the lithological variety and structural constraints that control relief in these locations.

From the arrival of the Portuguese colonizers until the present day, Serra do Mar has been seen as a very beautiful landscape but also as a great challenge—not only for geoscientists, who still seek to understand its origin and evolution, but also for national economy, given its position between the coastal ports and main urban centers of Brazil and related problems for transportation and land use in general. In the state of São Paulo, for example, there have been several attempts to overcome this immense natural barrier, with emphasis on Tupiniquins Trails (Trilha dos Tupiniquins) (before 1560); the Walk of Lorena (Calçada do Lorena) (1790–1841); Maioridade Road (Estrada da Maioridade) (1841–1913); the Santos-Jundiaí Railroad (Estrada de Ferro Santos-Jundiaí) (1867–present day); Caminho do Mar (1913–1947); Anchieta Highway (Rodovia Anchieta) (1947–present day); and Imigrantes Highway (Rodovia dos Imigrantes) (1974–present day) (Santos 2004) (Fig. 26.3).

This landscape, with its exuberant geomorphological forms and geological structures, was described in the nineteenth century by the Swiss glaciologist Jean Louis Rodolphe Agassiz, on an expedition in Serra do Mar near Rio de Janeiro, as follows: “I renounce describing the charm of an excursion like this (…) the road winds gently down the sides of the mountain and sometimes gives such a short turn that all the land that was just walked over is seen underneath one’s feet (…) here in narrow gorges where magnificent forests unfold, from the heart of which great escarpments emerge; ahead, in large, extensive valleys; further below, in the lowland we just crossed, one’s gaze reaches far into the distant bay, its archipelago of islets and its fringe of mountains” (Agassiz and Agassiz 1975).

During the same century, in the state of Paraná, an English engineer, Thomas P. Bigg-Wither, on a trip to the coast and the plateau and traveling up the Graciosa Road (Estrada da Graciosa), which was built in the same century, described it thus: “Most of us preferred walking to being jolted along in the springless waggons, though (except for one length of about five miles, where the metaling had not yet been put down) the road was first rate, and did great credit to the engineers who had planned and constructed it up this difficult Serra (Bigg-Wither 1974)” (Fig. 26.3).

The natural processes in the current area of Serra do Mar, a region subjected to high annual average rainfall and prolonged periods of rain, primarily involve mass movements, such as

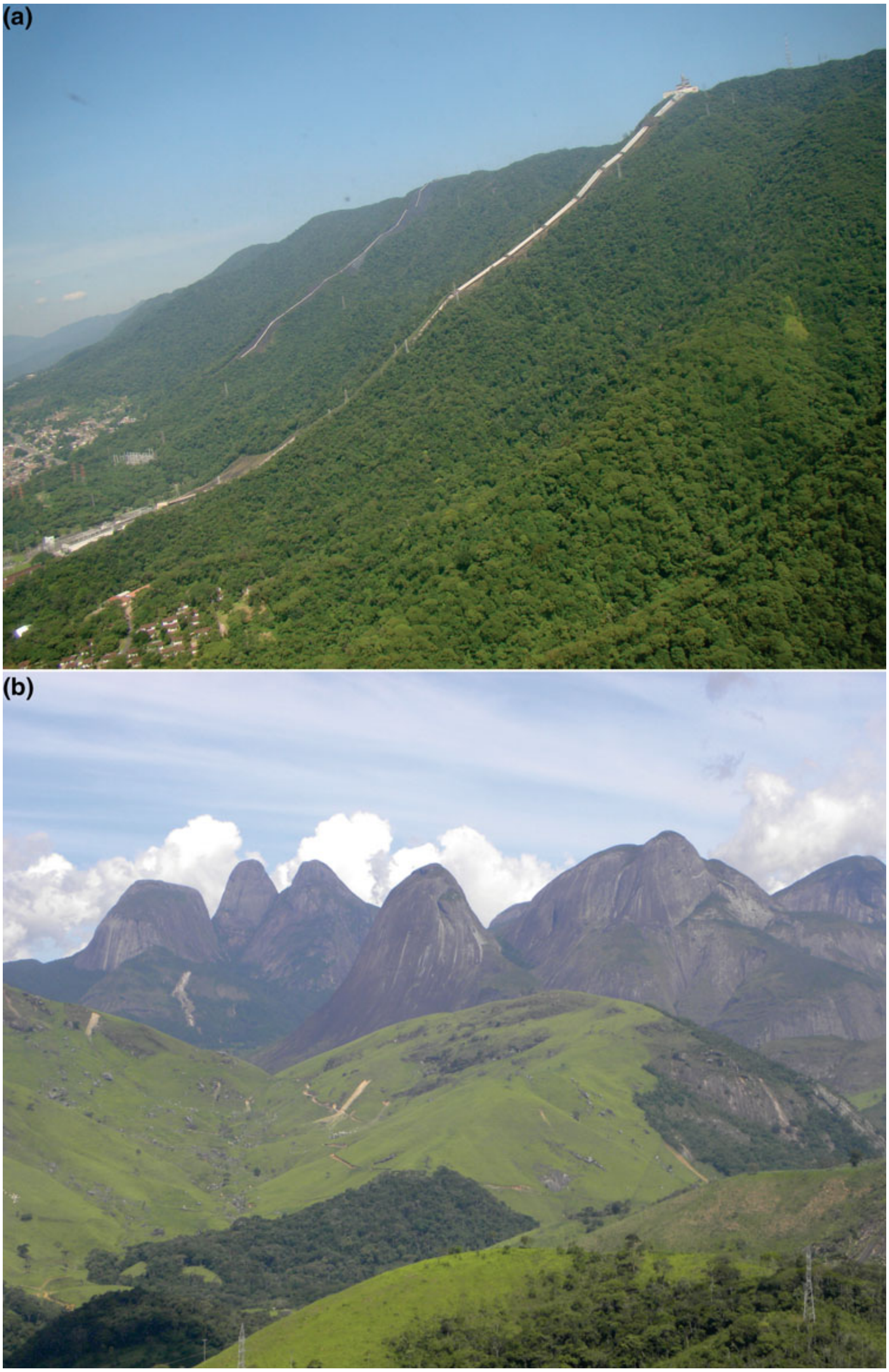

Fig. 26.2 Serra do Mar sections in **a** the state of São Paulo (*Source* Marcelo F. Gramani) and **b** the state of Rio de Janeiro (*Source* Bianca C. Vieira)

landslides and debris flows. It is noteworthy that one of the places with the largest volume of rain in Brazil, in addition to the Amazon region, is the stretch of Serra do Mar in the state of São Paulo, where approximately 5,000 mm/year has been recorded.

Considered a Historical Landmark, with emphasis on the beauty of the landforms, Serra do Mar houses a lush forest and an immense diversity of fauna and flora, preserving the largest area of Atlantic Forest in the Brazilian territory. Thus, some national parks have been created here, including Bocaina, Tijuca, and Serra dos Órgãos. Within the Serra do Mar State Park, all types of vegetation from the coastal region are present as follows: dense ombrophilous forest, sandbanks, montane grasslands, mangroves, and floodplains. Species such as the “jequitibá-rosa” (*Cariniana legalis*),

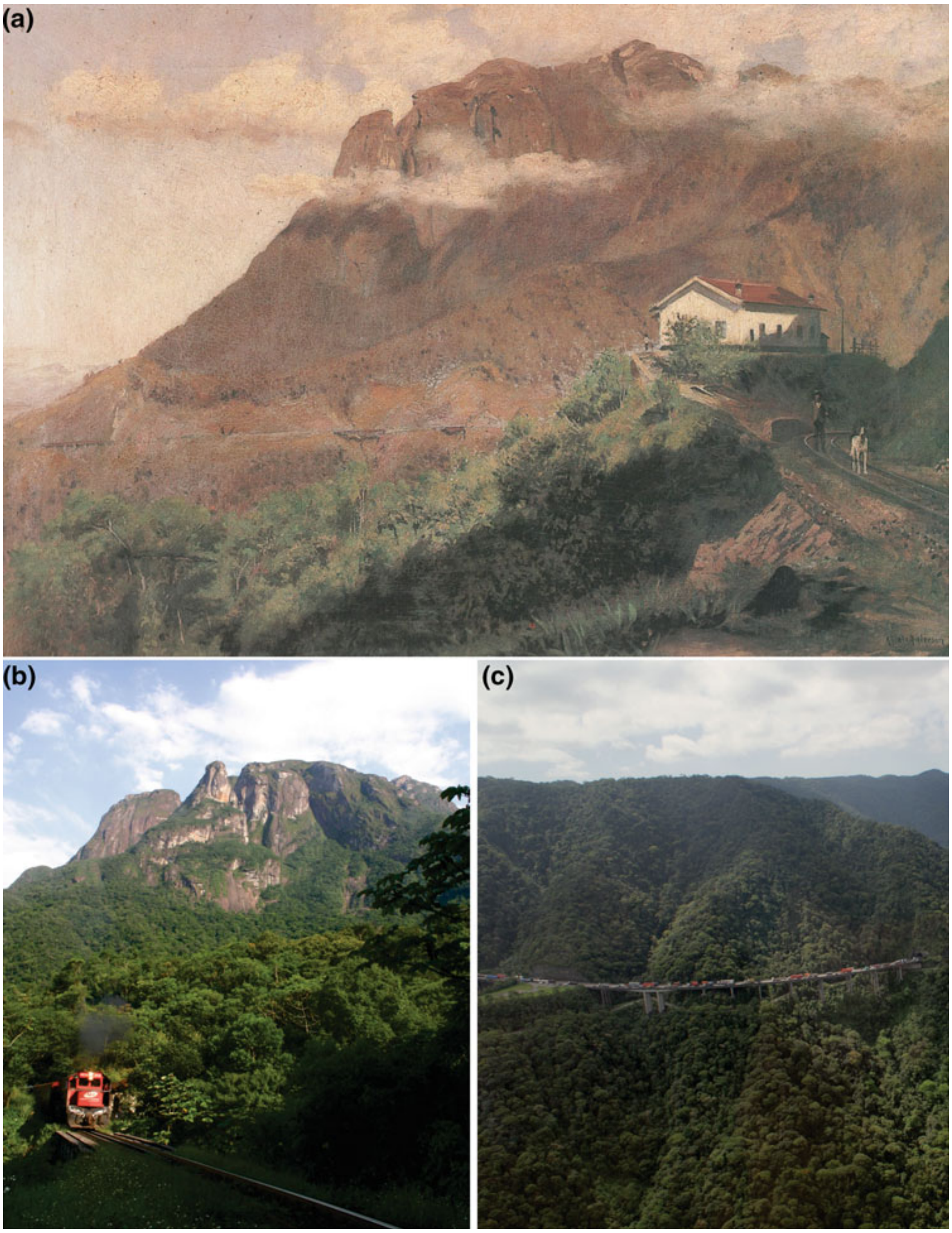

Fig. 26.3 **a** The first paintings of Serra do Mar in the nineteenth century, by Alfredo Andersen (1860–1935), showing the Graciosa Railway, constructed in the nineteenth century, in the state of Paraná (*Source* Secretaria de Estado e Cultura: Solar do Rosário 2001). **b** Photograph of the same stretch as shown in Fig. 26.3a, with emphasis on the Serra do Marumbi in the background (*Source* Tiago D. Martins). **c** Imigrantes Highway (Rodovia dos Imigrantes) in Serra do Mar in the state of São Paulo (*Source* Marcelo F. Gramani)

which can reach 40 m high and 4 m in diameter, can also be found. Several other species are also noteworthy, including the Paraná pine, cedar, fig trees, the "ipê," Brazilwood, and many others.

26.2 Origin and Evolution

Considering that the mountain system represented by Serra do Mar and Serra da Mantiqueira constitutes an outstanding orographic feature of the Atlantic border of the South American continent in a very intriguing way, Zalán (2012) makes us ponder the following question: why are there high mountain chains parallel to each other and parallel to the coastline, separated by deep valleys/plains in a passive plate margin setting? After the consolidation of the theory of plate tectonics, the answer to this question has become simpler.

Since the nineteenth century, particularly after the 1920s, dozens of studies have been conducted on the origin of Serra do Mar (Paes Leme 1930; Lamego 1938; Ruellan 1944; Moraes Rego and Almeida 1946; Freitas 1951; Almeida 1964; Hasui and Sadowski 1976; Asmus and Ferrari 1978; Almeida and Carneiro 1998; Riccomini 1989; Zalán and Oliveira 2005, among others). In 1933, De Martonne claimed that Serra do Mar was a set of faulted blocks downthrown in the direction of coastal lowlands, although the presence of faults had not been shown. Later on in 1953, the same author stated that there were no modern faults directly responsible for the relief, which was actually the result of differential erosion acting on schistose rocks intercalated with porphyric and quartz gneisses rocks (support the promontories), cut by ancient faults.

The stages of geological–geomorphological evolution of Serra do Mar from the periods of regional uplift until the phases of subsidence are summarized in Fig. 26.4. In the first stage, during the Cretaceous (90 Ma), the westward drift of the South American plate from the center of the meso-Atlantic seafloor spreading began to be affected by the presence of a mantle plume. The effects of this plume included gradual homogeneous upward movement of the crystalline basement of the entire southeast region of Brazil, ending at 65 Ma. In this context, large volcanic/plutonic centers of alkaline nature occurred (e.g., São Sebastião Island and Itatiaia Massif) (Almeida and Carneiro 1998; Zalán and Oliveira 2005; Zalán 2012). Vignol-Lelarge et al. (1994) confirmed this uplift as occurring 86 Ma ago using the fission track dating method in apatite from rocks in the crystalline basement of Serra do Mar. Associated with this uplift, denudational processes occurred in the Atlantic Plateau called “Cretaceous Serra do Mar,” with the developing of flatlands (e.g., Japi Surface), which provided material for the sedimentary basins of Santos and Paraná (Almeida and Carneiro 1998; Zalán and Oliveira 2005).

During the Paleocene, a regional tectonic event initiated the formation of taphrogenic basins (e.g., São Paulo basin, Curitiba basin, and Resende basin). The Santos fault separated the western block subject to uplift and subsiding eastern block; the formation of a “Proto-Serra do Mar” occurred at this time, approximately 100 km from the current coastline.

In later stages, there was a retreat and dissection of the escarpment due to geomorphological processes associated with paleoclimatic regime very different from the current one (Ab’Saber 1955). In a recent study, Salgado et al. (2013) found, through dating, that the coastal base level controls escarpment retreat toward the continental highlands and that basins facing the ocean were more intensely eroded than those facing the continent. Furthermore, these results also demonstrate the differential erosion along the Serra do Mar escarpment in southern Brazil during the Quaternary, where drainages over granites had lower average denudation rates in comparison with those over migmatites and gneisses.

Given the above, the configuration of the southeast shore of Brazil is characterized by mountains with steep meridional escarpments and gentle northern coasts, separated by straight valleys that are parallel to the coast. Is the result of Cenozoic extensional tectonics of gravitational nature, which acted on a Neo-Cretaceous epeirogenic mega-plateau of thermal nature (Zalán 2012).

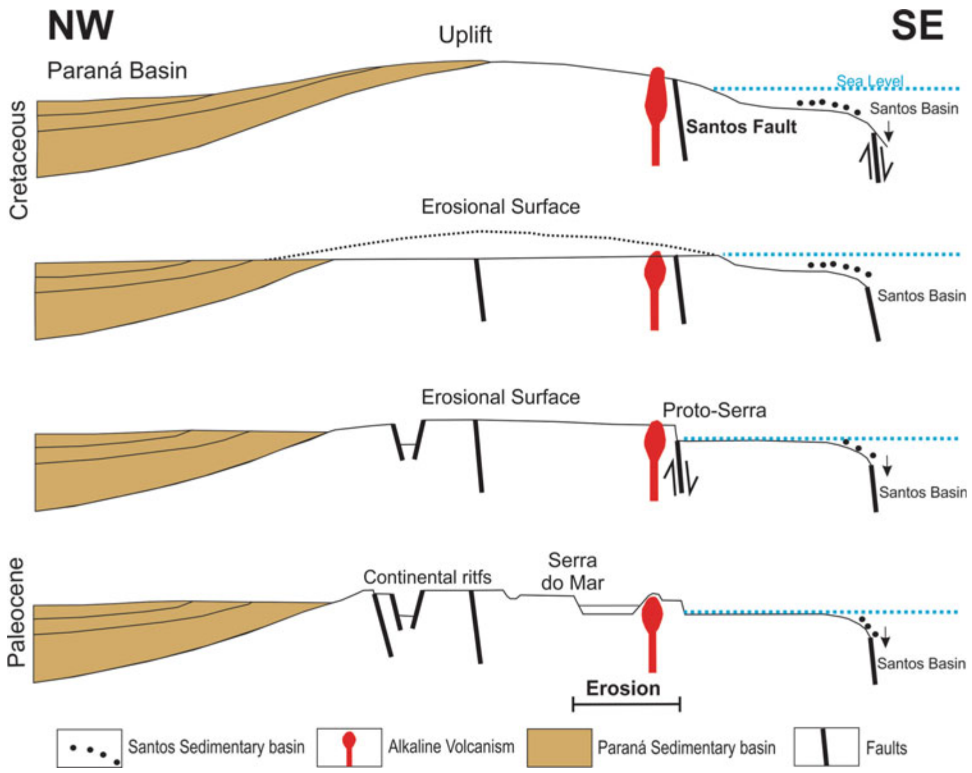

Fig. 26.4 Schematic drawing of the origin and erosive retreat of the Serra do Mar, in the section between the basins of Paraná and São Paulo (adapted from Almeida and Carneiro 1998)

Due to its extension across four states in south and southeast Brazil, its discontinuous outline, and its geological–geomorphological characteristics, Serra do Mar is subdivided into two different sectors: Santa Catarina–Paraná and São Paulo–Rio de Janeiro, considered separately in the following sections.

26.3 Serra do Mar—Santa Catarina and Paraná

In Santa Catarina, Serra do Mar is confined to the northern tip of the State, constituting a small extension of the Serra Paranaense. It ceases to exist as an orographic unit with a steep edge of a plateau, presenting itself as an inland-moving system, more retreated and dissected, with isolated hills and emphasis on the great plain in the Itajaí River Valley (Fig. 26.5a).

In the geological context, the whole framework consists of gneisses and alkaline migmatites and granites (Almeida 1953), all equally uplifted and displaced along faults between the Cretaceous and Paleogene, as well as due to the most recent tectonics, with neotectonic movements and the reactivation of faults. All units are truncated by large Cretaceous lineaments striking in a NW direction, generally with associated magmatism, and also in the ENE direction (Gontijo-Pascutti et al. 2012). According to these authors, more recent Cenozoic tectonic movements are recognized in Santa Catarina and these were very important for structural and tectonic configuration and partitioning, as well as for the control of erosion/sedimentation surface dynamics.

In Paraná, the first systematic studies were performed by the geographer Reinhard Maack after the 1940s. Maack (1981) divided Serra do Mar into separate high and low massifs, controlled by recent reactivation of faults developed in the Cenozoic and Cretaceous, with predominant NE and

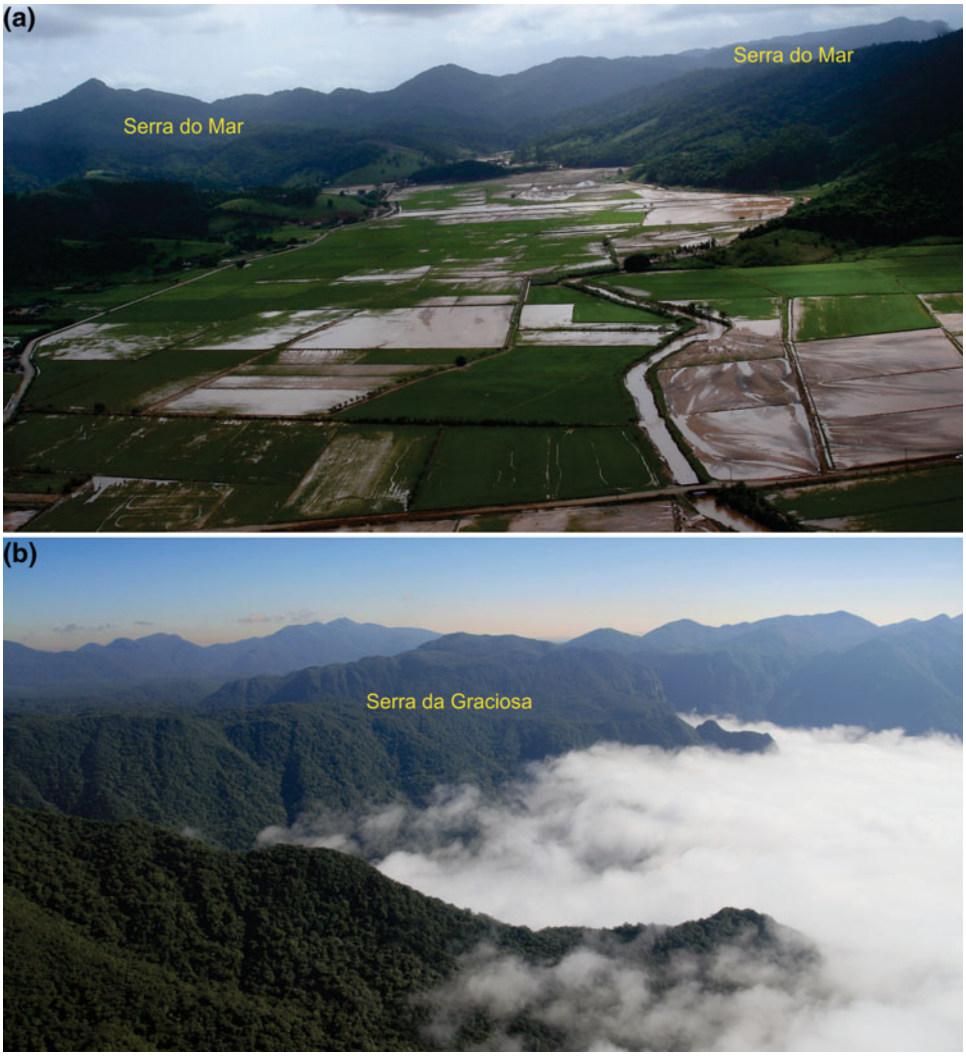

Fig. 26.5 **a** Serra do Mar in the state of Santa Catarina (*Source* Marcelo F. Gramani) and **b** Serra do Mar in the state of Paraná, with an emphasis on the Serra da Graciosa (*Source* Tiago D. Martins)

SW orientations. The author noted that the highest elevations are formed by alkaline granite and sodic syenodiorite in the north and central parts and by plutonites and basic aphanites from post-Triassic Gondwanic volcanism, diorites, diabase dikes, and andesites in the more southern part. Figure 26.5b shows aspects of Serra do Mar in the State, with an emphasis on the alignment of ridges and deep valleys following the main structural orientations of the massif.

Between Serra do Mar and the coast, the region presents the Coastal Granitoid Belt (including the Paranaguá[1] batholith), consisting of more or less foliated granites, granite–gneisses, migmatites and other foliated rocks with a primary NE orientation, which support rugged relief of hills and mountains (Maack 1981; Basei et al. 1990).

The region is very mountainous, with the escarpments facing the coast due to reactivation of faults running in NE and NNE direction. Alignments of small mountains and isolated hills occur in parallel, forming subsided steps with altitudes between 20 and 900 m a.s.l., truncated by N–W and E–W faults. The altitudes of this stretch vary between 800 and 1,300 m a.s.l., with peaks above 1,800 m supported by granitic massifs (Almeida 1953; Gontijo-Pascutti et al. 2012). These include the peak of Paraná (1,877 m) formed by alkaline granite, with its steepest parts supported by andesite and diabase dikes, and the Serra do Marumbi (1,539 m) formed by alkaline microcline–biotite–granite (Fig. 26.3b). The flanks of the youngest granites are formed partially by lenticular coarse-grained gneisses and partially by schistose biotite-gneisses (Maack 1981).

The erosive retreat may be associated with (i) the presence of less resistant lithologies, such as phyllites, meta-arenites, schists, carbonate/dolomitic rocks, and sometimes volcanic rocks and banded iron formations, that may also have been affected by thrusting, folding, and transcurrent faulting and (ii) the faults, shear zones, fractures, and supracrustal rocks that determine the major lineaments and local segments of the drainage network (Fiori 1994; Almeida and Carneiro 1998).

26.4 Serra do Mar São Paulo and Rio de Janeiro

In the State of São Paulo, Serra do Mar imposes itself as a typical edge of the plateau, frequently leveled at the top, at altitudes from 800 to 1,200 m a.s.l., and can be divided into two distinct sectors (south and north). The south sector extends between Santos and the Ribeira do Iguape River Valley, while the north sector occurs between São Sebastião Island and the State of Rio de Janeiro. Figure 26.6a shows the division of these sectors, the main structural lineaments in the southeast, the great erosive retreat of the Ribeira River Valley, and the proximity of the escarpment to the coast beyond the city of Santos.

The main geomorphological characteristics include the presence of very intense forms of dissection, with deeply engraved valleys, high drainage density, steep slopes with sharp ridge tops, and drainage pattern adapted to the directions of structures related to faults, fractures, and lithological contacts (Ponçano et al. 1981; Ross and Moroz 1997). Extremely scalloped at many points, the escarpment follows the SW–NE geographic and structural directions from the south to southeast Brazilian coast.

In the section, further south, Serra do Mar has an “interruption” with the opening of the Ribeira River Valley and retreats significantly away from the coast (Fig. 26.6a). There are a few reasons for this to have occurred as follows: (i) The presence of a structural alignment is characterized by intense fissuring and normal faults in the NW and NE direction, approximately 600 km long and 20–100 km wide; (ii) extension of metasediments of greenschist to amphibolite facies between the coast and the continental shelf; and (iii) tectonic movement in the Tertiary in the lower valley of the Ribeira River, with the formation of the Sete Barras graben (Melo et al. 1989; Almeida and Carneiro 1998). In the stretch of the Serra, the escarpments retreated up to one hundred kilometers inland on phyllites and schists, where drainage expands longitudinally in the paths parallel to the shoreline. The tops are supported by granite, granitic gneisses, and locally quartzite ridges, reaching approximately 1,300 m a.s.l. (Almeida 1964).

Close to the city of Santos, the Serra de Cubatão, the local name for Serra do Mar, is one of the most important parts of this sector. Major highways located in this section of Serra do Mar are used for most transportation and exports of Brazilian products through the Port of Santos and the Industrial Hub of Cubatão, composed of the major petrochemical industries in the country (Fig. 26.6b). Because of this history of occupation, several studies have been conducted, particularly those of a geotechnical, geological, and geomorphological nature. It is noteworthy that the origin name of “Serra de Cubatão” is very uncertain and for some authors signifies a “small elevation at the base of a mountain range,” and for others “port,” “prancing on the staircase” or “the formation of a river that falls from above.”

For some authors, its origin is due to the headward erosion controlled by the structure and a very heterogeneous set of rocks. Other authors associate its origin to fractures in narrow fault blocks that would have subsided toward the plain (Martonne 1933). Here, the Cubatão and Mogi Rivers

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[1] Paranaguá is a city on the coast of Paraná located on the front of Serra do Mar, where one of the main ports in the Brazil is located. Paranaguá in Tupi Guarani means “inlet from the large river or the sea”.

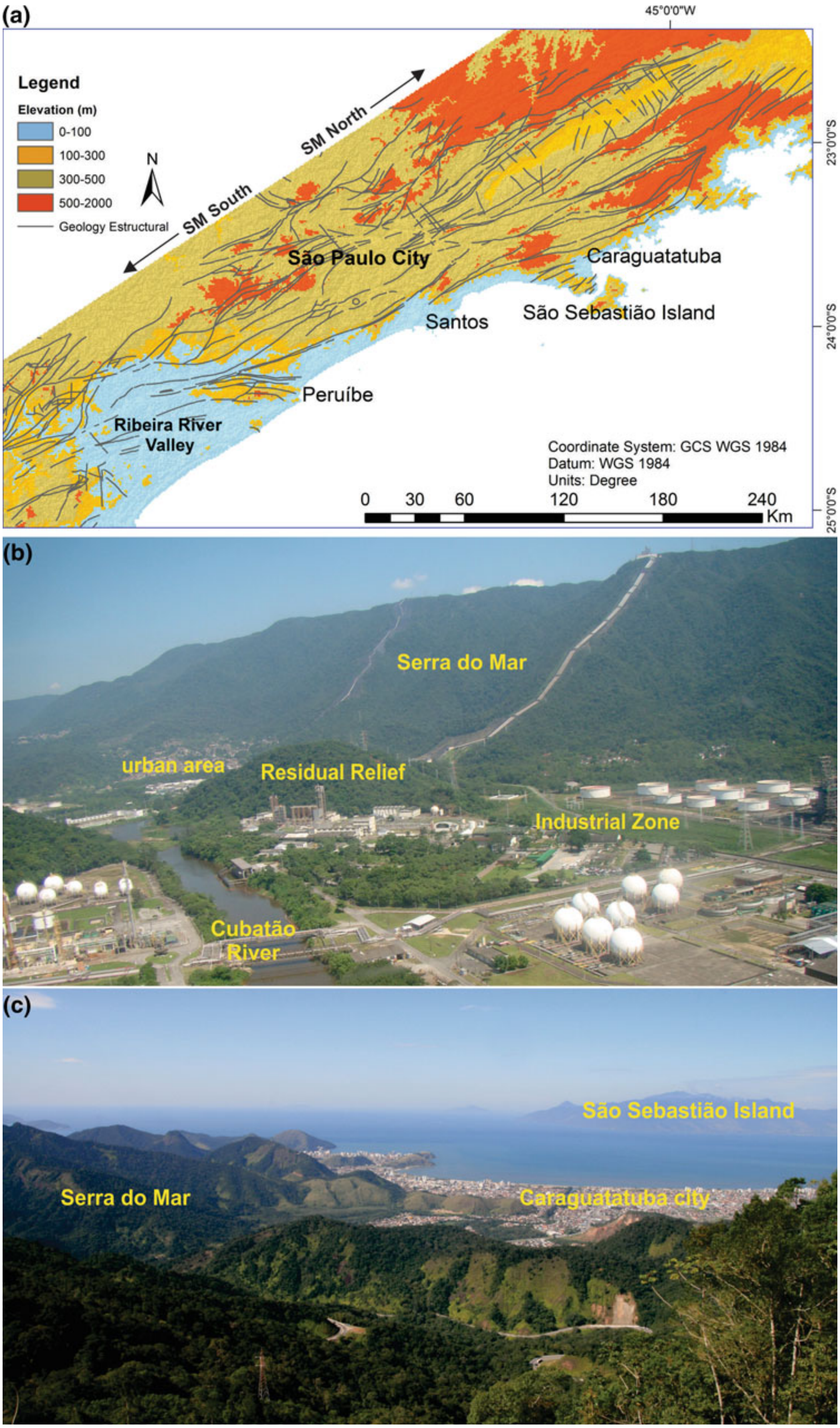

Fig. 26.6 **a** Location of the stretch of Serra do Mar in São Paulo. **b** Serra de Cubatão, the local name for Serra do Mar close to the city of Santos (*Source* Marcelo F. Gramani). **c** Serra do Mar in the town of Caraguatatuba, with São Sebastião Island in the background (*Source* Bianca C. Vieira)

run over the non-granitic schist belt, and at the northern edge of these rivers, schist migmatites prevent a more substantial retreat of the Serra (Almeida 1953).

In the north section, São Sebastião Island, for example, is sustained primarily by alkaline eruptive intrusions and andesite dikes, serving as “testaments” to the headward erosion of the Serra (Almeida 1964). In the municipality of Caraguatatuba (Fig. 26.6c), for example, Serra do Mar retreats inland, forming large alveoli and coves with large sedimentary plains. This retreat can be attributed to the encountering of and intersection with the structural directions or contact areas of regional metamorphism (De Ploey and Cruz 1979).

In the state of Rio de Janeiro, the first studies of Serra do Mar date from the 1930s and 1940s, with an emphasis on the works by Lamego (1938) and Ruellan (1944). Here, the escarpment changes direction and no longer borders the coastline, but becomes more recessed and is separated from the coastline by wide marine and fluviomarine plains (Gontijo-Pascutti et al. 2012). After the 1970s, studies on the geological–geomorphological context intensified and so did the morphostructural and morphotectonic descriptions, particularly in the works by Almeida (1976), Junho and Penha (1985), Ferrari (2001), Zalán (2004), and others.

In this section of Serra do Mar, erosive retreat was particularly large and differential, isolating hills and mountains that form the coastal massifs and some islands in the region. The current Guanabara Bay formed with the rise in sea level, bounded by the steep escarpments of Serra do Mar (Gontijo-Pascutti et al. 2012). Here, Serra do Mar is geomorphologically configured as a relief between high, uneven plateaus, bounded by escarpments facing south and southeast. In these plateaus, there are numerous small hills, larger residual hills, and granite peaks, with drainage lines that are well fitted and tailored to the fault zones and fractures (Fig. 26.7a). Its evolution is very much controlled by mass movement processes, especially shallow landslides, debris flow, and falling blocks. The detachment of the latter usually occurs along fracture systems, as confirmed by the presence of blocks

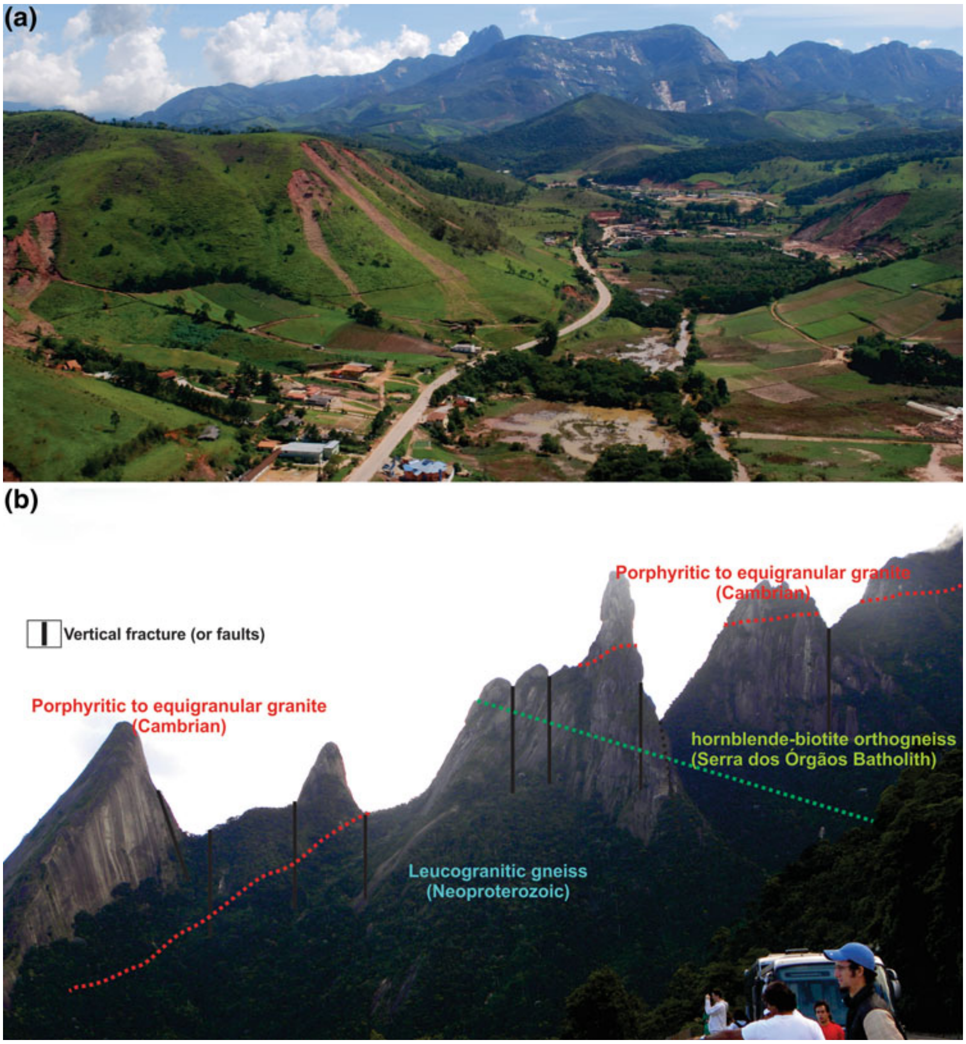

Fig. 26.7 Serra do Mar in Rio de Janeiro. **a** Very rugged relief with convex hills; the main drainage lines follow fault systems; in the background, rocky escarpments supported mostly by granite (*Source* Bianca C. Vieira). **b** Photograph and sketch of the lithologies and structures that form this section of the Serra dos Órgãos and Pico do Dedo de Deus (*Source* adapted from Fernandes et al. 2010)

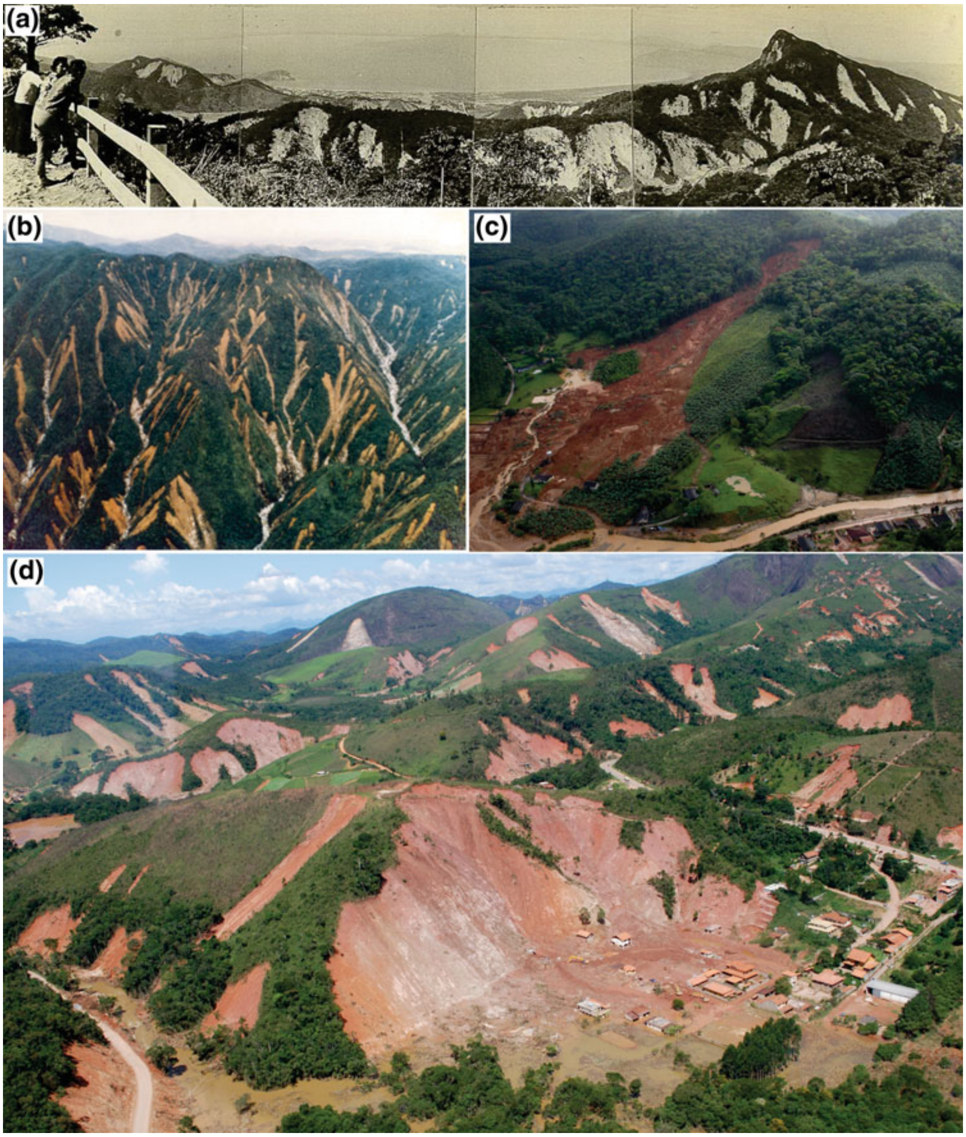

Fig. 26.8 Mass movements in SM in different municipalities: **a** Caraguatatuba (SP) in 1967 (*Source* Olga Cruz), **b** Cubatão (SP) in 1985 (*Source* Lara-CTGeo-IPT), **c** Ilhota (SC) (*Source* Marcelo F. Gramani), and **d** Nova Friburgo (RJ) in 2011 (*Source* Bianca C. Vieira)

dozens of meters in diameter at the base of the escarpment (Fernandes et al. 2010).

The Serra dos Órgãos, a local name for Serra do Mar due to the vertical topographic forms (differential erosion along the fault zones and fractures) that resemble the pipes of an organ, typical of Portuguese churches at the time of colonization, has an average elevation of 1,100 m a.s.l., with granite peaks of the "Batholith of Serra dos Órgãos" that exceed 2,000 m a.s.l. (Fig. 26.7b).

26.5 Mass Movements: Evolutionary Processes and Natural Disasters

One of the primary geomorphological processes in Serra do Mar is mass movements, which occur locally every year, causing environmental and social damages (Fig. 26.8). After the 1960s, important events that caused disasters nationwide were recorded, causing millions of dollars in economic losses and thousands of casualties and rendering thousands more homeless. Table 26.1 shows the mass movement events in Serra do Mar, with an emphasis on the states of Rio de Janeiro and São Paulo, which together have recorded 3,200 victims since 1928. These cases occurred in both the geomorphological compartment of Serra do Mar itself and the residual hills originated from its retreat, where the main urban sites are located.

Geological and geotectonic aspects have been the object of several studies since the beginning of the second half of the nineteenth century, when Charles Frederick Hartt (1870) described the geology of the sections of slopes for the construction of the Santos-Jundiaí railroad. Very little had been researched about the mass movements until the mid-1940s, although when Charles Frederick Hartt in 1870

Table 26.1 Occurrences of mass movements in SM

Year	LOCATION (STATE)	Rain	Area (Km^2) Speed (m/s) Volume (m^3)	LOSSES (nº deaths); other damage
1928	Monte Serrate (SP)	649 mm/Jan and 564 mm/Feb.	Vol: > 1x10^5	(60); destruction of Santa Casa
1958	Monte Serrate (SP)	373 mm/24 h	-	(43); destruction of 100 houses
1966	Rio de Janeiro (RJ)	> 250 mm/<12 h	-	(>230)
1967	Serra das Araras (RJ)	275 mm/24 h	Vol: > 10x10^6	(1200); > 100 houses destroyed, damage to highways, destruction of the hydroelectric plant
	Caraguatatuba (SP)	580 mm/48 h	Vol: > 7.6x10^6	(120); 400 houses destroyed, damage to highways
1971	Santos-Jundiaí Railway (SP)	-	Vol: 1x10^5 (estimated)	Steel viaduct destroyed, works for slope stabilization
1974	Tubarão (SP)	394 mm/ 72 h 742 mm/16 days	-	(195); urban area flooded
1975-1976	Grota Funda (SP)	-	S:8.4 Vol: > 10x10^6	Pillars of railway bridge damaged
1976	Cachoeira River (SP)	276 mm/24 h	A:4 Vol: 1x10^5	Flooding for industries, two rock-filled and earth-filled dams were built
1985	Cubatão (SP)	380 mm/48 h	-	(10)
1988	Petrópolis (RJ)	145 mm/24 h	-	(171); 5,000 displaced, 1,100 homes interdicted
	Rio de Janeiro (RJ)	-	-	(~300); destruction of dozens of homes
1994	Cubatão (SP)	60 mm/24 h	A:2.64 S:10 Vol: 3x10^5	Flooding of Petrobrás Refinery, interruption of operations and clean-up (US$44 mil)
1996	Cubatão (SP)		A: 2.64 S: > 10 Vol.: 1.6x10^4	Clean-up works
	Oswaldo Cruz Highway (SP)	10 mm/10 min 442 mm/13 h	-	Highway damaged, works for slope stabilization, water capture station affected
	Papagaio River Basin (RJ)	202 mm/24 h	A: 2.13 Vol.: 9x10^4	(1); hundreds of houses destroyed
	Quitite River Basin (RJ)	202 mm/24 h	A: 2.53 Vol.: 4x10^4	houses destroyed
	Rio de Janeiro (RJ)	301 mm/72 h		(54)
1999	Anchieta Highway (SP)	128 mm/24 h 274 mm/72 h	Vol.:3x10^5	200 m of affected area, traffic stopped for several weeks, water capture station affected
2001	Rio de Janeiro, Petrópolis (RJ)	300 mm/24 h	-	(40);164 wounded
2002	Petrópolis (RJ)		-	(88)
2008	Santa Catarina (SC)	720 mm/72 h	-	(135); 80,000 displaced/homeless, 85 municipalities in state of emergency
2010	Angra dos Reis (RJ)	143 mm/24 h	-	(53)
	Rio de Janeiro	120 mm/24 h	Vol: 680 m^3	(253) 1,410 displaced, 368 homeless
2011	Rio de Janeiro			
	Córrego Dantas (stream) (RJ)	269 mm/72 h	A: 52	(429); 3,220 disappeared, 2,031 homeless, displaced, and many economic losses,
	Córrego Vieira (stream) (RJ)	269 mm/72 h	A: 33	
	Córrego da Posse (stream) (RJ)	92.6 mm/72 h	A: 12	(343); 9,110 disappeared, homeless, 6,727 displaced and numerous losses
	Córrego do Cuiabá (stream) (RJ)	35.8 mm/72 h	A: 36	(71); 6,223 disappeared, homeless, 191 displaced and numerous losses
	Antonina (PR)			(4)
2013	Córrego do Pilões (stream) (SP)	23 mm/10 min 115 mm/1 h 273 mm09 h	-	Damage to water reservoir, chlorine cylinders and road service station destroyed
	Petrópolis (RJ)			(31); 4,000 displaced

The values for area, speed, and volume refer to the processes of debris flows described several accidents had already occurred, such as in the hills of Santos in 1928 and during and after the construction of Santos-Jundiaí railroad (Vargas 1999).

The geological and geotectonic aspects of Serra do Mar, associated with high rainfall volumes, determine the dynamics and mechanisms of mass movements. The key controlling factors are the amplitudes of the slopes, shape of the basins, high slope inclinations, slopes of drainage channels, variety of soil profiles, deposits of talus, and large amounts of material in the drainage beds.

In addition, a large variety of human activities have significantly influenced an increase in risk, such as housing units, land transportation network (e.g., highways and polyducts), petrochemical terminals, and water capture and supply systems (Fig. 26.6). In the state of São Paulo, for example, many problems with slope instability are caused by inappropriate human interventions. During the construction of the Anchieta highway in 1948, there was movement of a talus over 30 m thick and a volume of soil estimated to be 2 million m^3 (Rodrigues and Nogami 1950). In the period of 1974/1975, heavy rains triggered numerous landslides on natural slopes and excavation embankments located close to the Imigrantes Highway.

Some major historic events affected Serra do Mar, notably in the cities of Caraguatatuba and Cubatão (São Paulo), Ilhota, Gaspar and Luis Alves (Santa Catarina) and Petrópolis, and Teresópolis and Nova Friburgo (Rio de Janeiro). In Caraguatatuba, 947 mm of rainfall was recorded during the month of March 1967, with 115 mm on the 17th and 420 mm on the 18th. On these days, numerous landslides and debris flow with great mobilization of material occurred, reaching a radius of up to 15 km, causing approximately 440 fatalities (de Ploey and Cruz 1979). On January 23rd and 24th, 1985, with 379.4 mm of rain within 48 h, or approximately 40–60 % of the monthly total, the Serra de Cubatão was severely affected by shallow landslides that reached the main channels in the drainage network, increasing the volume of material and generating debris flow with great destructive capacity.

In Santa Catarina, on November 22nd and 23rd, 2008, one of Brazil's largest natural disasters occurred. During heavy rains, approximately 720 mm in 3 days, large, deep landslides and mudflows affected Serra do Mar and its surroundings, killing 135 people and leaving more than 80,000 homeless/displaced, with 85 municipalities in a state of emergency and 14 in a state of public catastrophe. The socioeconomic impact of this event was significant, including structural damage, a decline in industrial production, interruption of gas supply, and losses in tourism. Both the port and cultivated areas were silted due to sediment load transported during the event. After this disaster, approximately US$20 million was spent on emergency works alone.[2]

On January 11th and 12th, 2011, approximately eight municipalities in Serra do Mar (state of Rio de Janeiro) were affected by 3,562 landslides (Avelar et al. 2011), in particular along the soil–rock and colluvium–rock contacts, and debris flows that reached more than 20 km in length. They were responsible for more than 1,500 deaths and nearly 20,000 homeless. The disaster followed an interval of heavy rains between October and December, culminating during these 2 days at approximately 300 mm/48 h.

26.6 Conclusions

Throughout Serra do Mar, we observe a diversity of landscapes and landforms directly associated with the complex combination of structures and lithologies. Pronounced peaks, residual hills, and extensive fluvio-marine basins make this landscape unique in Brazil. In addition to the high diversity of landforms, Serra do Mar has the largest area of preserved Atlantic Forest in Brazil, with lush flora and many species of Brazilian fauna.

The current landscape is the result of geomorphological processes, particularly mass movements that occur frequently due to intense rains in the summer, from December to March. In addition, inappropriate occupation of certain sections in naturally susceptible areas, either for infrastructure projects (e.g., highways, railroads, pipelines) or housing units, causes enormous economic and social damages with implications for the whole country.

The geomorphology of Serra do Mar also includes landforms and processes that arouse the curiosity of Brazilian scientists because many questions still need answers. This extensive barrier must be overcome, considering that its geomorphological and geological aspects impose strong limits on its occupation and transposition.

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Itatiaia Massif: Morphogenesis of Southeastern Brazilian Highlands

27

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Abstract

The geomorphological region of the Serra da Mantiqueira represents one of the most elevated compartments of the entire oriental sector of the Brazilian shield. Its contemporary gross morphology results from Neogene to Quaternary differential uplift, and the area hosts a range of morphotectonic features. Alkaline intrusions of nepheline syenites dated from the end of the Cretaceous and the beginning of the Cenozoic support the highest massifs, with spectacular pointed peaks and crests, rock slopes, and boulder talus accumulation. These massifs constitute one of the more scenic tropical mountain landscapes in southeast Brazil, characterized by substantial extensions of semideciduous forests and high-altitude grasslands on the summit surfaces. Colluvial ramps are ubiquitous in the region, providing sedimentary record of Late Pleistocene and Holocene environmental changes, while the current dynamics of the landscape is mainly associated with mass movements and torrential floods generated by high rainfall events.

Keywords

Alkaline mountains • Itatiaia massif • Brazilian highlands • Serra da Mantiqueira

27.1 Introduction

The Serra da Mantiqueira is the second orographic step of the Brazilian Plateau. When traveling beyond the Serra do Mar and the graben where the Paraíba do Sul River is located, the Serra da Mantiqueira emerges in an imposing manner. It consists of a magnificent *horst* of regional expression that forms the most elevated compartment of the entire eastern portion of the South American shield. The genesis of this important geomorphological unit is related to the tectonic reactivation that affected the Brazilian shield and was a consequence of the disruption of the Afro-Brazilian Plate. The area was uplifted during the Late Paleozoic and hosted large, sediment-filled syneclises (Sgarbi and Dardenne 2002) which were subsequently further loaded with Mesozoic terrigenous deposits. Rifting that resulted in the opening of the Atlantic Ocean during the Mesozoic caused a considerable uplift and, at the same time, generation of extensive depressions which provided the main lines of drainage. These geological events are known as the Wealdenian Reactivation (Almeida 1967), South Atlantic Event (Schobbenhaus et al. 1984), or the Continental Rift of southeastern Brazil (Riccomini 1989).

Saadi (1991) characterized the region of Mantiqueira by grouping of elongated mountain ranges, mainly of SSW–NNE orientation, into larger units. The compartment in question is thus subdivided into the following geomorphological entities, going from southeast to northwest: (1) southern escarpment of a tectonic origin, which links the

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high peaks (more than 2,700 m) and the Paraíba do Sul River Valley (500 m); (2) upper step, with blocks tilted to the NW or NE, including the alkaline massifs of Itatiaia and Passo Quatro and the Plateau of Campos do Jordão (more than 2,000 m); (3) middle step, with a plateau physiography (around 1,600 m), ridges trending ENE to NE, hills of different size, and intense tilting of blocks.

Regarding the most general geomorphological aspects, the Serra da Mantiqueira is characterized by elongated mountain ranges and frontal escarpments that correspond to major shear zones as well as by extremely steep hills that are highly dissected with a considerable drainage density and pronounced vertical carving. Depositional landforms are more extensively developed where the major fault lines are away from the main slope breaks that exist between the most elevated compartments and less elevated assemblages of predominantly convex hills, which occur between an altitude of 1,000 and 1,200 m. The first significant tract of landscape due to aggradation formed at this altitude range at the contact zone with the Alto Rio Grande Plateau. Here, fairly continuous and well-developed alluvial plains are present. Hanging valleys and high mountain alluvial floodplains occur on the summit plateaus, forming important local base levels. These features, in combination with other morphological evidence, indicate that the regional tectonics is active and ongoing.

The RADAMBRASIL project (1983) subdivided the Serra da Mantiqueira into northern and southern branches. The batholiths of Itatiaia and Passa Quatro, both alkaline stocks marked by nepheline syenites that rise above 2,700 m (Fig. 27.1), are the prominent morphostructural compartments of the southern Mantiqueira, forming the most *sui generis* landscapes of all southeastern Brazil. Realizing the uniqueness and high geomorphological, ecological, and landscape importance of the southeastern Brazilian highlands, this chapter aimed to present and discuss fundamental aspects of the geomorphology of the southern branch of the Serra da Mantiqueira, focusing in particular on the Itatiaia alkaline massif and its surroundings. Environmental issues, including problems related to land use and occupation, will be also dealt with.

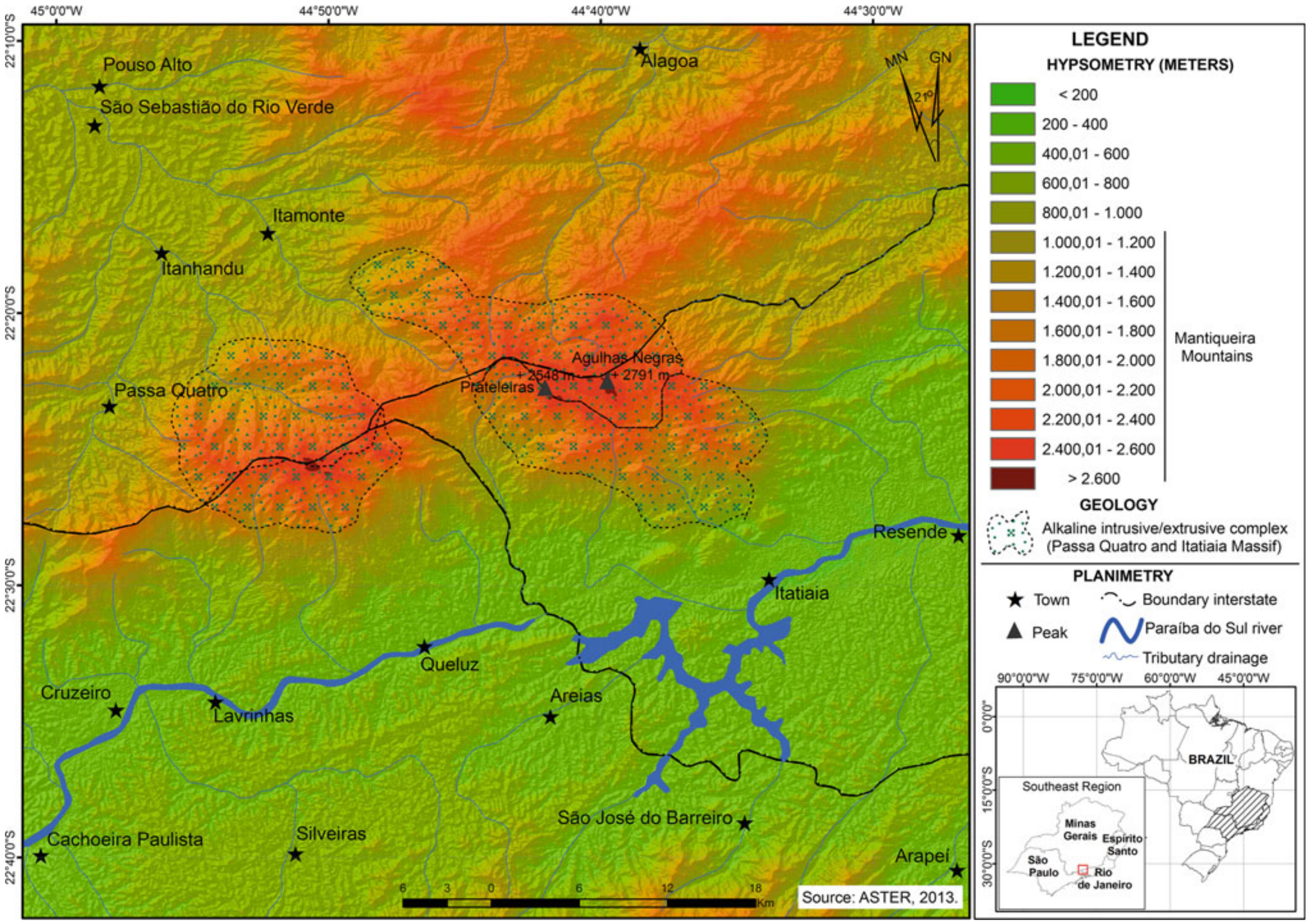

Fig. 27.1 Location of the Itatiaia alkaline massif and its surroundings in southeastern Brazil

27.2 Landscape in the Region of Itatiaia Alkaline Massif

27.2.1 Physical Environment

The southern Mantiqueira can be divided into two compartments of regional expression: the Itatiaia Plateau and the Campos do Jordão Plateau (Radambrasil 1983). The alkaline intrusive massifs, which are the focus of this study, reside on the Itatiaia Plateau (Fig. 27.2), a compartment with an area of 4,348 km^2.

The Itatiaia Plateau and its alkaline massifs have been a recurring subject of general considerations and of more specific studies focused on tropical morphogenesis (De Martonne 1943; Raynal 1960; Lehmann 1960; Clapperton 1993; Modenesi 1992; Modenesi and Toledo 1993; Modenesi-Gautieri and Nunes 1998; Santos 1999; Chiessi 2004; Lima and Melo 2013). The intrusive bodies form the most elevated compartment of the southern Mantiqueira and, along with the Caparaó massif, located at the border between the states of Minas Gerais and Espírito Santo, reach the highest elevations of the entire eastern Brazil, above 2,790 m at Pico das Agulhas Negras and at Pedra da Mina. Other prominent high peaks are Serra Negra (2,572 m), Pedra do Couto (2,681 m), and Prateleiras (2,548 m) (Fig. 27.3).

The geological framework of the Itatiaia Plateau consists of intrusive alkaline rocks of the Passa Quatro and Itatiaia massifs and of Precambrian granites, gneisses, migmatites, schists, and quartzites. This plateau can be subdivided into two compartments. The western compartment features relief marked by various dissection patterns, structural valleys, escarpments, symmetrical ridges of long extension, and edges of circular structures. The eastern sector is formed by a bundle of ridges of WNW–ESE orientation, with deep-seated perpendicular faults that have developed in migmatitic, gneissic, and charnockitic rocks (Radambrasil 1983). Figure 27.4 shows several representative aspects of the Serra da Mantiqueira in the region of the alkaline massifs, including high ridges and steep slopes covered by forest formations and high-altitude open areas located on the summit surfaces.

The alkaline intrusions are Late Cretaceous in age and define the limits of the Itatiaia and Passa Quatro massifs. They are mainly composed of nepheline syenite, foyaite, magmatic breccia, nordmakite, quartz–syenite, and alkaline granite (Penalva 1967). These intrusions are in abrupt contact with the regional Precambrian gneissic–granitic lithologies (Fig. 27.5). The presented profile allows for the contextualization of the Serra da Mantiqueira as well as the Serra do Mar (Bocaína Plateau) with regard to taphrogenic tectonics, which have resulted in the uplift of these blocks and the formation of the graben of the Paraíba do Sul River.

The landscape consisting of the high peaks of Itatiaia and the sharp shapes of the Agulhas Negras peak, evocative of an alpine scenery, was described by De Martonne (1943) during his excursions into the region. Reflecting on these landscapes, Raynal (1960, p. 5) made the following general comments regarding the Itatiaia alkaline massif:

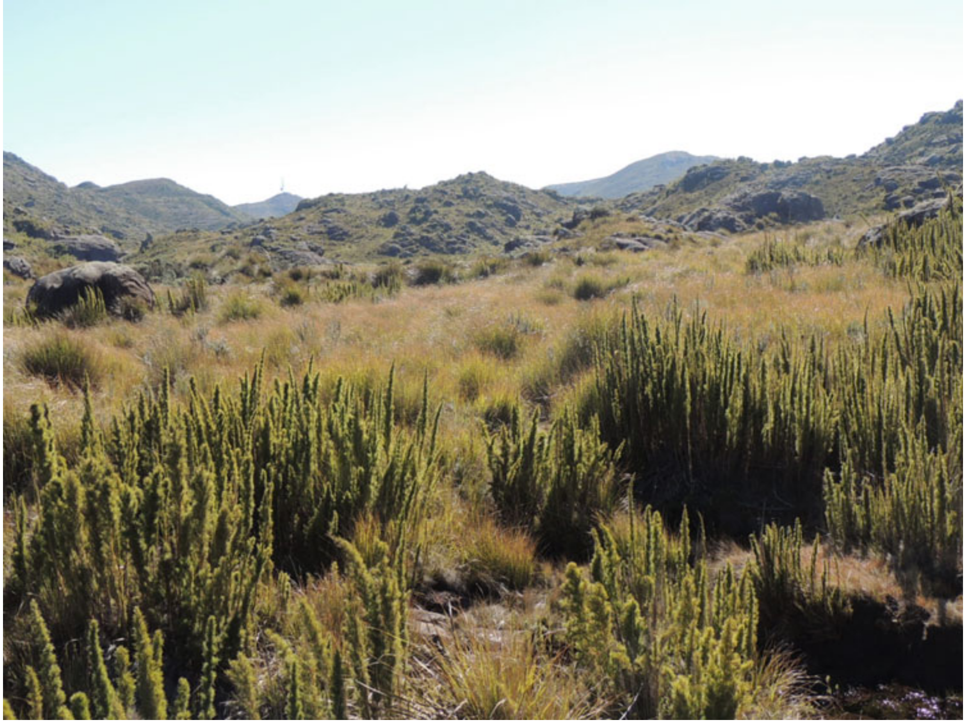

Fig. 27.2 General appearance of the landscapes of altitude on the plateau of Itatiaia

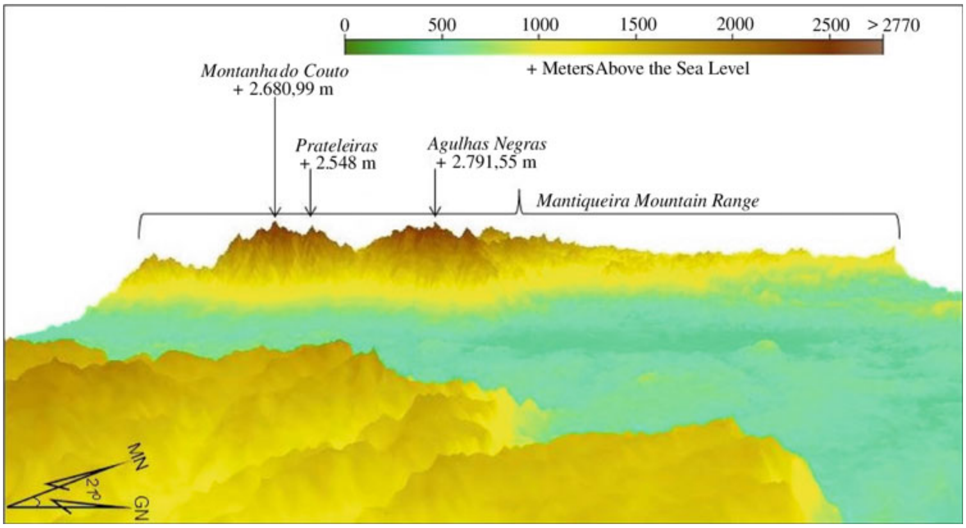

Fig. 27.3 Digital terrain model of the Itatiaia alkaline massif, highlighting the highest elevations and their respective altitudes

Fig. 27.4 Tropical mountain landscape in the region of the alkaline massifs: rugged and deeply dissected reliefs with extremely steep slopes covered with forest vegetation and high-altitude fields at the summit plateaus. *Photograph* Marques Neto, R

> A seemingly convex topography, wide basins, which are juxtaposed or elevated a few tens of meters, one relative to the other, the uncertainties of a network of streams that seem barely organized in the middle of bog grasslands, all of these features make up a landscape where various authors saw the mark of an ancient glaciation, located at the high mountain.

Linear grooves and channels appear on the rock faces and these used to be interpreted as a result of glacial erosion (De Martonne 1943; Lehmann 1960), which would have occurred on the tops of the peaks of Agulhas Negras and Prateleiras. This interpretation was supported by the fact that rainfall volumes did not dramatically decrease at these higher altitudes during the last glacial period. However, it is no longer accepted, following the explanations proposed by Modenesi-Gauttieri and Nunes (1998). These authors agree that the amount of rainfall at the higher compartments during the last glacial period may have been similar to the present-day levels and assume that cryogenic processes occurred above an altitude threshold of 2,000 m a.s.l. However, the average altitude of the massif would have always remained below the altitude thresholds that define the perennial snowline, even during the Pleistocene glaciations (Clapperton 1993). This renders the existence of a geomorphological system with periglacial or glacial dynamics impossible.

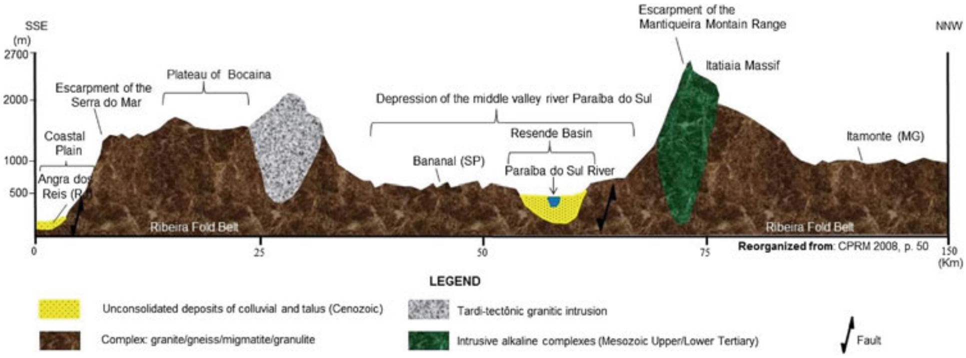

Fig. 27.5 Geological and geomorphological profile between Angra dos Reis (RJ) and Itamonte (MG), covering the sectors of the Serra do Mar, the Paraíba do Sul valley, and the Serra da Mantiqueira

The Itatiaia highlands have specific climatic conditions. These high landscapes differ from their surroundings in terms of humidity, cloudiness, precipitation, and temperature because of the altimetric prominence of the batholith. Tropical climate features are clearly attenuated on the summit plateaus of the Itatiaia alkaline massif due to landscape dynamics. Cyclopean rock blocks lie on the slopes (Fig. 27.6a), while basins and depressions that have formed above 2,000 m are rich in bogs. In these depressions, an organic horizon has developed within the slopes covered by high-altitude grasslands, which are characterized by their own floristic and physiognomic patterns, with a high rate of endemism (Fig. 27.6b). Hence, the high-altitude landscape is composed of a combination of heterogeneous features, such as rocky outcrops, various grassland physiognomies (depending on the growth of vegetation on rocks or on shallow soils), and wetland depressions in which organic soils have developed and hygrophilous plants are dominant. The Pico das Agulhas Negras, the highest point with a distinctly unique morphology, is distinguished among this mosaic by the sharp appearance of its peak (Fig. 27.7).

The landscape throughout the long and steep cliffs of the alkaline massif deeply contrasts with that of the high peaks. The fundamental character of the forested, mountainous landscapes of the Atlantic coast, which fortunately remains very similar to its original vegetation state, typifies the flanks that connect the summit surfaces to the low elevation compartments. Semideciduous Seasonal Montane Forest and Mixed Ombrophilous High Montane Forest occur successively in various sections of the hillsides, in addition to the presence of the Semideciduous Seasonal Submontane Forest (sensu IBGE 1992) and cloud forest, associated with the high incidence of fog throughout practically the entire year.

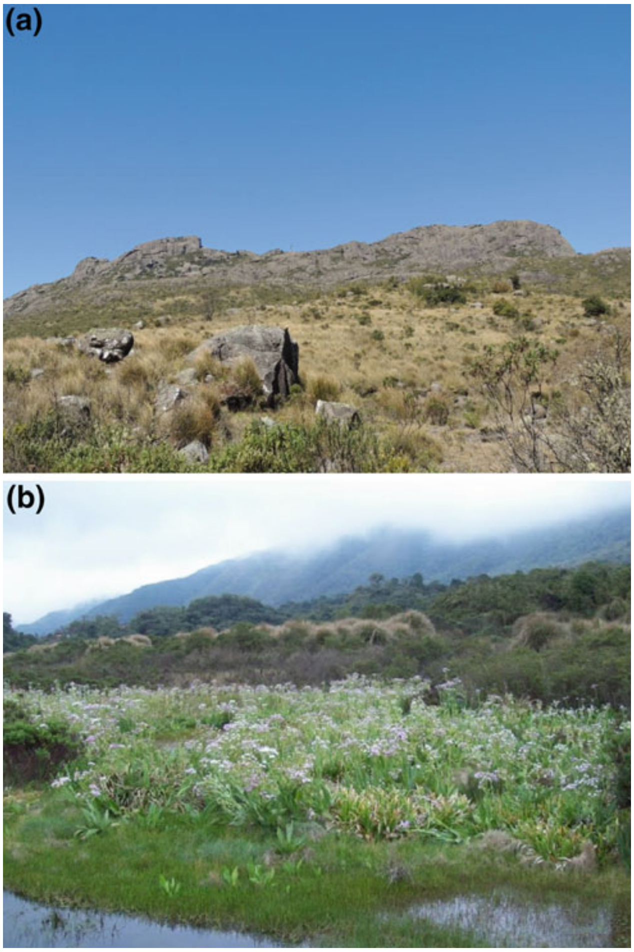

Fig. 27.6 Landscape of the high peaks of the Itatiaia massif: **a** continuous outcrops with large-sized blocks scattered throughout the grass-covered slopes (Resende, RJ); **b** a bog that formed in a depression at 2,200 m a.s.l., distinguished by a unique floristic arrangement that includes several endemic species (Itamonte, MG). *Photographs* Marques Neto, R

27.2.2 Historical, Cultural, and Environmental Aspects

The first pre-Columbian native people believed to inhabit this region belonged to the Puri tribe (of the Tupi ethnicity), who colonized the Paraíba do Sul River Valley. The name *Itatiaia* is also thought to have originated from the Tupi language through the hybridization of the two words *Ita* = stone and *tiããi* = tip or tooth, clearly inspired by the very sharp rocky peaks of the alkaline massifs (Santos and Zikán 2000).

Fig. 27.7 View from Pico das Agulhas Negras (2,791 m) showing a high-elevation valley packed with boulders mainly detached along the preexisting joints. Border of the states of Minas Gerais (Itamonte) and Rio de Janeiro (Resende). *Photograph* Marques Neto, R

In the sixteenth century, the region was a route of passage for the *Bandeirantes* (leaders of expeditions into the interior of Brazil), who used the topographic prominence of the peak of Agulhas Negras as a reference point. The use of this route was reinforced by the discovery of gold deposits in Ouro Preto and Mariana. Hence, the area became a connection point between the port region of Parati and the inland colony. With the decline of gold exploration, the economic activity in the nineteenth century focused on agriculture again. The monoculture strategy that marked the period of sugarcane production in the plantation system during the colonial period returned, but now under the aegis of coffee. During this period, the level of rainforest destruction in southeastern Brazil increased, expanding the gaps already present from the times of sugarcane monoculture practices.

Scientifically, the nineteenth century was marked by the arrival of major European naturalists who traveled to Brazil as part of exploration campaigns searching for environmental resources. Several naturalists, such as Auguste Saint-Hilaire, Von Martius, Oliver von Spix, and Derby, visited the region during their expeditions, also taking advantage of the Paraíba do Sul River Valley as a very convenient path and of the Pico das Agulhas Negras as a point of permanent reference. Unfortunately, the legacy of such incursions does not include illustrative prints of the eighteenth-century landscapes of the region.

The geometric characteristics of tectonic relief, which features deeply and densely dissected slopes, were rather influential in preserving several forest remnants of the tropical Atlantic domain and their genetic heritage. These forest formations were also spared from deforestation because of the difficulties associated with access and the existence of projects that promoted more intensive land use and occupation elsewhere. Within this context, the Itatiaia National Park was created as the first Brazilian conservation unit in 1934 on lands that belonged to Visconde de Mauá. This park is a fully protected area that includes varieties of the Atlantic rainforest along the slopes, as well as high-altitude grasslands and other unique ecosystems with high levels of endemism. Some of them are related to rocky biotopes, and others have developed from relationships that the biota have established with waterlogged depressions, including vegetated bog areas that are delimited by rocky sills carved in the syenitic rocks.

In addition to the Itatiaia National Park, the region benefits from the presence of another fully protected conservation unit, Serra do Papagaio State Park, distributed across territorial areas among the municipalities of Alagoa, Aiuruoca, Baependi, and Itamonte. Forest extensions that largely consist of primary vegetation extend beyond the perimeters of the protected areas and spread over elongated mountains and steep cliffs where agricultural activities are impractical.

The land devoted for agricultural and farming purposes on the Itatiaia alkaline massif and surrounding areas is mainly used for livestock grazing in small- and medium-sized farms. The rural landscapes do not contain agricultural crops despite the fact that in other compartments of the Serra da Mantiqueira, the cultivation of coffee (municipality of Carmo de

Minas) and banana (municipality Cristina) is of significant importance to the regional economy. *Eucalyptus* is cultivated in a more dispersed manner, as it has been adopted as a very profitable alternative source of income in various regions of Brazil. The urban centers are generally small and are accommodated within the valley bottoms on the alluvial plains and had not experienced any significant growth until recently.

27.3 Morphogenesis of the Itatiaia Alkaline Massif

The geomorphological history of the Itatiaia alkaline massif dates back to the very origin of the Serra da Mantiqueira. This important orographic step was generated due to rifting responsible for continental separation of South America and Africa in the Late Mesozoic, reactivation of Precambrian faults, and uplift of the eastern edge of the Brazilian Plate. This uplift was associated with the taphrogenic tectonics, which resulted in two uplifted compartments—the horsts of the Serra do Mar and of the Serra da Mantiqueira, separated by a graben oriented in the same general direction as the mountain ranges, known as the Paraíba do Sul River Graben. This process was accompanied by extensive basaltic magmatism in the Paraná Sedimentary Basin (Serra Geral Formation), which covered the Paleozoic–Mesozoic sediments, and by periodic alkaline intrusive manifestations, such as those found in the municipality of Ponte Nova (MG), on the São Sebastião Island (off the coast of the state of São Paulo), and in the Serra da Mantiqueira in the triple frontier among the states of São Paulo, Minas Gerais, and Rio de Janeiro. This same region hosts the Itatiaia and Passa Quatro alkaline massifs.

The genesis of the alkaline massifs of Serra da Mantiqueira, in its initial phase, dates back to the Cretaceous/Paleocene, when the rocks that had formed from the alkaline magmatism intruded into the Proterozoic crust during the same period as the uplift of the continental margin took place. Pacca and Montes-Lauar (1997, cited in Santos 1999) dated the alkaline intrusions of Itatiaia to 70–77 Ma. Subsequently, its morphological evolution occurred in line with denudation and tectonic processes that occurred during the Cenozoic.

The intrusions into the Precambrian rocks generated arched blocks with flattened tops, especially characteristic for the Itatiaia massif, giving rise to summit surfaces intercalated with rocky peaks and sharp crests and characterized by continuous outcrops of alkaline rocks. Such surfaces were considered to be of Cretaceous age by De Martonne (1943) and designated as *Surface of the Fields*. Lower plateau levels were generally considered to be of Early Cenozoic age and were collectively designated as the *Paleogenic Surface*, or the *Surface of Mid Ridges* (Ab'Sáber 1962). These initial studies and the subsequent reflections on the morphological evolution of the region and other geomorphological areas of eastern Brazil agree that we deal with the same surface, dated to the Early Cenozoic, but broken by faults (Freitas 1951; Almeida 1964; Valadão 1998; Almeida and Carneiro 1998; Magalhães and Trindade 2004; Zalan and Oliveira 2005; Marques Neto 2012). In the Brazilian geomorphic literature, the surface in question is repeatedly referred to as the *South American Surface* (King 1956) or *Japi Surface* (Almeida 1964).

Zalan and Oliveira (2005) have correlated the high-altitude surfaces (above 2,000 m a.s.l.) in southeastern Brazil (alkaline stocks of Itatiaia as well as Passo Quatro, Serra da Bocaína, Serra dos Órgãos, and Campos do Jordão Plateau) with the same surface, which also occurs as extensive flat-topped peaks at altitudes of 1,000–1,300 m in the Serra do Mar and in lowered highlands located at ~700 m a.s.l. The authors hypothesize that the highest altitudes would be closer to the original position of that surface at the end of the Cretaceous.

However, the definite dating of these surfaces still requires improvement. The rarity of preserved and datable materials from the Cretaceous and Paleogene on the high peaks of the Mantiqueira hampers the precise measurement of the age of the summit plateaus and the systematic establishment of a chronology of denudation. The tectonic origin of the Serra da Mantiqueira and the post-Cretaceous uplift and deformation effects did not allow for shaping a homogeneous flat surface. Instead, a series of topographic levels was generated by denudation and erosion, reflecting also the influence of structure and tectonic effects on the Mantiqueira region. However, aluminum bauxite genetically linked to the alkaline massif has been discovered in Passa Quatro, which constitutes a correlative deposit (Marques Neto 2012). These materials are found as slope deposits that overlie the Precambrian metamorphic rocks and form extremely hard crusts covered by lithic neosols (Entisols). Thomas (1994) explains that formation and destruction of ferruginous or bauxitic profiles record important episodes of tropical landscape evolution. Similar deposits of the same origin, located in other parts of the alkaline massif, were dated by Sígolo (1997) as from between the Eocene and the Oligocene, subsequent to the alkaline intrusions themselves. This age indicates the most likely age of the materials found in Passa Quatro, which must have been deposited after the Cretaceous/Paleocene, at the end of the alkaline magmatism event. Laterization processes can be observed even on the high peaks, which experience the same chemical weathering processes as the syenitic rocks.

The supergene processes of lateritic weathering were quite common during the Eocene–Oligocene, a time period with a relatively hot and humid climate that favored the widespread formation of bauxitic and lateritic profiles, eventually preserved on paleosurfaces. This type of climate was inferred for the region from pollen analysis of Upper Eocene fluvial sediments that contained lignite layers belonging to the Resende Formation, located in the Paraíba do Sul Valley (Lima and Amador 1985). Lima and Melo

(2013) analyzed pollen in rudaceous deposits of Oligocene age located in the proximal alluvial fan present along the southern flank of the Itatiaia alkaline massif; their results also indicated a tropical to subtropical humid climate.

The development of the South American surface from the Late Cretaceous period most likely occurred during a period of tectonic stability that marked the morphological evolution of the eastern sector of the Brazilian shield and lasted until the Miocene, when a new uplift phase strikingly affected the Atlantic coast (Hasui 2010). This tectonic phase initiated a new stage in the regional geomorphic evolution that lasted from the Middle Miocene onward. It terminated the origin of the South American surface and marked the beginning of the neotectonic period for the Brazilian shield, with an eminently transcurrent character associated with the extensive Neogene deposition of the Barreiras Formation along the majority of the Atlantic coast.

In the regions of southeast Brazil, which are geomorphologically characterized by gross relief of tectonic origin, the Serra da Mantiqueira is one of the most important domains. Its response to neotectonic processes was a subject of several studies conducted in the region (Ribeiro 1996; Santos 1999; Gontijo 1999; Hiruma 2007). The Miocene uplift, responsible for reshaping of the escarpments and formation of topographic steps, enhanced the dynamics of erosion and the development of a high-density, deeply incised drainage network. Simultaneously, the regional river system was reorganized. The fragmentation of laterite must have occurred throughout the Neogene, followed by the formation of autochthonous and allochthonous gravel.

The neotectonic movements continued during the Quaternary and proved to be influential in the ongoing evolution of relief (Hasui 1990; Santos 1999). A wide range of evidence, provided by landforms and the drainage pattern, strongly suggests the existence of active tectonics in the Itatiaia alkaline massif and other morphostructural compartments of the Serra da Mantiqueira region. It includes the development of trapezoidal facets, offset ridges, river captures, shutter ridges and deflections in river channels, lateral migration of water bodies, asymmetric drainage basins, rocky outcrops in river terraces, faults in Quaternary deposits, uplift of floodplains, the presence of hanging valleys and high mountain alluvial floodplains, and deposits in the drainage headwaters that are disjointed from the base level. Uplifted alluvial deposits are abundant in the Serra da Mantiqueira region and carry paleosols that currently exhibit an overlapped neopedogenesis. Such materials have been dated by optically stimulated luminescence (OSL) and their ages cover the last 100,000 years (Marques Neto 2012), which corroborates the active tectonics in the region.

Climatic conditions were not uniform throughout the Quaternary. Oscillations caused by alternation of glacial and interglacial periods affected the Brazilian territory, including the highlands of the Serra da Mantiqueira. These effects, superimposed on the ongoing tectonic processes, greatly increased the complexity of the morphogenesis. Sedimentary record of changing climates exists mainly in the form of colluvium ramps and alluvial packages, in addition to bog sediments on high mountain floodplains, whose ages are mainly attributed to the Late Pleistocene and Holocene.

Modenesi (1992) has recognized two generations of colluvium ramps on the Itatiaia Plateau. The older ramps, from the Late Pleistocene (13,000/12,700 BP), truncate the top of weathered rock and have a thickness of generally less than 1 m, whereas the more recent (Holocene) colluvial sequences form the lower level and extend over bog deposits on the floodplains, with thicknesses of approximately 2.5 m. A discontinuous stone line separates the two colluvial sequences, marking the transition from the Pleistocene to the Holocene. These colluvial sequences are preceded by very coarse deposits older than 15,000 BP, whose occurrence reflects the prior impact of a cold and wet climate with freezing and thawing cycles. These processes were presumably more common during the last glacial period, enabling the frozen water contained in pores and joints within the rock to dislodge large rock masses, as witnessed by a large number of boulders associated with the Neopleistocene deposits. Moreover, the influence of the Cenozoic tectonics and related seismicity on the destabilization of slopes and the release of huge blocks and boulders currently found in talus deposits have also been considered (Modenesi 1992).

Regarding the genesis and the paleoenvironment during the formation of colluvial sequences, Modenesi (1992) interpreted these sediments as deposited under a relatively warmer and less humid climate and developed through mud or earth flows and solifluction caused by the saturation of weathered material forming the talus during occasional intense rainfall. The correlative deposits of the slower solifluction processes are the second-generation colluvia, in which the amount of coarse material is less than in the deposits of the first generation. The mineralogy of both generations of colluvia indicates the presence of kaolinite and gibbsite, confirming the existence of an environment suitable for lateritization throughout the Holocene. The effect of cooler thermal conditions at high altitude is apparently offset by the tropical rainfall rhythm and good drainage conditions (Modenesi and Toledo 1993).

27.4 Current Landscape Dynamics

The physical processes associated with colluvial deposition and mass movements typify the current geomorphological dynamics in the southern Mantiqueira. Thick ramps of colluvial material due to both fast movement and slow movement of the regolith in the form of talus deposits delimit a belt starting at 1,900 m of altitude on the north-facing slopes of the Passa Quatro alkaline massif. Colluvial packages, which partially underwent pedogenesis, also occur in more elevated compartments (above 2,000 m) and are more visible on the left bank of the Verde River. In the Itatiaia alkaline massif, they can be observed at even higher altitudes, from approximately 2,500 m and spreading down slope toward the Grande River and the Paraíba do Sul River Basin.

The contemporary dynamics of the landscape is influenced by interactions among the regional geomorphological configuration, the patterns of land use and occupation, and the dominant tropical climate. The tectonic character of the relief provides considerable potential energy to the geomorphological system and catalyzes mass movements, which often occur even in the presence of vegetation cover (Fig. 27.8).

The region of the Itatiaia alkaline massif is strongly influenced by the action of the Tropical Atlantic Mass, which is responsible for providing a considerable amount of rainfall, the effects of which are enhanced by the orographic influence. In certain circumstances, the typical amount of rainfall substantially increases in association with climate events. For example, this was observed in January 2000, when most of the southern portion of the state of Minas Gerais suffered from widespread landslides and flooding, which led to material losses and fatalities. Conti (2001) reported that the consequences of this event were felt across an area of 20,000 km^2 because of the stationing of the Polar Front over the area for three consecutive days, which was aggravated by a previous cold front. In particular, the municipality of Passa Quatro, one of the hardest hit municipalities, received 600.6 mm of rainfall in the first four days of the year (322.7 on day 3 alone).

Mass movements processes in the geomorphological system of the Serra da Mantiqueira are characterized by their perennial nature and occur as episodic events related to specific weather conditions. These processes occur more frequently during the months with the highest amounts of rainfall, between October and February, but may also be triggered at other times of the year. Thus, in terms of geomorphic hazard and risk, the Serra da Mantiqueira is composed of high-risk landscapes that should be spared from more intensive land use, thereby allowing for the conservation of the last major extensions of Atlantic Forest in this region, the presence of which is a *sine qua non* condition for maintaining the stability of the slopes.

27.5 Final Considerations

Among the mountainous landscapes of tropical Brazil, the fold belt domain in the southeast, where the Serra da Mantiqueira is located, constitutes one of the major extensions of continuous highland and contains several of the highest points in the country. Generated from crustal uplift that was associated with the separation of the Afro-Brazilian paleoplate, the Serra da Mantiqueira has been affected by more recent uplift during the Neogene continuing into the Quaternary. As a consequence, the effects of neotectonic deformations are clearly visible in the relief and the drainage network.

In the region of the alkaline massifs, the most elevated morphostructural compartments of the whole southern Mantiqueira are located, featuring peaks exceeding 2,000 m of altitude. They occur along the eastern edge and extend inland, toward the tectonic contact with the lowered, westernmost portion of the Serra da Mantiqueira. The presence of active tectonics influences the geomorphological scenery, which is characterized by high slopes and deep vertical incision of the drainage network. Therefore, the effects of tropical climate and extreme weather events are more pronounced in terms of triggering physical processes, in particular mass movements.

The contemporary steep relief of the Mantiqueira region provides limits to any more intensive land use, thereby supporting important remnants of native vegetation of the

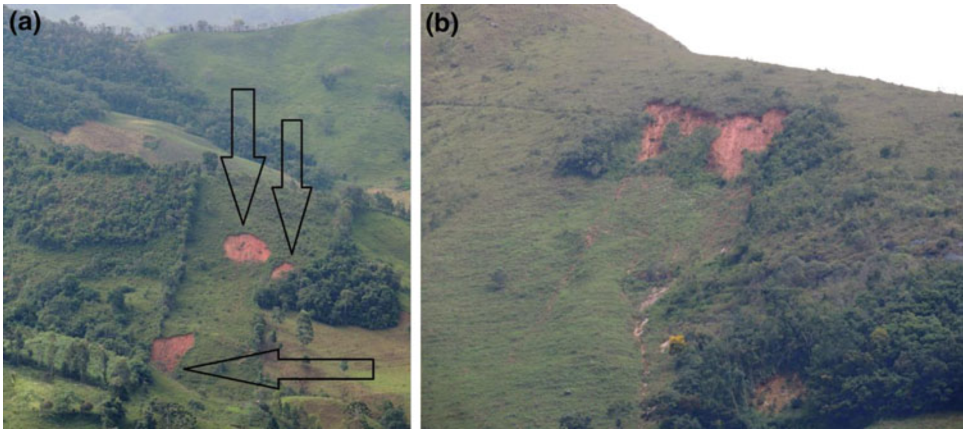

Fig. 27.8 Scars of mass movements in the Serra da Mantiqueira (**a**), especially in segments where the native vegetation has been removed, a process observed in detail in photograph (**b**) (Alagoa, MG). *Photograph* Marques Neto, R

tropical Atlantic domain with respect to both forest communities and high mountain grasslands. This level of preservation provides the region with a high degree of scenic beauty and environmental importance. The slopes of the orographic belts that belong to the southern Mantiqueira and face inward enshrine the headwaters of the Grande River (one of the rivers that forms the Paraná River) and its main upper-reach tributaries, thus constituting one of the more important hydrographic areas in the large Silver River Basin. This situation renders these areas a priority for the conservation of environmental resources, especially since the presence of vegetation is essential to counterbalance the hillslope erosion and to ensure adequate water supply. In summary, the Serra da Mantiqueira region is distinguished by the challenging nature of the relief, the forest corridors that strategically contribute to the conservation of the last remnants of Atlantic Forest, the valuable water resources, the indisputable function of recharging the underground aquifer, and the scenic value of the rural and natural environment highly suitable for tourism and other leisure activities.

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Southern Plateau and Itaimbezinho Canyon

28

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and Luís Eduardo de Souza Robaina

Abstract

The Itaimbezinho canyon is located in the Southern Plateau, between the states of Santa Catarina and Rio Grande do Sul, in Brazil. This area, popularly known as *Aparados da Serra* (Mountain Range Trims), is mainly characterized by extensive vertical escarpments. The landforms in the northeastern portion of the Southern Plateau were carved from volcanic rocks of basaltic and acidic compositions that belong to the Mesozoic Serra Geral Magmatism. The effusive rocks show the existence of vertical and horizontal joints which provide preferential drainage paths, both at the plateau and within the scarp. Continuous erosion of the plateau edge has produced steep and deeply dissected relief, with scenic canyons that gradually widen to alluvial surfaces and the coastal plain. Therefore, the formation of the present relief is associated with tectonic uplift of the Southern Plateau coupled with continuous fluvial erosion.

Keywords

Southern plateau • Volcanic rocks • Itaimbezinho canyon • Structural and lithological control • Alluvial fans

28.1 Introduction

The escarpment that follows the coast in the southeastern-southern regions of Brazil, between the states of Rio de Janeiro and Rio Grande do Sul, for an approximate distance of 1,100 km, is known as Serra do Mar (see Chap. 22). A portion of this escarpment, associated with the northeastern side of the plateau in the state of Rio Grande do Sul, between the municipalities of Osório and Torres, and the southeastern side of the plateau in the state of Santa Catarina, between the municipalities of Praia Grande and Morro Grande, has very unique characteristics with respect to its proximity to the Atlantic Ocean and the height that it reaches, which is in excess of 1,000 m above sea level (Fig. 28.1). This area, popularly known as "Região Serrana" ("Mountainous Region"), "Serra Geral" ("General Mountain Range"), or "Aparados da Serra" ("Mountain Range Trims"), is mainly characterized by the abrupt, vertical rock walls in volcanic rocks of the Serra Geral Formation of Paraná Magmatic Province, which occur in a succession of canyons of particular beauty. Furthermore, in a relationship that can be called symbiotic with the uniqueness of the relief, there are the geological history of millions of years and biodiversity of ecosystems that have gradually evolved and are enriched with endemic peculiarities. This escarpment of the Southern Plateau ("Planalto Meridional") in Rio Grande do Sul is separated from the Atlantic Ocean by a coastal plain approximately 13 km wide, where a series of wetlands and lakes are located; Itapeva and dos Quadros lakes are among the largest lakes, within only two to three meters above sea level (Fig. 28.2).

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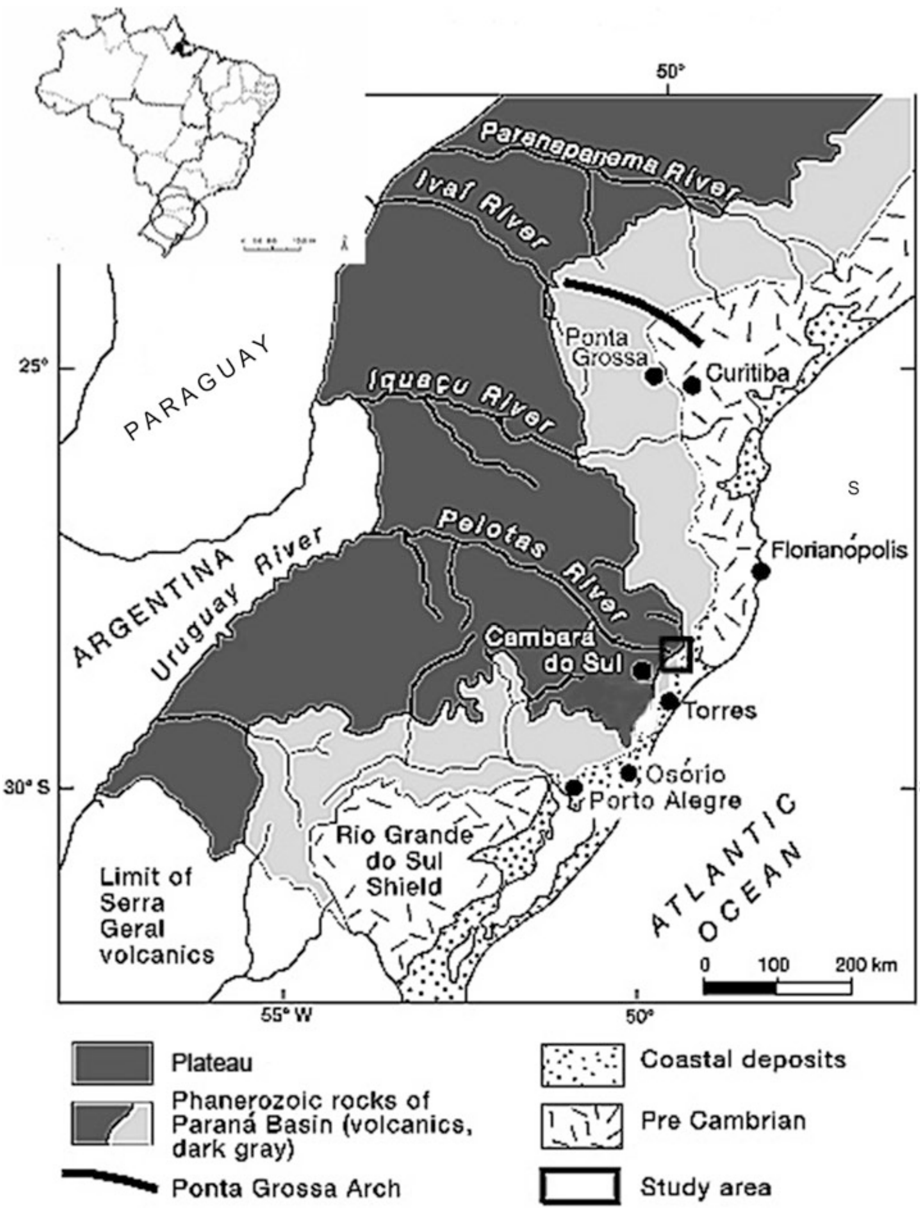

Fig. 28.1 The State of Rio Grande do Sul and Santa Catarina on the passive margin of South America. Regional setting, major structural features, and study area (Modified from Potter et al. May/2013)

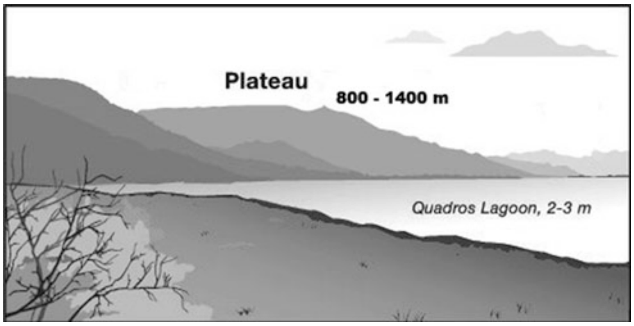

Fig. 28.2 The escarpment of the Southern Plateau (“Planalto Meridional”) in Rio Grande do Sul and the Quadros Lake (Modified from Potter et al. May/2013)

Between this portion of the escarpment and the Atlantic Ocean, five main rivers can be identified, whose waters descend from high altitudes (above 900 m a.s.l.) toward either the lakes or the sea. These are the Maquiné and Três Forquilhas rivers (Rio Grande do Sul State), the Mampituba River (Rio Grande do Sul and Santa Catarina states), and the Araranguá and Itoupava rivers (Santa Catarina State). These rivers run parallel to each other and can be considered short, if the distance between the sources (upstream) and the mouth (downstream) is taken into account, which is approximately 50 km. However, the importance of the volume of transported water and the ability to build extensive alluvial plains can be realized by considering the areas of the drainage basins (the

Maquiné river basin—422 km^2, the Três Forquilhas basin—512 km^2, the Mampituba river basin—1,224 km^2 and the Araranguá river basin—3,000 km^2), in addition to the large altitude difference between the sources and the mouths (approximately 900 m), and the annual rainfall of approximately 1,900 mm. Therefore, it is worth noting that the escarpment acts as a static element of considerable importance in controlling condensation of humid air masses coming from the Atlantic Ocean and the resulting precipitation. Rainfall tends to be higher in the northern portion of the coastal plain. The presence of the escarpment affects the wind regime by influencing circulation from both the sea and the continent.

Due to natural diversity of this portion of the Southern Plateau range, it is one of the most popular tourist destinations in the southern region of the country. Thus, the geological, geomorphological, and endemic characteristics of several elements of the local ecosystems led to the creation of two National Parks. The National Park of Aparados da Serra was created first, established in 1959, followed by the National Park of Serra Geral, established in 1992; both parks are managed by the Chico Mendes Institute of Biodiversity Conservation (Instituto Chico Mendes de Conservação da Biodiversidade—ICMBio).

The National Park of Aparados da Serra covers an area of 10,250 ha and contains the Itaimbezinho Canyon. It is located between the cities of Cambará do Sul and Praia Grande and is considered the most famous canyon, actually including a set of canyons therein. The Itaimbezinho Canyon extends for 5,800 m with a maximum width of 2,000 m, where the rocky walls rise up to a maximum of 720 m. They are covered by herbaceous vegetation and forest with Paraná pines (*Araucaria angustifólia*), which are symbolic of the Southern Plateau located in the Paraná Basin. The name of this canyon originated in the Tupi-Guarani language, where *Ita* means rock and *Ai'be* means sharp. The National Park of Serra Geral covers an area of approximately 17,300 ha and includes, among others, the spectacular Fortaleza canyon. Other canyons can also be highlighted in this portion of the Southern Plateau escarpment, including the Malacara, Churriado, Faxinalzinho, Josafaz, Índios Coroados, Molha Coco, Leão, Pés de Galinha, das Bonecas, and Macuco canyons (Fig. 28.3).

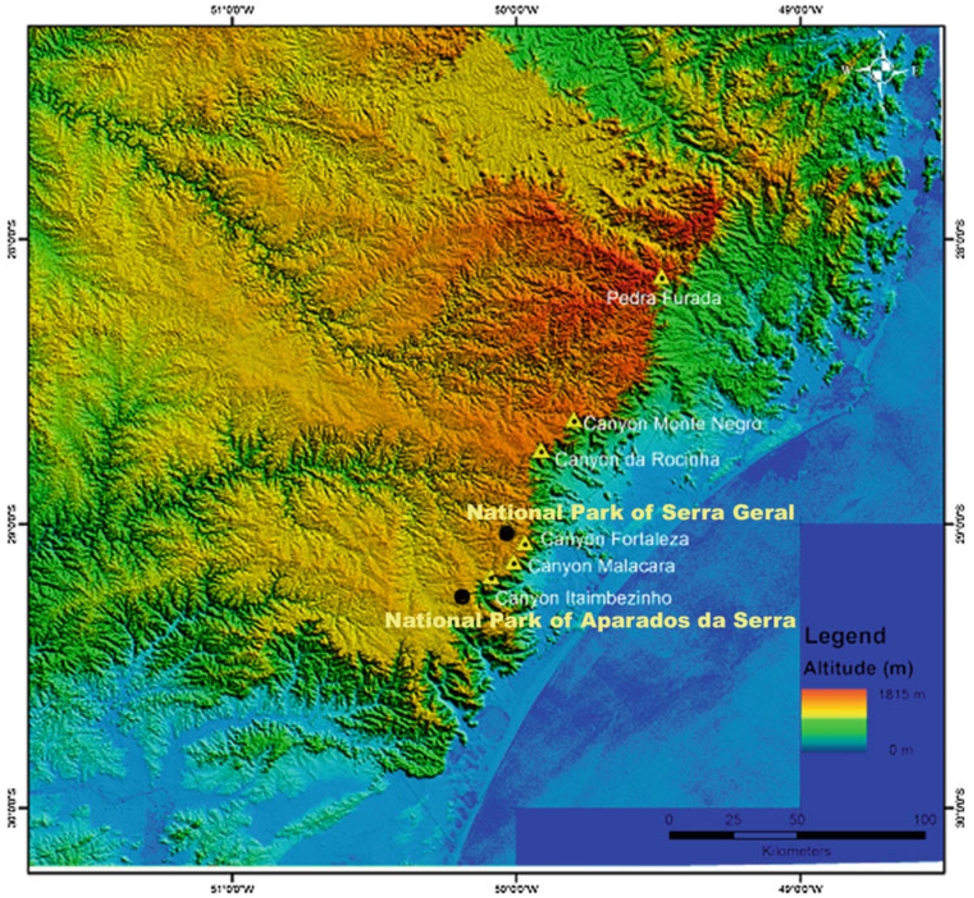

Fig. 28.3 The canyons of the Southern Plateau escarpment and the National Parks (By Luís Eduardo de S. Robaina, May/2013)

28.2 Highland Grasslands

Due to lithological differentiation, several types of geomorphological landscapes exist in the plateau. The difference between basic and acidic effusive rocks of the Serra Geral Formation corresponds largely to changes in the existing types of weathering effects, from relatively intact flatlands to areas where dissection focused along main drainage courses, allowed for the formation of a more fragmented relief.

The areas subject to limited geomorphic change correspond to the tops of relief units and are represented by planar surfaces that have usually developed in the areas of acid effusive rocks, regionally known as "Campos Gerais." In the areas where basic effusive rocks occur, relief characteristics almost invariably change, going from hills with a small elevation range that follows the drainage axes to a deeply dissected relief with deep valleys and terraces, such as that which occurs in the Itaimbezinho canyon. The highest elevations of the Araucárias Plateau occur in its eastern portion and exceed 1,200 m near the escarpment known as "Serra Geral."

For Wildner et al. (2004), the geomorphological context of the Itaimbezinho canyon is provided by the area historically known as "Aparados da Serra" ("trimmed from the range"). This name is derived from the remarkable geomorphological feature formed by abrupt truncation of volcanic rocks, which gives rise to vertical walls extending for approximately 250 km along the Atlantic coastal plain, between Rio Grande do Sul State and Santa Catarina State, in a succession of canyons that are up to 900 m deep. With these characteristics, the authors adopt the definition of this geomorphological unit as the Campos de Cima da Serra Plateau.

In this sense, it is worth mentioning that the name "Serra Geral" ("general mountain range") symbolizes a milestone of territorial occupation and transits between the current states of Rio Grande do Sul and Santa Catarina. That is, it represents a true orographic barrier between the south and southeast regions ("the mountain range"), which has been crossed by drovers transporting cattle from the south to the southeast since eighteenth century. Moreover, due to the non-ownership condition of the land and its common use by the few occupants within that historical period, it was informally known as the "campos gerais" ("general fields") of hilly relief at the top of the plateau, covered by typically herbaceous vegetation, which exists to this day and is associated with grazing.

Rückert (2006) analyzed the historical occupation process of these fields in the northeastern portion of the top of the plateau in Rio Grande do Sul and reported that, because of the isolation of the Rio Grande Province at the time, the fields were once considered "no man's land." However, the author emphasizes that considering the "Campos de Cima da Serra" ("above-the-range fields") as "no man's land" did not exactly correspond to reality. Although scarcely occupied, these fields were the home of native tribes, who originated there and either roamed or used the fields; these tribes were also referred to as missionary Indians. The cattle from the farms did not develop by spontaneous reproduction but were raised in these fields. Thus, southern Brazil was not a "no man's land" waiting to be occupied but the land of a native population that was subject to a violent process of ethnocide and genocide (Barcellos, Chagas, Fernandes et al. 2004, cited by Rückert 2006).

28.3 The Origin of the Paraná River Basin

The Paraná-Etendeka Basin, which is the geological designation of the structure within which the Itaimbezinho canyon lies, covers the entire central-eastern portion of South America, extending to northwestern Namibia in the west of the African continent. These areas were once part of a single continent called Gondwana, whose fragmentation began approximately 120 Ma ago during the Early Cretaceous, with the opening of the Atlantic Ocean. The rupture of this supercontinent represented the most violent tectonic phase in the history of the basin, accompanied by an expressive volcanic event that covered the central-south portion of South America and the northwest portion of Namibia with extensive lava flows, giving rise to one of the largest igneous province plateaus of the planet, the Paraná-Etendeka Province.

The Paraná basin, in the South American portion of this geological entity, is elongated in NNE–SSW direction, measuring approximately 1,750 km in length and extending through the Brazilian states of Mato Grosso do Sul, Minas Gerais, Goiás, São Paulo, Paraná, Santa Catarina, and Rio Grande do Sul. Its minor axis has a NW general direction and extends from Rio Grande do Sul State to the Chaco-Paraná basin in Argentina, through northern Uruguay and western Paraguay, reaching a maximum width of 1,200 km. The total area covers approximately 1,200,000 km^2 (Cordani and Valdoros 1967). The basin is home to a succession of rocks with ages between the Late Ordovician (approximately 450 Ma) and the Early Cretaceous (approximately 120 Ma). Its evolution can be understood in terms of four major events (Almeida 1981), each being characteristic of a complete tectono-sedimentary cycle (Sloss 1963). The former two cycles are related to sedimentation in a subsiding synform basin, and the latter two cycles correspond to phases of uplift and extrusion of large amounts of tholeiitic lavas due to crust swelling. Two-third of the Brazilian portion of the Paraná Basin, which measures approximately 730,000 km^2, is covered by eolian sandstones of the Botucatu Formation and lava flows of the Serra Geral Magmatism, which together form the Gondwana III supersequence (Milani 1997).

The volcanic sequence and its corresponding intrusive rocks, representing the last stage of the basin fill, were defined by White (1908) as the Serra Geral Formation. It is composed of a succession of flows reaching approximately 1,700 m in thickness at its depocenter, located in western Paraná State (Milani and Zálan 1998). This large volume of magma, estimated as 790,000 km^3 (Bellieni et al. 1984), was generated within a short-time interval between 137 and 127 Ma (Turner et al. 1994), and its origin is related to the mantle dynamics of the Tristão da Cunha plume (Morgan 1971; Richards et al. 1989; White and MaMcKenzie 1989; Ernst and Buchan 2001), although the characteristics of the plume are still debated (Marques et al. 1999; Comin-Chiaramonti et al. 2004).

The Serra Geral Magmatism is dominated by basalts and basaltic andesites of tholeiitic affiliation, which constitute approximately 95 % of these rocks; the remaining 5 % is formed by rhyolitic to rhyodacitic lavas that occur on the top and within the scarp of the Southern Plateau. Hence, magmatism is characterized by a bimodal lithological association (basalt–rhyolite) (Piccirillo and Melfi 1988). According to several authors (Bellieni et al. 1984; Mantovani et al. 1985), basic rocks can be divided into two groups based on their Ti content: high-Ti basalts have $TiO_2 > 2$ %, and low-Ti basalts contain TiO_2 contents lower than 2 %. Based on the abundance of major elements, trace elements and the ratios between the trace elements, these volcanic rocks were subdivided by Peate et al. (1992) and Peate (1997) into six magmatic groups. They were called Pitanga, Paranapanema, and Ribeira, which have Ti/Y ratios > 300 and occur predominantly in the northern portion of the province, and the Gramado, Esmeralda, and Urubici magmas, which have Ti/Y ratios < 300 and occur in the southern portion. The acidic volcanic rocks were divided by Bellieni et al. (1986) into two types: the Palmas type, concentrated in the southern portion of the Paraná Basin, with low contents of incompatible elements, and the Chapecó type, which is present in the north and center of the basin and is comparatively richer in TiO_2, P_2O_5, Zr, Ba, and Sr.

28.4 The Southern Plateau and Itaimbezinho Canyon: Geological and Geomorphological Context

Ab'Saber (2003) explains that the "Serra Geral" in northeastern Rio Grande do Sul State is a high edge of the Southern Plateau, which forms one of the most extraordinary landscape marvels of Atlantic Brazil, previously named as "Aparados da Serra." However, according to Ab'Saber (2003), this portion of the plateau is positioned as a part of the Serra do Mar sequence but, due to its geological composition, is completely different from the tropical forest scarps of Paraná, São Paulo, Rio de Janeiro, and Espírito Santo states. The landforms in the northeastern portion of the Southern Plateau in Rio Grande do Sul State were carved from volcanic rocks and were composed of a succession of rhyolitic rocks accompanied by interspersed basalts, in addition to diabase dikes. The acidic volcanic rocks are geographically located in the Palmas rhyolitic unit, according to the regional studies by Bellieni et al. (1986), Peate et al. (1992) and Milner et al. (1995).

The escarpments carved from the volcanic rocks have rock walls with an upper frontage toward the east. Short and deep canyons have developed within these escarpments, generating particularly exceptional geomorphological features. In the Rio Grande do Sul territory, the top of the plateau is characterized by smooth hills ("coxilhas") and shallow river valleys; additionally, this part of the relief is abruptly truncated by scarps, which lead to the coastal region and is incised by canyons, such as Itaimbezinho, Malacara, and Fortaleza. The relief in southeastern Santa Catarina State is accentuated by a sequence of escarpments and deep valleys, which cut into the edge of the plateau.

According to the studies by Justus et al. (1986) and Wildner et al. (2004), the area where the Itaimbezinho canyon lies corresponds to geomorphological features that were formed by the tectonic rupture of relief at the edge of the plateau along its eastern side. This escarpment is characterized by vertical walls of volcanic rock, where the headwaters of the watercourses of the coastal basins are located (the Mampituba basin, between Rio Grande do Sul and Santa Catarina states, and the Araranguá basin, in Santa Catarina State) (Fig. 28.4).

Because the effusive rocks show the existence of vertical and horizontal joints, the edge of the Southern Plateau consists of preferential drainage paths, both at the top and within the escarpment. The continuous fluvial erosion of this edge has gradually produced steep and deeply dissected relief. The structural and lithological control can be seen in the form of the valleys, which assume shapes of canyons that gradually widen to the alluvial and coastal plain. The erosive action is conditioned by the variable rainfall regime that is associated with subtropical climate, with annual averages around approximately 1,900 mm. The annual rainfall variability influences the formation and development of alluvial fans, which are anchored at the base of the escarpment. That is, the variation in the amount of water seems to be directly reflected in the formation and development of the alluvial fans throughout the recent geological history (Pontelli 2005).

The drainage network on the Atlantic side of the escarpment has developed under a strong influence of lithological diversity and geological structure of the volcanic sequence. The system of terraces descending from the top to the base of this plateau is notable. The presence of terraces is mainly conditioned by the number of lava flows and the

Fig. 28.4 The Itaimbezinho canyon representing a geomorphological feature that corresponds to a major disruption of the plateau escarpment (*Photo* Ricardo A. Ramos, June/2007)

lithological characteristics of each flow. Further, control on the drainage network is imposed by a system of tectonic lineaments that cut the entire structure, which focus the carving of “V-”shaped valleys, leading to the formation of scarps, canyons, and amphitheaters (Figs. 28.5, 28.6, and 28.7).

The fluvial factor is considered to interfere directly with the development of the vertical rock walls of the valleys, with the “V-”shaped slopes of triangular facets in addition to the consequent canyon development. The headwaters of the Perdizes River develop at the top of the plateau and descend across the rocky walls, thereby forming the Andorinhas falls.

Fig. 28.5 The “V-”shaped valleys resulting from tectonic control (*Photo* Ricardo A. Ramos, June/2007)

Fig. 28.6 The “V-”shaped valley of the Itaimbezinho canyon (*Photo* Bianca Carvalho Vieira, February/2014)

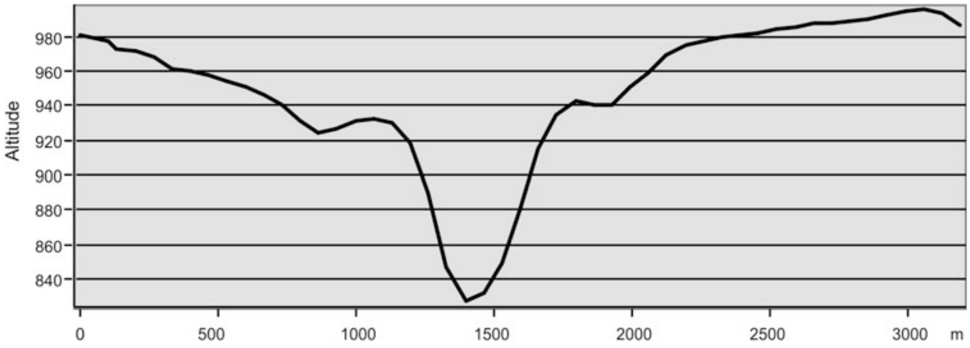

Fig. 28.7 The transverse profile of the Itaimbezinho canyon (From Luís Eduardo de S. Robaina, May/2013)

The Boi River drains into the bottom of the canyon, forming a series of waterfalls, which direct its waters to the border between the states of Rio Grande do Sul and Santa Catarina. The Itaimbezinho canyon is an excellent example of the influence of the regional tectonics on the morphology of these upright walls.

According to Wildner et al. (2004), the regional drainage follows three major directions, which are dictated by the course of faults and fractures.

(a) The first direction has a general 330°–310° pattern, following the direction of the Rio Grande (Rio Grande do Sul State), São Gabriel (Rio Grande do Sul State), and Ponta Grossa (Paraná State) arcs; the rivers and the main lineament of the Itaimbezinho canyon opening are positioned in this direction.
(b) The second direction roughly follows the coastal line in the Rio Grande do Sul State and is positioned between 10° and 30°, causing deep incisions that limit the Coastal Plain and the escarpments of the Southern Plateau.
(c) The third direction follows the 60°–70° lineament and is responsible for both carving of the Fortaleza canyon, located further north, and the Itaimbezinho canyon.

The study in the Cambará do Sul region (Rio Grande do Sul state) by Umann et al. (2001) revealed that the volcanic sequence is fractured, allowing three main lineament patterns to be observed. The first pattern, 340°, is expressed in two large regional structures. Regional lineaments of 20°–30° direction, measuring up to 50 km in length, are quite common. A lineament of the Itaimbezinho canyon exists in the municipality of Cambará do Sul. Smaller structures with 70° direction are common too and significantly affect the drainage network and relief forms.

Wildner et al. (2004) described the Itaimbezinho and Fortaleza canyons and identified a sequence of flows of acidic composition (rhyolites–rhyodacites) with perfectly tabular boundaries and thicknesses ranging between 15 and 55 m. The contact between the flows is enhanced by the presence of vesicular horizons at the top and a centimetric tabular disjunction at the base of each flow, which allows greater intake of water and the development of a more pronounced alteration profile. In turn, this allows for the development of denser shrub vegetation along the contact line and the presence of relief breaks, especially in the upper horizons between flows. The base of the canyon is situated at an intercalation of acidic and basic flows, going through a package that consists mainly of basalts belonging to the Gramado Facies. This compositional difference is also reflected in the geomorphological transition between the top of the plateau and the escarpment, where the basalts predominate, to the lower areas where the sedimentary rocks of the Botucatu Formation crop out, at elevations lower than 100 m.

The classical profile of the flows shows, from bottom to top, a dense and partially glassy zone that is relatively thin, followed by a zone of predominant horizontal diaclases that are equally thin, while the central and more voluminous portion shows columnar jointing. Another zone of horizontal diaclases overlaps, while the top of the flow appears significantly amygdaloidal, with vesicles whose density, frequency, and size vary with no defined pattern, reaching up to two meters in thickness. The contact areas show concentration of groundwater flow that promotes weathering and erosion processes, causing soil formation and generating the steps where vegetation emerges.

The plateau corresponds to the outlying projections of the escarpments isolated due to differential scarp retreat. It forms elongated and irregular interfluvial spurs that advance over the lower terrain in the middle and lower sections of the escarpment, the valley bottoms and especially in the areas near the Coastal Plain.

28.5 The Canyons, Valleys, and Alluvial Fans of the Southern Plateau

According to Schmiguel et al. (2009), the depositional system of alluvial fans is composed of a set of sedimentary facies, resulting from transportation processes associated with the hillsides of the Southern Plateau highlands. In its proximal portion, there are deposits resulting from gravity processes (rock falls, creep, and debris flows), which give way, in the distal sections, to alluvial deposits. Morphology of these fans, of essentially Holocene age, is attributed to the existence of points of sedimentary influx, favoring the coalescence of fans, and to the effects of reworking and subsequent erosion. This includes channel incision and marine and lagoon trimming, which affected the distal portions of the fans and occurred as a result of the relative sea level oscillation during the Quaternary. Over time, the intensity of these processes varied as a function of climatic variation and its implications with respect to rainfall rates and vegetation development.

The fans fed by rocks, which compose the Paraná Basin, occupy the inner part of the Coastal Plain along the slopes of the Southern Plateau. Due to the geomorphological characteristics of the source area and the composition of the volcanic and sedimentary rocks therein, the facies of the system are lithic and coarse in nature. Therefore, these characteristics indicate the predominance of subaerial gravity processes (rock falls, landslides, and debris flow) over subaqueous processes (alluvia) in the evolution of the fans.

In studying the Santa Catarina portion of the Southern Plateau scarp between the cities of Praia Grande and Timbé do Sul (Itoupava River—Araranguá River hydrographic basin), Pontelli (2005) identified the existence of alluvial fan deposits in the confined areas of the river valleys. These deposits are identified as being a part of the morphological sequence of the canyon sides, with rock walls in the upper slope sections and the aprons of slope deposits in the middle and lower sections. Interested in morphological, stratigraphic and soil characteristics of these alluvial fan deposits, Pontelli (2005) showed that their degree of alteration has a direct relationship with the position along the valley slopes. The analysis and mapping of these alluvial surfaces indicates that the fans are in fact a large alluvial apron that has developed by coalescence of many individual features.

With respect to the state of alteration of these deposits, the most altered deposits occur predominantly upstream, in the more confined sections of the valley heads, while the less altered deposits are located downstream. This spatial distribution of the deposits along the valleys indicates the down-valley development of alluvial aprons along the main channels draining the plateau and the escarpment.

From the temporal point of view, the hillslope and valley floor deposits were identified by Pontelli (2005) as Quaternary in age and ascribed to the middle and upper Pleistocene. Thus, two distinct stages may be recognized in the history of the alluvial fans: an aggradation stage followed by surface dissection. The former were associated with dry climate conditions (arid to semiarid), which occurred during the glacial periods of the Quaternary, with the oldest record related to the Middle Pleistocene. Dissection of fan surfaces occurred in climate conditions similar to the current ones, that is, in interglacial periods. At that time, the presence of a significant amount of water resulted in general incision of the drainage and entrenchment of fan surfaces, which continues today.

It is worth noting the relationship between the various compartments of the relief and the occurrence of certain soil units, as proposed by Dalmolin et al. (2004). Five main domains may be recognized, including the top, escarpment, terraces, slopes, and foothills. At the top, with a gently rolling relief and volcanic rock substrate, the soils are shallow, rarely exceeding one meter in depth, and stony. Within the escarpments, there are exposed rock walls and small ledges along the contacts between the flows where vegetation is present and shallow soils develop. In the terraces and slopes, formed on the base of the scarps by alluvial fans, the soils can vary from well developed to shallow ones, with a high content of large rock clasts. Finally, the foothill relief has deeper soils over a sedimentary rock substrate.

28.6 Conclusions

This area, popularly known as “Highlands,” “Serra Geral,” or “Aparados da Serra,” is characterized mainly by abrupt relief with vertical walls of rocks in a succession of canyons of particular beauty. Moreover, in a symbiotic relationship with this exceptional relief, there is the geologic history of millions of years and rich biodiversity, with many endemic species.

The geological history included generation of a sedimentary package at the base of the present-day plateau, followed by a sequence of volcanic flows that constitute the most striking manifestation of continental flood volcanism of the planet. Thus, the formation of the present relief seen as of exogenous origin is in fact coupled with the fragmentation of the Gondwanaland, which gave rise to significant tectonic uplift associated with the origin of major fault systems millions of years ago.

In addition, biodiversity characteristics place the Southern Plateau among the 220 areas of the planet which concentrate a large number of endemic species. However, some of them are threatened by extinction. In this sense, this portion of the Southern Plateau is considered a priority for conservation, maintenance of habitats, and ecological relationships between the different species. Hence, both the rich biodiversity of native grasslands and the Atlantic forest play a major ecological and socioeconomic role. Thus, the scenic beauty of this landscape, together with the sociocultural richness built throughout human occupation, empowers ecotourism activities, that together with scientific knowledge can be important tools for conservation of this place.

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‘Quadrilátero Ferrífero’: A Beautiful and Neglected Landscape Between the Gold and Iron Ore Reservoirs

29

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Abstract

Located in the central-south region of Brazil (State of Minas Gerais), ‘Quadrilátero Ferrífero’ is a region of immense historical, economic and cultural significance for Brazil. This region is also characterised by its beautiful mountain scenery and unique biodiversity, thus attributing their existence to a complex lithology and a rich geotectonic framework. Therefore, Quadrilátero Ferrífero is an excellent example of how lithostructure can create and scale a beautiful, rich and varied landscape, despite its location in a region of tropical and humid climate.

Keywords

Quadrilátero ferrífero • Differential erosion • Lithostructural control • Geosystems

29.1 A Region of Great Historical and Economic Significance

The ‘Quadrilátero Ferrífero’ (Iron Quadrangle) is located in the central portion of the State of Minas Gerais, Central-south Brazil, and it is a region of immense historical, cultural, economic and environmental significance. Indeed, the discovery of vast gold reservoirs in the Quadrilátero Ferrífero in late seventeenth century caused a huge migration from Portugal to Brazil. It also triggered the Brazilian inland expansion given that the entire small colonial population was previously concentrated on the coast. Opulent baroque cities emerged from this movement, and consequently, Brazil became urbanised and experienced a cultural and artistic awakening (Fig. 29.1). The economic significance of the Quadrilátero Ferrífero was so great during the eighteenth century that the capital of colonial Brazil was transferred from Salvador to the city of Rio de Janeiro because the latter was located nearest to this new economic hub. Moreover, the amount of gold explored was arguably so large that even the whole Portuguese colonial empire became economically dependent on mining conducted in the Quadrilátero Ferrífero. However, the reserves of gold inevitably decreased over the centuries, and in the twentieth century, gold mining gave way to iron ore mining and industries linked to this type of extraction, for example, steel mills. This exploration has been so intense that during most of the twentieth century, the Quadrilátero Ferrífero was largely responsible for Brazil being one the largest world producers of this type of ore. This production has increased exponentially in the beginning of the twenty-first century.

However, the Quadrilátero Ferrífero region is remarkable not just for its vast gold and iron reservoirs or for its significance in the history and culture of Brazil. Slightly forgotten and hidden behind these economic resources and the historical and cultural significance are beautiful mountainous landscapes. Such landscapes are characterised by steep slopes, numerous and beautiful waterfalls, enclosed valleys and high-biodiversity geosystems closely related complex lithostructure of the region.

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Fig. 29.1 Partial view of the baroque city of Ouro Preto in the Quadrilátero Ferrífero. *Photo* by authors

29.2 Geology

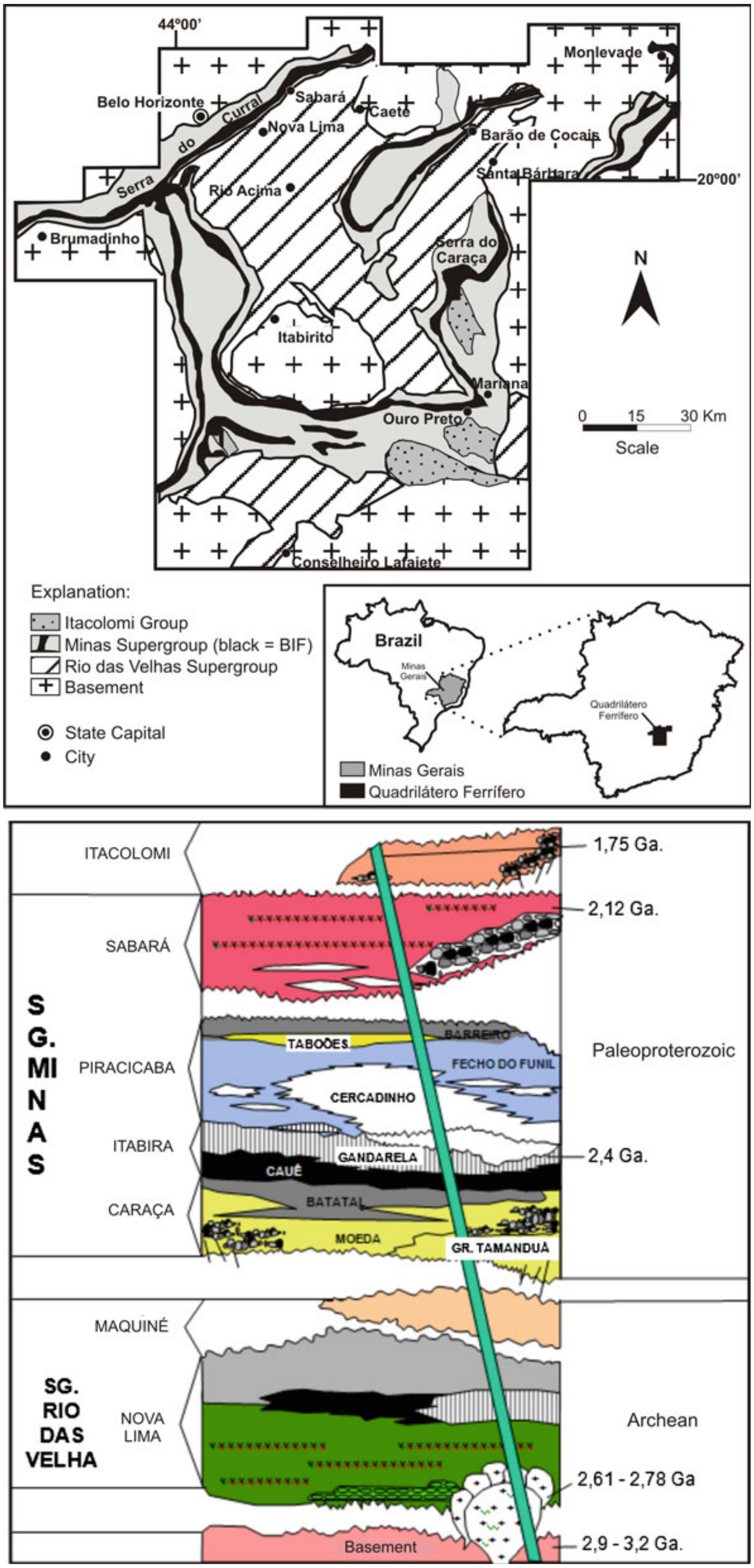
The Quadrilátero Ferrífero (Iron Quadrangle) has an area of approximately 7,200 km^2 and is located in the central-south portion of the State of Minas Gerais, near the southern edge of the São Francisco Craton (Fig. 29.2). The regional landscape is characterised by a rugged terrain with a close relationship to the complex lithostructural framework. The lithological substrate can be summarised as follows (Alkmin and Marshak 1998) (Fig. 29.2): (i) crystalline basement rocks, (ii) Rio das Velhas Supergroup, (iii) Minas Supergroup, and (iv) Itacolomi Group.

The basement corresponds to a metamorphic complex of Archaean crystalline rocks aged between 3.28 and 2.61 billion years (Machado and Carneiro 1992), which are shaped in the form of domal structures. These structures crop out mainly in the central-south portion of the Quadrilátero Ferrífero (Complexo do Bação [Bação Complex]). The basement is primarily composed of polydeformed gneissic–migmatitic rocks of tonalitic to granitic composition and, secondarily, by granite, granodiorite, amphibolite and ultramafic rocks.

A large sequence of rocks of volcanic and sedimentary origin (Fig. 29.2) formed through a continuous process of sedimentation that lasted approximately a billion years covers the crystalline basement. The base of this sequence is made by rocks of the Rio das Velhas Supergroup (Fig. 29.2). This supergroup consists of a greenstone belt-type volcano-sedimentary sequence with an approximate age between 2.7 and 2.6 billion years (Lobato et al. 2007). Its lithology consists of packages of komatites and basalts, rhyolitic lavas and sedimentary rocks. The basal unit of this supergroup is the Nova Lima Group that is mainly composed of schists and has a wide geographic range across the Quadrilátero Ferrífero. This group usually crops out at the bottom of eroded anticlines and is the main unit for the occurrence of gold deposits found in the Quadrilátero Ferrífero. However, in addition to schists of the Nova Lima Group, the sedimentary units of the Rio das Velhas Supergroup also include banded iron formations (BIFs), carbonate rocks and siliciclastic rocks. In contrast, the top of the Rio das Velhas Supergroup consists of the Maquiné Group which includes quartzites, conglomerates and phyllites (Vial et al. 2007).

The Minas Supergroup is superimposed on the Rio das Velhas Supergroup (Fig. 29.2). The Minas Supergroup constitutes a metasedimentary unit of the lower Proterozoic, with a discordant boundary on the Rio das Velhas Supergroup. The basal units of the Minas Supergroup—the Tamanduá and Caraça groups—have an alluvial origin and are composed of alluvial metaconglomerates and quartzites transitioning to pelitic marine sediments. The age of the base of the Minas Supergroup is approximately 2.65 billion years (Renger et al. 1994). It is noteworthy that the occurrence of

Fig. 29.2 Location and Geology of the Quadrilátero Ferrífero. Adapted from Alkmin and Marshak (1998)



gold is also sometimes linked to the Caraça Group (Vial et al. 2007). The Itabira Group, present above the Caraça Group, is 2.42 billion years old (Babinski et al. 1993) and composed of iron formations (Cauê Formation), whose roughly quadrangular cartographic distribution gave rise to the name of the Iron Quadrangle region and carbonate formations (Gandarela Formation). It is noteworthy that the iron ore fields of the Quadrilátero Ferrífero are found in the Cauê Formation. However, the Itabira Group is not the last unit of the Minas Supergroup. It is covered by the Piracicaba Group composed of terrigenous rocks from deltaic and continental environments intercalated with carbonate lenses (Alkmin and Marshak 1998). The most recent unit of the Minas Supergroup is the Sabará Group, which is basically composed of a sequence of turbidites, tuffs, volcanic clastic rocks, conglomerates and diamictite lenses, dated to 2.125 billion years (Machado et al. 1992).

Atop the stratigraphic column of the Quadrilátero Ferrífero, the Minas Supergroup is partially covered by the Itacolomi Group, which is approximately 2.1 billion years and is composed of quartzites and metaconglomerates. The entire Quadrilátero Ferrífero shows intrusive dykes of basic rocks, either outcropping or not, that are 1.714 billion years old (Silva et al. 1995) (Fig. 29.2). In certain regions of the Quadrilátero Ferrífero, notably in the Gandarela and Fonseca basins, there are sedimentary covers of Phanerozoic age.

The geotectonic framework is marked by two main compression events (Chemale et al. 1994; Alkmin and Marshak 1998; Cunningham et al. 1998): (i) the Trans-Amazonian event, between 2.2 and 2.0 billion years old and (ii) the Brasiliano event, between 630 and 520 million years old. The former had an approximate NW to SE trend, whereas the latter had an E to W trend. Consequently, the regional structural framework is marked by the existence of domes and large folds recognised as the "dome-and-keel" type, but at a more detailed scale, there are frequent occurrences of other structures, especially various types of folds, thrust faults and shear zones (Alkmin and Marshak 1998). These structures indicate a geotectonic shift from ESE to WNW, despite the variable direction. In this context, the most reliable geotectonic model for the Quadrilátero Ferrífero indicates that the dome-and-keel structure had been formed after sedimentation of the Minas Supergroup, approximately 2.1 billion years ago (Chemale et al. 1994), resulting from the Trans-Amazonian event (Alkmin and Marshak 1998). In contrast, at a more detailed scale, the visible structures originated during the Brasiliano event in the Proterozoic. It is noteworthy that these two events also favoured uplift of the whole region and allowed for the start of a long and continuous erosion process in the Quadrilátero Ferrífero.

29.3 Climate

The current climate can be defined as tropical semi-humid, with rainfall concentrated between October and March (spring and summer). The temperature and rainfall vary with altitude, which in the region ranges between 700 and 2,000 m above sea level. In the less elevated regions, the average annual temperature is 20.1 °C (Behling and Lichte 1997). These temperatures tend to decrease in the higher areas. In general, the amount of rainfall ranges between 1,024 and 1,744 mm per year. However, it can reach 2,000 mm annually in some regions of the eastern portion of the Quadrilátero Ferrífero.

Although the topic of regional paleoclimate has not been systematically studied in the Quadrilátero Ferrífero, palynological studies have allowed for the assertion that the region was drier and colder during most of the Pleistocene than it is currently and that the forest areas were reduced and largely replaced by grasslands (Behling 2002). Other than that, geomorphological evidence also indicates that the region experienced alternations between periods of wet and dry climates during the Tertiary (Barbosa and Rodrigues 1967; Barbosa 1980).

29.4 Relief Evolution

Given the high economic significance of the Quadrilátero Ferrífero, the relief of the region has been studied since the first study by Hader and Chamberlin in 1915. According to these authors, the regional landscape results from geological structure and differential erosion, wherein quartzites, itabirites (haematite schists) and the lateritic covers—cangas of iron—and aluminium (bauxites) associated with them are the substrate of the highlands; the schists and phyllites comprise the substrate of the middle lands; and the lowlands are moulded on the granite–gneisses (Figs. 29.3 and 29.4). Spatially, the highlands are a set of ridges and uplifted erosion surfaces, which have a roughly rectangular shape (Quadrilátero Ferrífero) and form the surroundings of the lowlands through which the Rio das Velhas (das Velhas river) river flows, at the base level of the Quadrilátero Ferrífero central region.

The existence of this lithostructural control is the main consensus point among the various geomorphological studies that sought to understand the evolution of the Quadrilátero Ferrífero landscape (James 1933; De Martone 1940; Freitas 1951; King 1956; Tricart 1961; Barbosa and Rodrigues 1967; Dorr 1969; Maxwell 1972; Barbosa 1980; Varajão 1991; Salgado et al. 2004, 2007a, b, 2008). This consensus also highlights slow but continuous tectonic uplift that the region underwent throughout geological time. In contrast, attempts to understand the genesis and evolution of relief show a wide variety of interpretations. The difference in interpretation occurs because the majority of the researchers who studied the landscape of this region (James 1933; King 1956; Barbosa and Rodrigues 1967; Dorr 1969; Maxwell 1972; Barbosa 1980) sought to identify the cycles

Fig. 29.3 Erosional escarpment of Serra do Caraça (Caraça Mountain Range). There is a noticeable height difference between Serra do Caraça peaks (2,000 m above sea level)—the eastern portion of the Quadrilátero Ferrífero—where quartzites are the substrate, and its surroundings, which are located on weaker lithologies comprising granite–gneisses (figure **a**: 950 m a.s.l.) and schists and phyllites substrates (figure **b**: 1,000 m a.s.l.). The waterfall in detail in the figure **b** is the Capivari waterfall. *Photographs* by authors

of uplift and planation by means of identification of different erosion surfaces using the altitude as a criterion. These erosion surfaces, when identified, were argued to be remnants of the periods of tectonic calm, and the escarpments between the different surfaces levels were interpreted to be the indirect evidence of tectonic uplift. However, the analyses were all subjective, and as proven by Varajão (1991), it is impossible to use altitude as an instrument to identify periods of tectonic calm or movement in the Quadrilátero Ferrífero. The difficulty of using altitude as a marker for tectonic instability arises because of the strong lithostructural control, which leads to significant differential erosion and the existence of different local base levels that control the formation of these erosion surfaces. Moreover, the number of erosion surfaces that each worker identified varied greatly according to their definition of an erosion surface. In this context, the latest studies on the evolution of the Quadrilátero Ferrífero terrain tend to focus on understanding how the lithology, structure and tectonics, including neotectonics, controlled the landscape evolution.

The clearest evidence of this lithostructural control is visible in the Quadrilátero Ferrífero major landform pattern. The two main tectonic events that affected the region left, in general terms, a folded terrain in the north/south direction—a legacy of the Trans-Amazonian event and in the east/west direction—a legacy of the Brasiliano event. However, subsequent to the folding, erosion favoured terrain inversion through removal of material from the anticlines whilst the synclines could have survived. Drainage system was installed along the axis of eroded anticlines, which favoured deepening and widening of the valleys. However, these valleys became further dissected at the anticline/syncline inflection point because the erosional forces excavated the tougher lithotypes, that is, the itabirites and quartzites. These lithotypes are resistant to erosion, as evident from the ^{10}Be cosmogenic isotope concentrations (Salgado et al. 2007b, 2008), up to ten times more than in other lithotypes found in the Quadrilátero Ferrífero (carbonate rocks, schist–phyllites and granite–gneisses). Thus, an erosional escarpment began to form in these points that marked the contact between (1)

Fig. 29.4 Aerial view of Serra da Piedade (Piedade mountain range) at the north end of Quadrilátero Ferrífero. There is a large erosional escarpment that marks the contact between the Serra da Piedade itself (substrate of quartzites, itabirite and canga) and its surroundings (schists and phyllites) at the *bottom* of the photograph and the granite–gneisses at the *top*. The eighteenth-century baroque church built on *top* of the mountain is highlighted. *Photograph* by Alice Okawara

the valleys that formed along the eroded anticlines where the rocks forming the base of the Quadrilátero Ferrífero stratigraphic column crop out and (2) the topographically suspended synclines where the youngest rocks crop out (Fig. 29.5).

The end result of this process is the formation of a terrain that can be divided into three compartments: (1) **highlands,** encompassing the portions of terrain protected from erosion by the tougher lithotypes, namely itabirites and quartzites, that underpin the escarpments; (2) **lowlands,** encompassing the valley floors that were preferentially developed along the eroded anticlines; and (3) **intermediate lands** that developed between the lowlands and the highlands and generally have schists and phyllites as a substrate and often have a morphology of steep erosional escarpments that can reach up to a 1,000 m of elevation.

Regarding the morphology, the highlands are similar in appearance to a group of erosional surfaces of limited extent, with variable altitudes intersected by escarpments and peaks that, at their highest points, exceed 2,000 m in altitude. In a study on the highland terrain evolution, also including itabirite and quartzite substrate, Salgado et al. (2007b) used ^{10}Be cosmogenic isotopes to demonstrate a large difference between the erosion rates in the escarpment areas, with rates between 12.71 and 14.60 m/Ma, and those on the erosion surfaces, with rates between 1.71 and 2.58 m/Ma. Therefore, the quartzite and itabirite escarpments are eroded much faster—approximately five to almost nine times as fast—than the erosional surfaces with the same substrate. Therefore, the highlands of Quadrilátero Ferrífero, although extremely resistant to downwearing, show a certain vulnerability to backwearing (slope retreat). This vulnerability is linked to the erosion of the weakest lithotypes, namely the schist–phyllites and granite–gneisses, that generally form the base of these escarpments, causing the collapse of the toughest overlapping lithotypes. Noteworthy, in this section of the terrain and associated to the banded iron formations, there are two sites selected by the Brazilian Commission of Geological and Paleobiological Sites (Comissão Brasileira dos Sítios Geológicos e Paleobiológicos—SIGEP) as

Fig. 29.5 **a, b** Typical landscape of suspended syncline of Gandarela. *Photographs* by authors

candidates to world heritage sites of UNESCO. One of the sites is located at the Moeda syncline and is called the Itabira Peak, representing the type locality where the German naturalist Wilhelm von Eschweg described the itabirite in the 1822. Itabirite is the designation of the predominant type of banded iron formation in Brazil (Rosiere et al. 2005). The other site is Serra da Piedade (Piedade Mountain Range), whose scientific significance is evident in the large itabirite outcrops (Cauê Formation) indicating the paleoatmospheric changes during the Archaean–Proterozoic transition (Ruchkys et al. 2005).

The lowlands are spatially almost entirely contained within the basin of Rio das Velhas, a river that drains the entire Quadrilátero Ferrífero's central area and is the main watercourse of the region. The morphology of these areas, especially in the regions with granite–gneisses as substrate, is a sequence of undulating "half-orange" slopes. These lands evolve by adjustment of the drainage system to the tectonic pulses and processes of sediment accumulation at the bottom of the valleys (Santos et al. 2009; Lana and Castro 2010; Magalhães et al. 2011, 2012). One of main characteristics of the neotectonic activity is the differential movement of various crustal blocks within the tectonic reactivation that has typified the entire region (Lipski 2002). Furthermore, during each tectonic pulse, the entire drainage system responded by excavating the terrain and deepening its valleys. In turn, valley deepening tends to increase the steepness of the slopes, which favours acceleration of erosion and, consequently, promotes a larger inflow of sediments towards the waterways. This sediment delivery is sometimes so intense that it eventually clutters the river channel itself, thereby limiting the continuous dissection of the terrain. Thus, the drainage system of the Quadrilátero Ferrífero lowlands has a complex system of terraces, in addition to a strong lithostructural control (Cherem et al. 2011), because although the general trend is for the waterways to erode the terrain, processes of sediment accumulation may occur simultaneously at the bottom of the valleys (Santos et al. 2009; Lana and Castro 2010; Magalhães et al. 2011, 2012).

One of the most interesting results of this process in the regional landscape was the occurrence of many large gullies in the region of Bação. Bação is located in the south of the Quadrilátero Ferrífero and is the main area in the region where the crystalline basement crops out (Fig. 29.2). The development of these gullies appears to be related to the erosion of long colluvial ramps that occupy the middle and lower portions of the slopes in this region, despite having its intensity increased by human action. Destabilisation and consequent erosion of these colluvial ramps occurs due to excavation of the drainage system caused by neotectonic pulses (Bacellar et al. 2005; Salgado et al. 2007a; Magalhães et al. 2012). Consequently, there was a large inflow of sediments towards the river valleys of Bação, which crammed the river channels of the region with sediments, despite the excavation of their riverbeds (Santos et al. 2009; Lana and Castro 2010; Magalhães et al. 2011). It is noteworthy that the drainage system response to these tectonic pulses is less visible in the highlands because the erosional escarpments resulting from the differential erosion form the local

Fig. 29.6 Capivari waterfall. This waterfall is approximately 50 m high and is one of several that mark the passage of the Capivari river through the erosional escarpment that indicates the contact between the highlands supported by quartzites and the intermediate lands/lowlands that have schist–phyllites as substrate. *Photograph* by authors

base levels that mitigate the terrain excavation along the waterways. Therefore, the most striking aspect of this landscape are the numerous and massive waterfalls (Figs. 29.6 and 29.7).

It should be emphasised that not all intermediate lands are, in the strict sense, escarpments that mark the transition between lowlands and highlands. Many portions of these areas are a sequence of slopes with medium/high declivity and schists and phyllites as substrate. In this case, this sequence of slopes tends to gain altitude as they are located closer to the erosion escarpments marking the transition to the highlands. This fact enables the contact between the highlands/lowlands or between the highlands/intermediate lands to occur in the form of large abrupt escarpments or a series of treads in the terrain.

The study of autochthonous soils all over the Quadrilátero Ferrífero, regardless of the lithotype on which they develop, indicated that such soils, despite the tropical and humid climate throughout the region, are young and immature and, therefore, indicate intense and constant surface erosion processes (Varajão et al. 2009). These processes, especially in areas that have schists, phyllites and granite–gneisses as substrates, seem to be related to the neotectonic activity that favoured, at least during the Quaternary, erosion stronger than the weathering.

29.5 Speleological Heritage and the Geosystems

The Quadrilátero Ferrífero contains carbonate rocks (Fig. 29.2). Nevertheless, the most notable karst landforms, mainly caves, develop in the iron formations, that is, on the ferruginous laterite crusts (termed cangas) and itabirites. Simmons (1963) highlighted that the high number of karst landforms, especially caves, is due to mechanical erosion processes. However, he argued that the largest caves of the region would have originated by dissolution processes that would occur within the iron formations. These dissolution caves could then have been developed or opened by

Fig. 29.7 **a** Sol waterfall (approximately 12 m high); **b** Santo Antônio waterfall (approximately 15 m high). Both waterfalls are in Prata River in Gandarela mountain range. *Photographs* by authors

mechanical erosive processes, but most of their development could still be attributed to the dissolution. These observations have been confirmed by the few studies that have examined this topic since then. Indeed, Piló and Auler (2005), Pereira (2012) found various evidences in iron ore-caves of the region, for example, speleothems, which indicate that such caves would have their genesis in the dissolution processes. It is noteworthy that although little studied and with smaller dimensions than those developed in the carbonate rocks, the iron ore caves are extremely common in the Quadrilátero Ferrífero. Indeed, hundreds of caves have already been catalogued, including the two largest (365 and 345 m) within any iron formation catalogued in Brazil and outside the Amazon. A rather different community of cave invertebrates are common at this speleological site compared to other sites that are developed on quartzite, carbonate or granite–gneiss lithotypes from eastern Brazil (Silva et al. 2011) because the region harbours a high number of rare species (troglobitic organisms), most yet unknown to the world; for example, specimens of the *Onychophora Phylum* were recently inventoried in some of the caves. The species belonging to this phylum are a group of invertebrates that have existed for over 500 million years and, hence, have substantial scientific significance; they are known as 'living fossils' (Monge-Nájera and Hou 1999).

There are also several caves that developed in quartzites in the Quadrilátero Ferrífero, particularly in the quartzitic massifs of Serra do Caraça. Three of the four caves with the steepest inclination found in Brazil are in this locality. These caves reach depths of 481 m and are up to 4,700 m long, making them among the world's deepest caves developed in this lithotype (Dutra et al. 2002).

Fig. 29.8 Typical physiognomy of the plants growing on cangas in the 'Serra do Gandarela' (Gandarela Mountain Range) region. *Photograph* by authors

Regarding the geosystems, there is usually a wide range of environmental conditions in the landscapes characterised by geomorphological heterogeneity, which favour a high diversity of ecological niches that, in turn, affect the distribution, abundance and diversity of the biota (Burnett et al. 1998; Stallins 2006). The connection between the geodiversity and biodiversity is remarkable in the Quadrilátero Ferrífero because the region is situated in the transition zone between two biomes, namely 'Mata Atlântica' or the Atlantic Forrest and 'Cerrado' or the Brazilian savannah. Both biomes have been designated as worldwide biodiversity hotspots (Myers et al. 2000). The large geological structures and the topographical contrasts affecting the local climate and the various types of substrates (outcrops and soils derived from the different lithotypes) create a mosaic of geoecosystems (sensu Huggett 1995) harbouring forest, savannah, grassland and rock communities that are often interconnected.

The forest formations predominate on the deeper soils (Latosols) or are linked to the complex drainage system. The most significant forest remnants are located in the eastern sector of the Quadrilátero, where the highest averages of annual rainfall are recorded (2,000 mm/year). Large-sized animals are found in these formations, including the largest neotropical land mammal, the tapir (*Tapirus terrestris* Linnaeus); the world's largest rodent, the capybara (*Hydrochoerus hydrochaeris* Linnaeus); the largest canid of South America, the maned wolf (*Chrysocyon brachyurus* Illiger); and the largest felines in the Americas, the jaguar (*Panthera onca* Linnaeus) and the cougar (*Puma concolor* Linnaeus) (Reis et al. 2011). The savannah and grassland formations develop predominantly on the extensive colluvial ramps developed on the flanks of large synclines and hogbacks, which have shallow soils (Cambisols and Neosols). The rock plants are found in large granite–gneiss, quartzite and itabirite rock massifs (Fig. 29.8). Cloud forests, which are communities characterised by the abundance of bryophytes (mosses), bromeliads and orchids covering the substrate and tree trunks, can be found at altitudes above 1,500 m (some massifs exceed altitudes of 2,000 m, for example, Serra do Caraça) and where the relative humidity is high, with frequent fogs.

The Iron geoecosystem is the most peculiar among those found in the Quadrilátero Ferrífero (Fig. 29.8). Formed by the cangas and lithotypes of the Itabira Group (Minas Supergroup), the Iron geoecosystem hosts biota characterised by a high degree of endemism and rarity. The extreme environmental conditions of cangas, such as substrates with high concentrations of metallic minerals and surface temperatures up to nearly 70 °C, an insular layout along the geological megastructures that may favour the process of genetic isolation between the populations of plants and invertebrates and the geological age of the terraces, probably contributed to the creation of evolutionary scenarios responsible for the uniqueness of the associated biota. This geoecosystem concentrates on dozens of endemic species of metallophilic plants and is one of the most significant plant diversity hubs in Brazil (Jacobi and Carmo 2012).

29.6 Conclusions

The Quadrilátero Ferrífero is a region of tremendous diversity and landscape beauty with an immense environmental richness. However, it is currently also one of the most environmentally threatened regions because of its vast reservoirs of iron ore and the high value this mineral has in the international market. The exploration of ore deposits is often responsible for the ‘decapitation’ of entire mountains, and few iron ore areas are protected inside Quadrilátero Ferrífero from this impending menace. The future of this region will be determined by the conflicting interests of large mining companies, state focus and political pressure from the environmental NGOs.

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Campos Gerais of Paraná: A Regional Palimpsest

30

Tiago Damas Martins, Claudinei Taborda da Silveira,
and Maria Lígia Cassol Pinto

Abstract
In the south-central region of the state of Paraná, there is a landscape known as Campos Gerais. Its genesis dates to the Pleistocene, when a colder and drier climate favored the emergence of grassland vegetation interspersed with *Araucaria* pine forests. The relief in this regional palimpsest, which is composed of rocks from the Paraná Sedimentary Basin, includes peculiar shapes of great scenic beauty, most notably the Vila Velha sandstones and sinkholes regionally known as Furnas. Mesozoic tectonic activity marked the landscape with intrusions of igneous rocks in the form of dikes and the uplifting of the eastern portion of the region, which resulted in a system of faults and fractures. Over time, these faults and fractures were transformed into canyons of widely varying sizes by the erosive action of rivers. The native vegetation, which was generally favorable to grazing, led to colonization of this landscape by non-indigenous peoples.

Keywords
Vila Velha • Furnas • Sandstones • Ruiniform

30.1 Introduction

The state of Paraná, located in southern Brazil, contains unique geomorphic and landscape features. The region known as Campos Gerais is characterized by a phytogeographic mosaic of grassland vegetation formations interspersed with zones of humid tropical and subtropical forests and an impressive ruiniform relief (Fig. 30.1).

The Campos Gerais landscape (Fig. 30.2) has been highlighted in the writings of travelers and researchers since the nineteenth century due to the curious nature of the landforms it contains and its great scenic beauty. For example, the following description was provided by the French anthropologist Lévi-Strauss (1996): “tread no farther when you come to the first of the uninhabited prairies, and to the great steamy codifar-forest.” Similarly, the French naturalist and traveler Auguste de Saint-Hilaire wrote about his trip through the region of Campos Gerais in 1820: “these fields are undeniably one of the most beautiful regions that I’ve travelled since arriving in the Americas” (Saint-Hilaire 1978).

The origin of this landscape was controversial among the first naturalists and researchers. Bigg-Whiter, the English engineer who travelled through the region in the second half of the nineteenth century, suggested poor soil quality as an explanation for the open grassland vegetation during a lecture at the Royal Geographical Society (Bigg-Whiter 1975). In the 1940s, researchers were still divided in their opinions. Some suggested that the grasslands were the legacy of fires

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World Geomorphological Landscapes, DOI 10.1007/978-94-017-8023-0_30,

Fig. 30.1 Ruiniform relief in Campos Gerais of Paraná. *Photograph* Tiago D. Martins

Fig. 30.2 Representation of Campos Gerais by Alfred Andersen (1860–1935). *Source* Secretaria De Estado da Cultura (2001)

set by indigenous peoples (Rawitscher 1942), while others implicated paleoclimatic conditions (Maack 1981).

Later, geoscientific studies showed that paleoclimatic drivers determined the composition of the grasslands, both floristically and in terms of shaping the underlying relief (Maack 1947, 1948, 1956; Bigarella 1964; Ab'Saber 2003; Bigarella et al. 2003). This region harbors an intricate set of geological and geomorphological features preserved in the landscape, similar to a palimpsest.

Ruiniform features in sandstones, especially those of Vila Velha, are unmistakable characteristics of the Campos Gerais landscape. The region also contains canyons that correspond to a system of faults and fractures in the underlying lithological groups, as well as a set of non-carbonate karst features related to the weathering of sandstone.

In addition to these superficial shapes and features, other geomorphological features have been created by underground erosion. The most notable among them are "Furnas," lakes, sinkholes, resurgences, and caves. Due to the occurrence of this assemblage of unique and unusually beautiful geomorphological sites, Campos Gerais has great potential for geological and geomorphological tourism.

30.2 Campos Gerais

With geological, geomorphological, and phytogeographical features that are unrivaled in other regions, the Campos Gerais landscape extends for 19,060 km^2 (Maack 1981) and is recognized regionally as an ancient landscape that is home to vegetation formations dating back to the Pleistocene (Maack 1981). The vegetation is characterized by low grasslands interspersed with *Araucaria* woodlands and gallery forests characterized as Mixed Ombrophilous Forest (Moro and Carmo 2007).

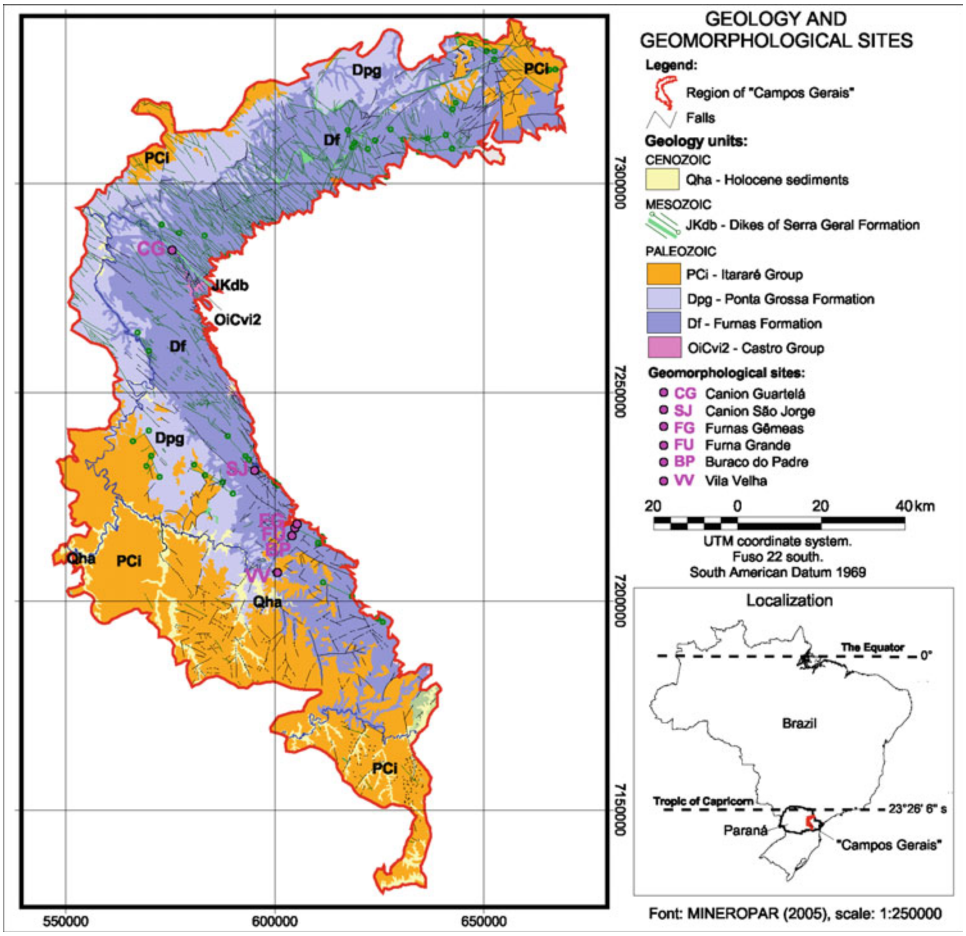
The regional substrate (Fig. 30.3) consists mostly of sedimentary rocks of the Paraná Sedimentary Basin from the Paraná and Itararé groups, which are of Paleozoic age. These rocks are cut by dike intrusions from the Serra Geral Formation that date back to the Mesozoic (Cretaceous period) and are overlain by unconsolidated Holocene sediments that are predominantly fluvial.

The Paleozoic assemblage known as the Paraná Group occurs as outcrops in the state of Paraná in the peripheral areas of the Paraná Sedimentary Basin. The base of the group is represented by the Furnas Formation, which consists of a succession of medium to large white quartz sandstones, kaolinitic clays, with the occurrence of whitish conglomerates. The Ponta Grossa Formation above is built of shales containing fine sandstone lenses with bedding indicative of wave reworking (Milani et al. 2007).

The Itararé Group comprises sediments deposited in a glacial environment between the Carboniferous and Permian and represents a very complex and varied assemblage. Three subunits have been recognized in this group: the Rio Sul Formation, which consists of shales and gray siltstones, fine to medium whitish sandstones, and diamictites; the Mafra Formation, with a lithology of fine to coarse whitish and yellowish sandstones, siltstones, and rhythmites; and the Campo do Tenente Formation, which consists of coarse reddish sandstones known as the Vila Velha sandstones, siltstones, rhythmites, and diamictites (Mineropar 2001).

The Arco de Ponta Grossa is a prominent lithology marked by the intrusion of diabase dikes. This network of structures oriented mostly in the NW–SE direction is related to the breaking up of Gondwana (Zalán et al. 1987) between the Jurassic and the Cretaceous, which caused uplift of the eastern portion of the regional plateau and the formation of prominent elevated areas known regionally as the Serra das Furnas and Piraí-do Sul Jaguariaíva. These features occur in

Fig. 30.3 Geology of Campos Gerais and major geomorphological sites



the compartment known regionally as the Second Paraná Plateau (Fig. 30.4). This name refers to the classical compartmentalization of the Paraná relief proposed by Reinhard Maack in 1947, which includes five large units of natural landscapes classified according to geological, geomorphological, pedogeological, and vegetation features.

The five compartments are called the coastal plain, the Serra do Mar, the First Paraná Plateau, the Second Paraná Plateau, and the Third Paraná Plateau (Fig. 30.4, Section A). In a recent study, Santos et al. (2006) redefined the compartments as morphosculptural units and identified a subunit of the Second Paraná Plateau that includes the ruiniform relief features and much of Campos Gerais. This subunit is called the Ponta Grossa Plateau (Fig. 30.4, Section B).

Another prominent aspect of relief in Campos Gerais is the network of canyons formed by the breaking up of the front of the escarpment in the shape of “percée” (carved valleys). One example is Guartelá Canyon, which contains the Iapó River (Fig. 30.5). In addition, some canyons are formed by rivers exploiting fracture zones, such as the São Jorge River Canyon, which has undergone a deepening of the thalweg and the development of dense forests (Fig. 30.6a). Additionally, on the front of the escarpment, there are monadnocks with flat hilltops, which are features that resulted from the long-term retreat of the plateau front (Fig. 30.6b).

Predominant soils in the region include Litholic Neosols, Humic Cambisols, Melanic Gleysols, and Haplic Organosols. These soils are characterized by a low degree of pedogenetic development due to high elevation, cloudy conditions, and mild temperatures in this area. Further back from the front, over the Ponta Grossa Formation, there is a predominance of deeper soils with greater pedogenetic evolution that are classified as red and red-yellow Oxisols. Behind the Ponta Grossa Formation, overlying the Itararé Group, the predominant soils are Haplic Cambisols and Regolitic and Litholic Neosols.

The physical–natural characteristics of Campos Gerais were also important for the occupation of the area by non-indigenous colonists in the middle of the eighteenth century. Prior to 1730, southern Paraná had a low population density, but the growth of animal trade between agricultural areas in the far south of the country and mining areas in the central region later favored the establishment of many villages (Nadalin 2001). This trade activity came to be known locally as “tropeirismo” and was part of an important economic system in southern Brazil (Furtado 1979) that became known as the Drovers’ Road or Viamão Path.

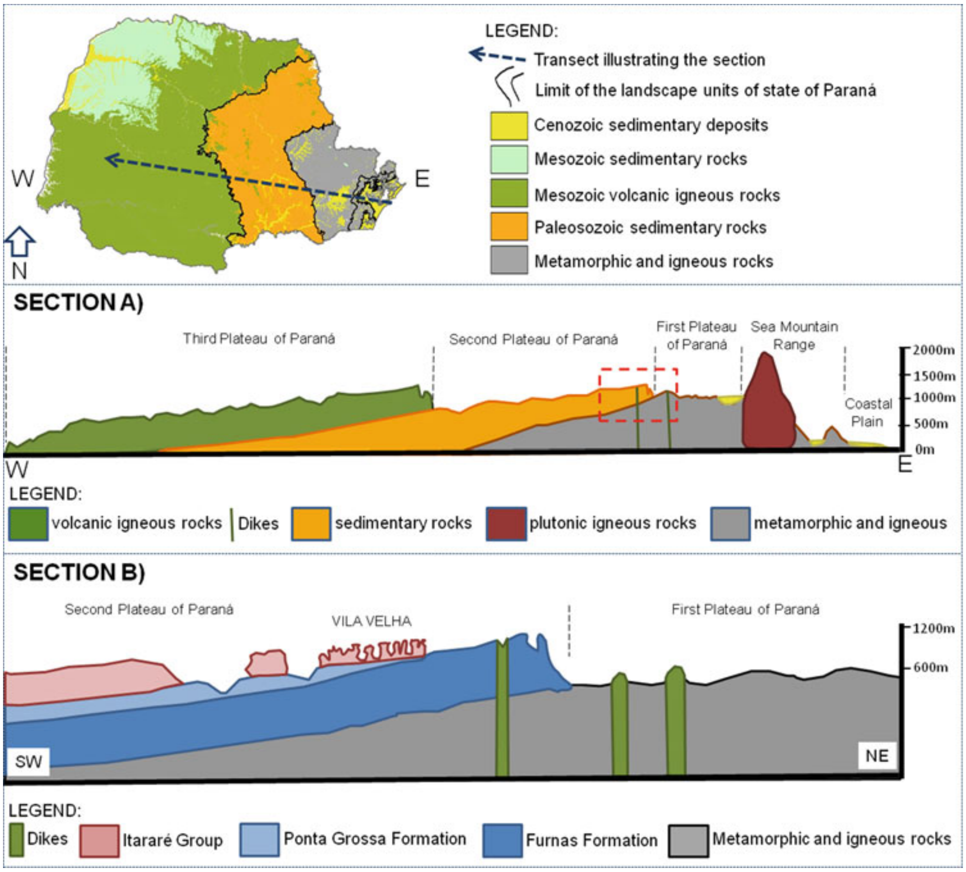


Fig. 30.4 Compartments of relief in the state of Paraná. *Section A* schematic east–west profile. *Section B* detail of the escarpment that borders the Second Plateau where the Campos Gerais landscape occurs showing the Vila Velha sandstones

Fig. 30.5 The Guartelá Canyon, a typical "percée" formed by the breaching of the escarpment that borders Campos Gerais by the Iapó river

Fig. 30.6 **a** Monadnocks formed by the erosive retreat of the plateau near the front of the escarpment. **b** São Jorge River Canyon. *Photographs* Tiago D. Martins

Within Paraná, the main stretch of the Drovers' Road passed through villages that later became some of the state's current municipalities, such as Palmeira, Ponta Grossa, and Tibagi. Tropeirismo, which had persisted since the eighteenth century and came to an end with the arrival of railroad transportation in the middle of the twentieth century. The Drovers' Road was gradually abandoned but remained known by the inhabitants of the cities it had created. In 1997, the Drovers' Road was restored for tourism. The main attractions were the route's historical and cultural significance and the nearby geomorphological sites (Piekarz and Liccardo 2007). In addition to the grassland vegetation and colonial architecture in the area, other attractions include the beautiful canyon landscapes at the headwaters of the Tibagi River, which extend to near the escarpment of the Fumas Formation (Martins and Bahl 2010).

30.3 Vila Velha and the "Furnas"

The extraordinary ruiniform features of the Vila Velha sandstones (Fig. 30.7) are today designated as a conservation unit (Vila Velha State Park) to protect the geomorphological site and the ecosystems associated with Campos Gerais. This unit was created in 1953 and covers 3,083 ha having on the Taça or "Cup," his most recognizable symbol reaching about 17 m high.

The Vila Velha sandstones, named by Maack (1946), include the Campo do Tenente Formation, whose most striking visual feature is its orange color. The sediments that formed this structure were deposited by gravitational flows at the base of glaciers dating to the end of the Carboniferous (Guimarães et al. 2007). Melo (2006) suggests that a combination of factors drove the development of the peculiar shapes in the Vila Velha sandstones. They may have resulted from the weathering of cemented compounds (iron oxide) combined with the brittle structure of the sandstone itself, such that percolating water eroded the rock from within.

Underlying the Campo do Tenente Formation are sandstones of the Furnas Formation, which consist of medium and coarse sandstones with cross-bedding that are of fluvial–marine deltaic origin and date from the end of the Silurian to the beginning of the Devonian (Guimarães et al. 2007). In this lithology have developed sinkholes, a set of unique landforms known regionally as "Furnas." Soares (1989) identified fourteen of these features in Campos Gerais and noted that they were similar in appearance to round craters. Some of them can reach over 70-m deep preserving *Araucaria* pine forest in its interior, and others can arrive at the underground water level exposing an inner lake. Among them, the sinkhole named Buraco do Padre with 40 m deep preserves a waterfall over 25 m high in its interior (Fig. 30.8).

In a pioneering study by Maack (1956), these features are described as karst phenomena that resulted from continuous water infiltration, breaking up of Furnas sandstone, and fluctuation of surface waters inside cavities in the rock. Melo et al. (2011) explained in detail how these features are a result of the specific petrographic properties of the sandstones, including soluble clay cementation and marked

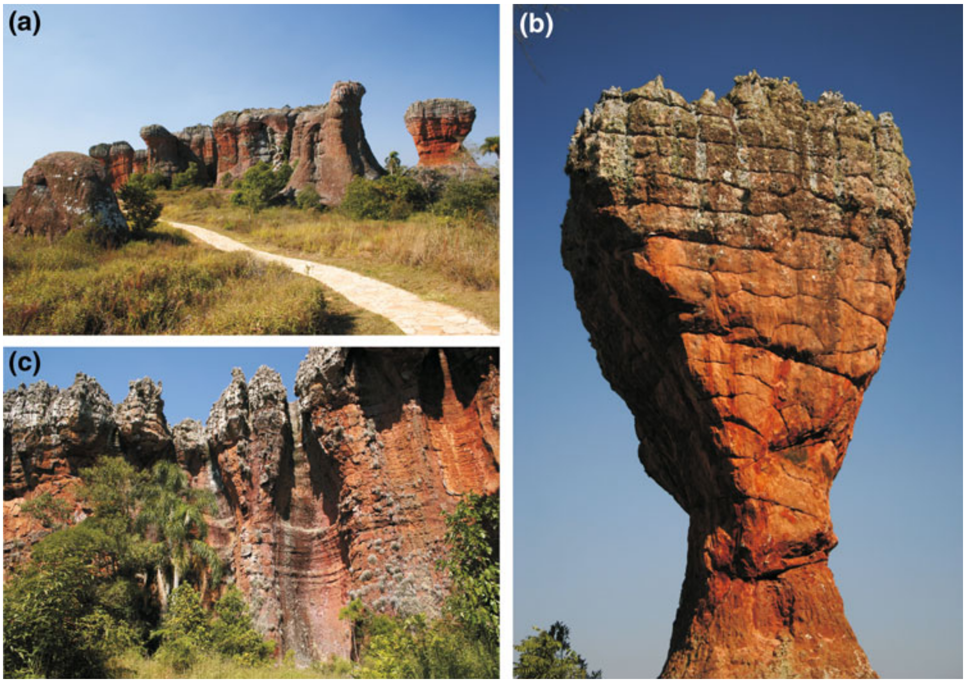


Fig. 30.7 **a** The sandstones of Vila Velha State Park. **b** The Taça or "Cup." **c** Ruiniform features resulting from sandstone erosion

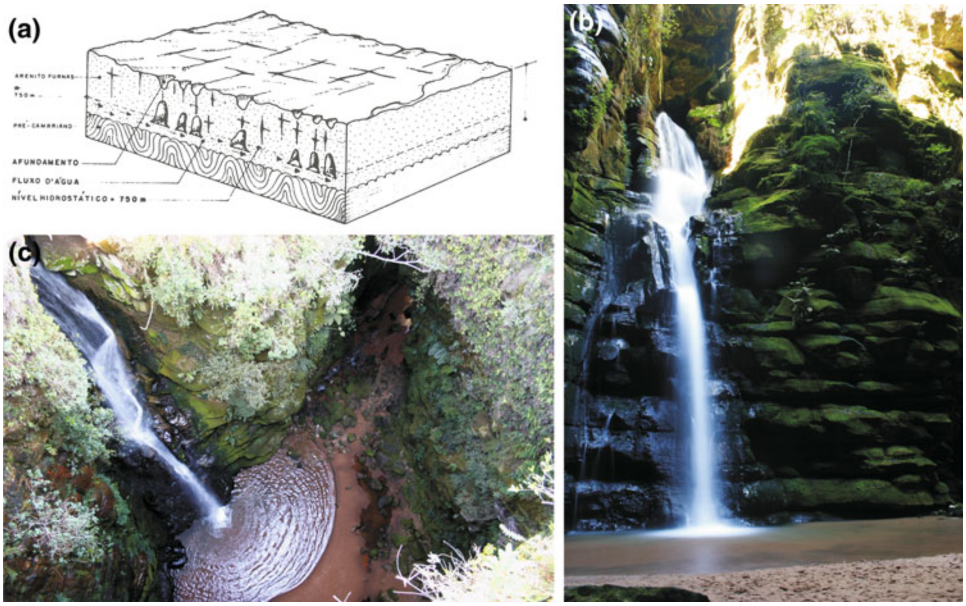


Fig. 30.8 **a** Block diagram showing the development of "Furnas" (Soares 1989). **b** Waterfall formed by the Quebra-Pedra River inside a Furna. **c** Buraco do Padre Furna. *Photographs* Tiago D. Martins

brittle deformation. Other factors involved in the weathering process include hydraulic gradient favoring the erosive action of water and a combination of mechanical erosion on the subsurface and chemical dissolution due to the relatively low-average porosity (9 %) of the rock and intense cementation by kaolinite (13 % on average) (Melo and Gianini 2007).

30.4 Final Considerations

A visit to Campos Gerais reveals the complex sum of processes that interacted to produce this landscape, which stands out in the region because of its geological context, peculiar phytogeography, and unique geomorphological sites such as the Vila Velha sandstones and the Furnas. The preserved geological elements in the region make it a landscape palimpsest.

The ruiniform features of the Vila Velha sandstones have resulted mainly from weathering of the rock. This phenomenon is linked to the solubility of the natural cement that forms the sandstones. The Furnas, which also reflect the process of weathering, are further influenced by the brittle structure of the sandstones, which were greatly disrupted by the intrusion of the igneous rocks known as the Arco de Ponta Grossa.

Another important aspect of Campos Gerais is the scenic beauty of the landscape, which impressed travelers and naturalists of the nineteenth century, and has been used to develop tourism projects around the natural and cultural heritage of the region. Thus, this study aimed to compile a variety of information about this unique landscape and highlight the studies that have helped to elucidate its various elements.

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Foz do Iguaçú: Geomorphological Context of the Iguaçú Falls

31

Marga Eliz Pontelli and Julio Cesar Paisani

Abstract

The city of Foz do Iguaçú is known for its cosmopolitan character and the beauty of the Iguaçú falls. These falls are located in the Iguaçú National Park, which was recognized as a World Natural Heritage Site by UNESCO. The origin of the Iguaçú Falls is associated with headward erosion of the Iguaçú River, which started approximately 1–1.5 million years ago from its confluence with the Paraná River canyon. The regional geomorphological context is provided by volcanic rocks of fissure origin; the geomorphic surface of the Missões Zone with superficial formations consisting of weathering profiles of volcanic flows; and alluvial, colluvial, and eolian deposits. The weathering profiles are predominant and indicate the action of etchplanation processes over the time in the evolution of regional relief in this subtropical region of South America.

Keywords

Basaltic plateau • Planation surface • Continental quaternary • Environmental changes

31.1 Introduction

The city of Foz do Iguaçú is located in southern Brazil, in a humid subtropical environment, and is recognized for its cosmopolitan character and the exuberance of its natural landscape. Located on the triple border junction of Brazil, Argentina, and Paraguay (Fig. 31.1), at 164 m above sea level, the city exhibits ethnic and cultural diversities resulting from the inclusion of more than 72 ethnic groups. Among the three countries, the city is considered a regional metropolis with a radius of 170 km and is one of the largest cities with a border population in Brazil (IBGE 2013). It was founded by workmen who have worked in the power plant of ITAIPU.

The city of Foz do Iguaçú has an area of 618 km^2, of which 138.60 km^2 are within the Iguaçú National Park (Parque Nacional do Iguaçú—PNI), which was created in 1939 and was recognized as a World Natural Heritage Site by UNESCO in 1986 (Salamuni et al. 2002; IBGE 2013). The PNI protects the largest remnant area of the Seasonal Semidecidual Forest in southern Brazil and the Mixed Ombrophilous Forest and Araucaria Forest (ICMBio-MMA 2013), which have been devastated by agricultural use since 1940s (Maack 1948). Therefore, the park has a rich genetic heritage of the Brazilian Atlantic Forest Biome. The area of more than 185,000 ha of the PNI harbors great biodiversity, as demonstrated by the number of cataloged species of fauna. As many as 257 butterfly species, 18 fish species, 12 amphibian species, 41 snake species, 8 lizard species, 340 bird species, and 45 mammal species are recorded (D'Oliveira et al. 2002).

In addition to its rich biodiversity, the PNI has one of the most spectacular waterfalls in the world, namely the Iguaçú Falls (Fig. 31.2). The significance of geological and geomorphological characteristics of the Iguaçú Falls allowed for its classification as a geomorphological site by the Brazilian Commission of Geological and Paleobiological Sites (Salamuni et al. 2002).

The origin of the Iguaçú Falls is associated with headward erosion of the Iguaçú River, which started approximately 1–1.5 million years ago from its confluence with the Paraná River canyon. The erosive action of the Iguaçú River

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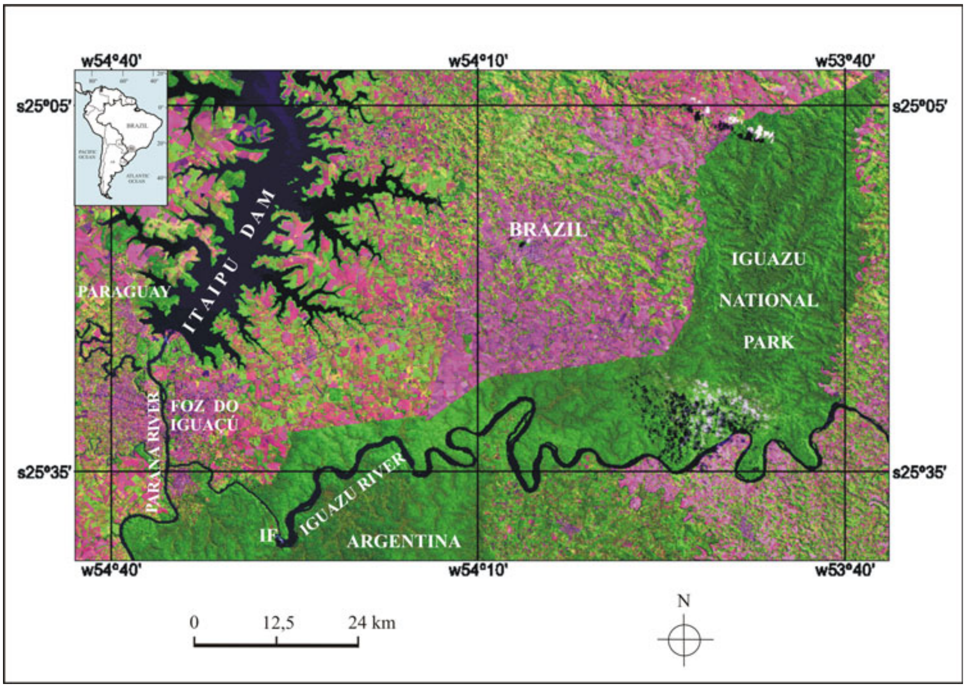


Fig. 31.1 Landsat image of the city of Foz do Iguaçú and the Iguaçú National Park

Fig. 31.2 Aerial view of the Iguaçú River, its falls, and the Iguaçú National Park

waters along faults and fractures in bedrock excavated a narrow canyon (Fig. 31.2) approximately 21 km long (Bartorelli 2004), approximately 80–90 m wide, and 70 m deep on average (MINEROPAR 2006). The current position of the falls in respect to the mouth of the Paraná River canyon allowed one to estimate the regression rate for between 1.4 and 2.1 cm year^{-1} (Bartorelli 2004).

The main waterfall of the Iguaçú Falls, known as Garganta do Diabo (Fig. 31.3), is approximately 80 m high. From this point, the Iguaçú Falls are distributed in a semicircle that is 2,700 m long, 800 m of which are within the Brazilian territory, with the remaining 1,900 m in Argentina (Fig. 11.3). Depending on water volume from the Iguaçú River, the number of individual falls varies from 160 to 200.

Fig. 31.3 Aerial view of Garganta do Diabo – Iguaçú Falls

The average annual discharge of the Iguaçú River recorded in the falls is approximately 1,500 $m^3\ s^{-1}$, ranging from approximately 500 $m^3\ s^{-1}$ during drought periods to close to 8,500 $m^3\ s^{-1}$ in flood conditions. The maximum discharge recorded in history was approximately 35,600 $m^3\ s^{-1}$, and the months of spring and summer are the periods of the largest water volumes annually recorded (MINEROPAR 2006; Stevaux and Latrubesse 2010). Because of this feature, the Tupi-Guarani native Indians, who inhabited this region before the European colonization that started in the sixteenth century, named this river "water" (ig) "large" (assu) (D'Oliveira et al. 2002).

The genesis and evolution characteristics of the Iguaçú Falls have already been addressed by Stevaux and Latrubesse (2010). However, the regional geomorphological context of the Iguaçú Falls is still relatively unknown. Thus, in this chapter, we present the regional geomorphological story of the Iguaçú Falls, which is one of the most important parks in Brazil and is recognized as a World Natural Heritage Site by UNESCO.

31.2 Geological Context

The basaltic bedrock that supports the Iguaçú Falls is of volcanic fissure origin and originated in the Cretaceous, between 135 and 120 Ma (Rocha-Campos et al. 1988). At that time, extensive flood basalts covered the Paraná Sedimentary Basin. The Paraná intracratonic basin transcends the political and administrative boundaries of South America, covering an area of approximately 1,600,000 km^2 (Melfi et al. 1988) which is shared by Brazil, Paraguay, Argentina, and Uruguay (Fig. 31.4).

Approximately, 75 % of the total area of the Paraná Basin ($\sim$1,200,000 km^2) was covered by lava flows during the Gondwana separation and subsequent opening of the South Atlantic Ocean. This process originated the Paraná Magmatic Province, which is one of the world's largest concentrations of continental basaltic lavas. Intrusive magmatism occurred along with volcanism, resulting in the concentration of dykes, the most important of which occur in the Ponta Grossa Arch region (Fig. 31.4) and run in the NW–SE direction (Melfi et al. 1988; Marques and Ernesto 2004).

The volcanic package of this province is formed by successive lava flows, which are collectively called the Serra Geral Formation. The thickness of this package is variable, with the maximum recorded in Brazil of 2,000 m, in the region of Pontal do Paranapanema, state of São Paulo (Milani 2004), in the central portion of the basin and along the axis of the Paraná River trough (Fig. 31.4). The average thickness of the magmatic package in the state of Paraná is between 450 and 600 m (Maack 1947), with a maximum of 1,460 m thus far, in southeastern Paraná (Paisani et al. 2008a).

Approximately, 90 % of the rocks from the Serra Geral Formation consist of tholeiitic basalts and tholeiitic andesibasalts, with two pyroxenes (augite and pigeonite). Approximately 7 % are tholeiitic andesites and 3 % are rhyodacites and rhyolites. In general, acidic rocks are

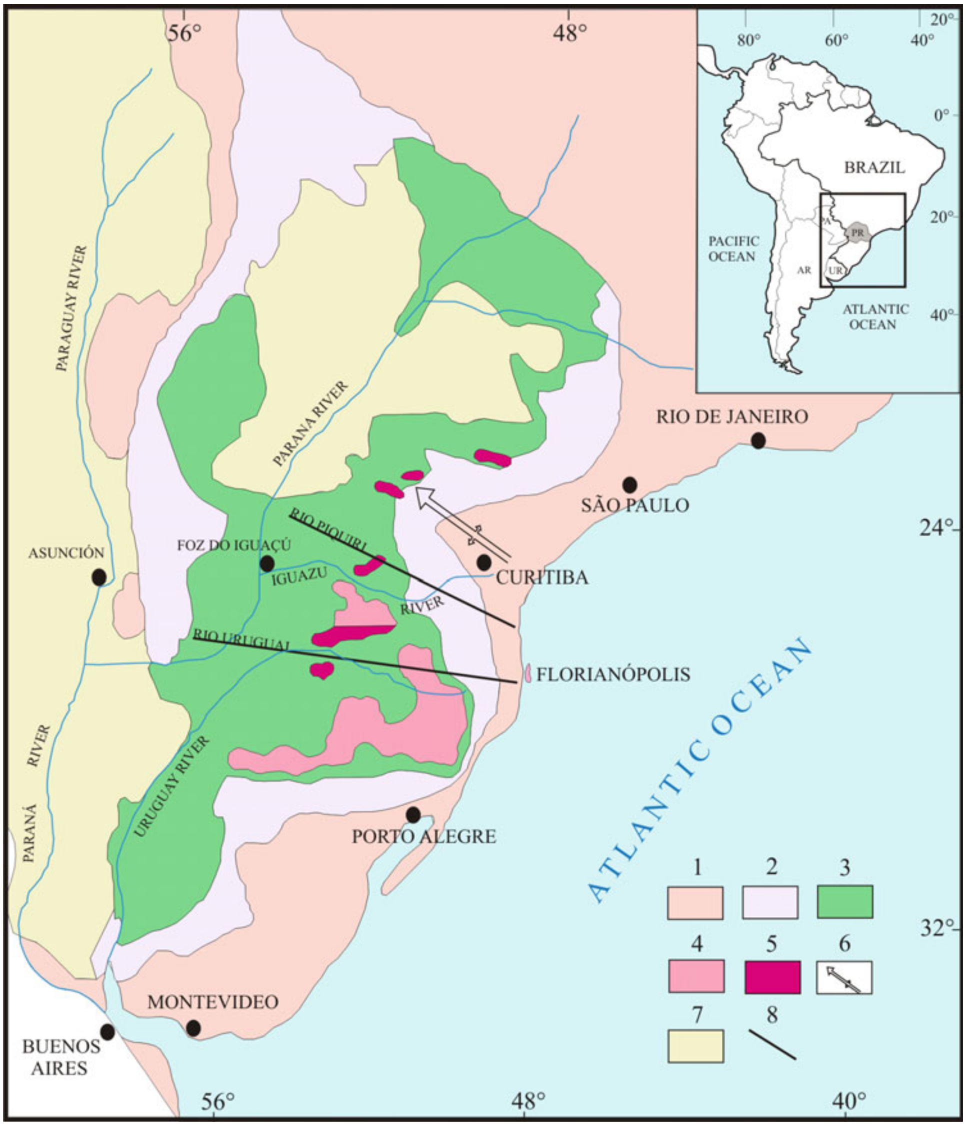


Fig. 31.4 Geology of the Paraná Basin (modified from Marques and Ernesto 2004): (*1*) crystalline basement; (*2*) pre-volcanic sediments, mostly Paleozoic; Paraná Magmatic Province: (*3*) basic to intermediate volcanic rocks; (*4*) acidic volcanic rocks of the Palmas type; (*5*) acidic volcanic rocks of the Chapecó type; (*6*) dyke swarms; (*7*) post-volcanic sediments, mainly upper Cretaceous; (*8*) tectonic lineaments

concentrated in the most superficial parts of the magmatic package and near the continental margin (Melfi et al. 1988; Marques and Ernesto 2004). This thick package of magmatic rocks supports the regional geomorphological structure that is known as the Basalt Plateau of the Paraná Basin (Almeida 1956).

31.3 Geomorphological Units of the Basalt Plateau

In Brazil, the Basalt Plateau of the Paraná Basin is subdivided into 4 smaller geomorphic units (Fig. 31.5), herein designated as morphosculptural units: (1) the Alto Paraná Basin, referring to the upper Paraná River; (2) the Araucárias Plateau because of the extensive cover of the Araucária Forest in southern Brazil up to the 1940s (Maack 1948); (3) the Missões Zone, a geomorphic surface between the Paraná and Uruguai Rivers in the "Provincia de Misiones" (Argentina); and (4) "Cuesta" of Haedo, a local designation for a system of cuestas that starts in the extreme south-western Rio Grande do Sul (Brazil) and extends to the Uruguai river valley (Almeida 1956). All these units are heavily dissected by major regional hydrographic systems.

Foz do Iguaçú integrates the north section of the Missões Zone (Fig. 31.5), which has a poorly dissected surface between 120 and 540 m a.s.l. with mesas with slightly convex tops, convex slopes, and V-shaped valleys (Santos et al. 2009). On a regional scale, the top of the mesas rarely coincides with the flow boundaries (Fig. 31.6). The same phenomenon does not occur in areas under direct influence of fluvial erosion, which registers waterfall unevenness from

Fig. 31.5 City of Foz do Iguaçú in the morphosculptural context of southern Brazil (adapted from Almeida 1956)

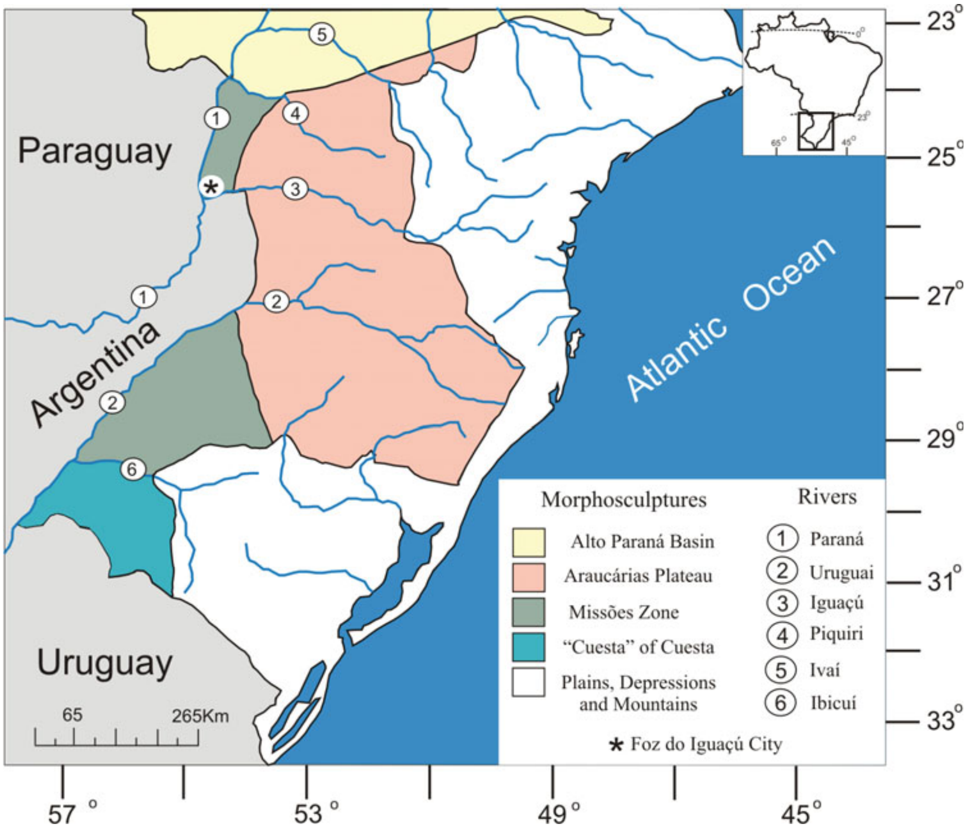
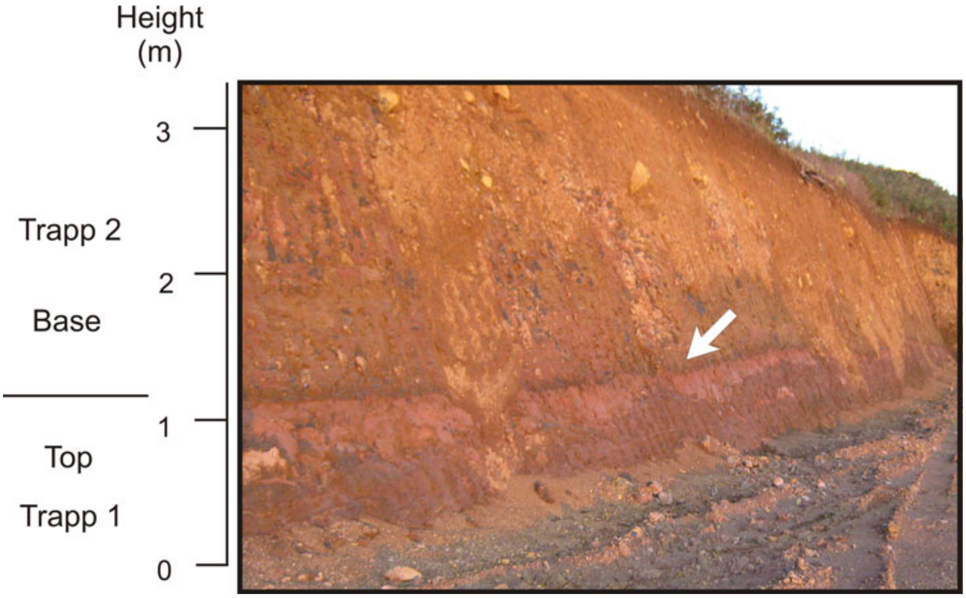


Fig. 31.6 Weathering profile transgressing the boundaries (*arrow*) between 2 flows in residual relief on the Araucárias Plateau



the Iguaçú and Uruguai Rivers and abutments in the valley bottoms of their main tributaries that are established in lava flow boundaries (Maack 1947; Bartorelli 2004; Stevaux and Latrubesse 2010; Guerra and Paisani 2010).

The Missões Zone has boundaries with the Alto Paraná Basin to the north, exactly where the Sete Quedas waterfalls of the Paraná River were located (24° Lat) (Fig. 31.1), but are now submerged by the ITAIPU Dam lake (Stevaux and Latrubesse 2010). The boundary with the Araucárias Plateau to the east of the Missões Zone is marked by a remnant of the planar surface called the Bernardo de Irigoyen Surface (Iriondo and Kröhling 2008), which is located at approximately 800 m a.s.l. (54° Long.).

The Missões Zone relief is characterized by remnants of planar surfaces organized in a staircase pattern, with the lowest altitudes near the plains of the Paraná and Uruguai Rivers (Kröhling et al. 2011). This organization pattern is maintained at the Araucárias Plateau, which gains altitude to the east until reaching the edge of the Basalt Plateau (Fig. 31.5), where residual landforms (mesas) are found above 1,300 m a.s.l. These planation surfaces have a complex evolutionary history which involves both neotectonics and surface geomorphic processes (chemical and mechanical) during the Quaternary (Popolizio 1972; Iriondo and Kröhling 2004; Paisani et al. 2008b, 2012a).

31.4 Superficial Formations: Records of Chemical and Physical Processes

The superficial formations within the morphosculptural units of the Basalt Plateau include weathering profiles of the volcanic flows as well as alluvial, colluvial, and eolian deposits. The weathering profiles result from pedogeochemical processes that are associated with hydrolytic conditions. Sialitization processes are predominant (Melfi and Pedro 1977), in which mono-sialitization is usually recorded in weathering profiles beneath the remnants of planation surfaces, while bi-sialitization is recorded beneath the remnants of dissected planed surfaces (Ker 1998). However, in the summit surfaces of the Araucárias Plateau, the allitization process is recorded under acidic flows (Clemente and Azevedo 2007). Within the remnants of planar surfaces in this geomorphic unit, as well as in the Misiones Zone, certain weathering profiles have been subjected to two hydrolysis phases, namely mono-sialitization and allitization. These profiles are interpreted as polygenetic due to climatic variations during the late Quaternary (Kämpf and Klamt 1978; Morrás et al. 2009) and indicate the action of etchplanation processes over the time in the evolution of regional relief (Paisani et al. 2013). From the edaphic perspective, the weathering profiles of this geomorphic unit are in the Oxisol class (Bhering and Santos 2008).

The alluvial deposits are more expressive along the Paraná and Uruguai Rivers, attesting to the strong dissection of the Araucárias Plateau and Missões Zone during the Cenozoic (Stevaux 1994; Iriondo and Kröhling 2008). Drainage basins of low hierarchical order sometimes exhibit flat-bottomed valleys with sediment retention and buried paleosols (Paisani et al. 2014). Colluvial deposits are found on the slopes located on the margins of valley bottom abutments (Paisani and Geremia 2010) and cluttering paleovalleys of low hierarchical order, especially near the summit surface of the Araucárias Plateau (Paisani et al. 2012a) (Fig. 31.7).

Eolian sediments are found in the Alto Paraná Basin morphosculptural unit and correspond to the Caiuá Group from the Upper Cretaceous (Fernandes and Coimbra 1994). Moreover, it is believed that reworked loess (clayey loam to loamy clay) from the Pampeano Aeolian System of central Argentina (Kröhling 1999) covered the Misiones Zone and a part of the Araucárias Plateau and Late Argentina, southeastern Paraguay and south Brazil, between the Upper Pleistocene and the Holocene (Oberá Formation, Iriondo and Kröhling 2004). This fact would indicate a record of loess in an area near the Tropic of Capricorn (Iriondo and Kröhling 2007). However, the sedimentological characteristics of the material interpreted as loess are similar to the weathering products of basalt, which has generated a debate regarding the genesis of the Missões Zone soils (Morrás et al. 2009; Kröhling and Iriondo 2010). Micromorphological analysis has yielded results that allow one to differentiate between allochthonous and autochthonous formations in the region (Paisani and Pontelli 2012) and that might help to elucidate this issue. There is a contribution of dust from the volcanic eruptions of the Andes, although in smaller quantities and

Fig. 31.7 Filled paleochannel of second hierarchical order in the Araucárias Plateau. (*1*) Alluvial conglomerate. (*2*) Cgb—buried hydromorphic horizon and (*3*) Ab—humic horizon of alluvial paleosol. (*4*) organo-mineral alluvium colluvium

frequency (Iriondo and Kröhling 2004). In fact, sedimentation of a few millimeters of dust was recorded in June 2011 in southern Brazil from the eruption of the Puyehue volcano, located 870 km south of Santiago, Chile. Loess sedimentation is observed as proxy data of paleoclimatic changes that occurred during the Late Quaternary in central Argentina, southeastern Paraguay, and southern Brazil (Iriondo and Kröhling 2007).

31.5 Record of Climate Changes in the Missões Zone and Araucárias Plateau

The Missões Zone and Araucárias Plateau are located in the South America subtropical environment (Fig. 31.5). This region is strongly influenced by the Mobile Polar Anticyclone from Antarctica, which is responsible for the disturbing humid and unstable system that is called a cold front (Monteiro 1963). This system has a greater effect during winter in southern Brazil, when hot air masses coming from central Argentina (dry) and the Amazon (humid) lose strength. The only hot air mass that continues to operate throughout the year is the warm and humid mass from the Atlantic, which can extend throughout the Basalt Plateau in southern Brazil during winter (Sant'Anna Neto and Nery 2005).

This climate scenario is responsible for the maintenance of three types of plant formations in these geomorphic units: (1) the Seasonal Semidecidual Forest, which is allocated along the main river valleys, usually in elevations lower than 600 m a.s.l.; (2) the mixed ombrophilous forest with Araucária Forest, which is characterized by the mixture of tropical and temperate flora; and (3) fields (savannas—Maack 1948) consisting of grasses and shrubs, which are distributed as islands in elevations above 1,000 m a.s.l. (Leite and Klein 1990). The main factor responsible for the current concomitant presence of these three vegetation formations is the thermal gradient imposed by the differences in altitude. However, it is believed that variations in the hydric regime, which are associated with temperature changes, were responsible for the vegetation exchanges between the field and forest during the Late Quaternary (Maack 1948).

The savanna vegetation reflects a drier and colder period, while the forest vegetation corresponds to a hotter and damper phase. At certain times, these vegetation replacements were in phase with the erosive/depositional or pedogenic processes. Multi-proxy geochemical analysis of sediments and paleosols in the Missões Zone reveals two humid phases with pedogenesis (~>40 Ky BP and ~20–11 Ky BP), interspersed with a dry phase that was associated with an erosive/depositional hiatus, and another humid depositional phase (≤10 Ky BP) (Zech et al. 2009). These humid phases were responsible for the predominance of pedogenesis in the slopes and valley bottoms of low hierarchical order on surface II of the central-northern Araucárias Plateau (Paisani et al. 2012a). Isotope carbon data and analysis of the silica phytoliths reveal that the savanna vegetation was present in this location during this period (Paisani et al. 2012b), suggesting that the vegetation response to climate change does not always coincide with the replacement of erosive/depositional processes for pedogenetic processes in the rest of the Basalt Plateau in southern Brazil.

31.6 Synthesis

Foz do Iguaçú is known worldwide for the beauty of the Iguaçú River waterfalls in the PNI. However, significantly less is known about the regional geomorphological setting of the PNI. The following brief remarks on this subject should be highlighted:

1. The Iguaçú Falls is composed of volcanic rocks that covered the Paraná Sedimentary Basin in the Cretaceous.
2. Foz do Iguaçú integrates the north sector of the Missões Zone geomorphic unit, which is a poorly dissected surface between 120 and 540 m a.s.l., with mesas with slightly convex tops, convex slopes, and V-shaped valleys. On a regional scale, this geomorphic unit is characterized by the remnants of planar surfaces organized in a staircase pattern, with the lowest altitudes along the plains of the Paraná and Uruguai rivers.
3. The superficial formations are formed by weathering profiles from the volcanic flows as well as alluvial, colluvial, and eolian deposits. The weathering profiles are interpreted as polygenetic with signs of mono-sialitization and allitization. The alluvial deposits are predominant along the Paraná and Uruguai Rivers, attesting to the strong dissection of the area during the Cenozoic. Colluvium deposits are found on the slopes situated on the abutment margins of the valley bottom and the cluttering paleovalleys of low hierarchical order. It is debated whether the reworked loess from the Pampeano Aeolian System of central Argentina covered the Missões Zone and a part of the Araucárias Plateau between the Late Pleistocene and the Holocene.
4. The Missões Zone is in subtropical region of South America that is naturally covered by the Seasonal Semidecidual Forest. The variations in the hydric regime, which are associated with temperature changes, most likely favored the replacement of this vegetation by savanna vegetation during the Late Quaternary. The savanna vegetation reflects a drier and colder period, while the forest vegetation corresponds to the damper and hotter phase. At certain times, these vegetation replacements were not in phase with the erosive/depositional or pedogenetic processes.

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The Canastra Range: On the Way to São Francisco River Spring

32

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Abstract

Canastra Range is located in Central Brazil, on the way to São Francisco River spring. The geomorphology shows strong structural control and is characterized by inverted relief on a synformal structure. The plateau has a smoother topography with an altitude ranges from 900 to 1,496 m a.s.l. and is supported by quartzite layers of the Canasta Group. Hydrological and soil conditions allow the development of Cerrado (Brazilian savanna) vegetation, mainly as wet grasslands (*Campos Úmidos*) with earth mounds (*murundus*). This region is a natural water that divides between the São Francisco and Paraná rivers, two of the major Brazilian watersheds. The boundaries of the Canastra Plateau are controlled by fault zones are developed as steep escarpments, where the main rivers leave the plateau over spectacular waterfalls. Among many waterfalls, the most famous is the 186 m high Casca D'Antas Falls, a symbol of Canastra Range and one of the most visited in the Brazilian territory. The region shows a variety of beautiful landscapes, with mountain ranges, hills, valleys, plateaus, and cliffs, and also shelters important plants and animals of the Cerrado biome, including endemic, rare, and threatened species.

Keywords

Cerrado biome • Fault zones • Inverted relief • Hydromorphism • Central plateau • Etchplain

32.1 Introduction

Serra da Canasta National Park (SCNP) was created in 1972 with the purpose of preserving the historical headwaters of the São Francisco River. This river was called by the native people as Opará (meaning river that looks like a sea) and is currently named 'River of National Unity' because it is the longest river entirely within the Brazilian territory (2,830 km), with a basin area of 640,000 km^2 that includes five states (Minas Gerais, Bahia, Pernambuco, Alagoas, and Sergipe). It was discovered by Florentine Américo Vespúcio while sailing within the river mouth on October 4, 1501. The name is a tribute to St. Francis of Assis, patron saint of animals and environment, celebrated on this date. Navigating the São Francisco River is a tour that explores the history of Brazil. The navigations until 1503 only occurred at the mouth of the river because of the dense forest and the savage tribes. Only the pioneer explorers (*Bandeirantes)* in search of gemstone began to enter into the country via the São Francisco River. In the seventeenth century, cattle ranching became the main activity along the São Francisco River. Gradually, other economic activities were developed, such as rice planting in fertile floodplains.

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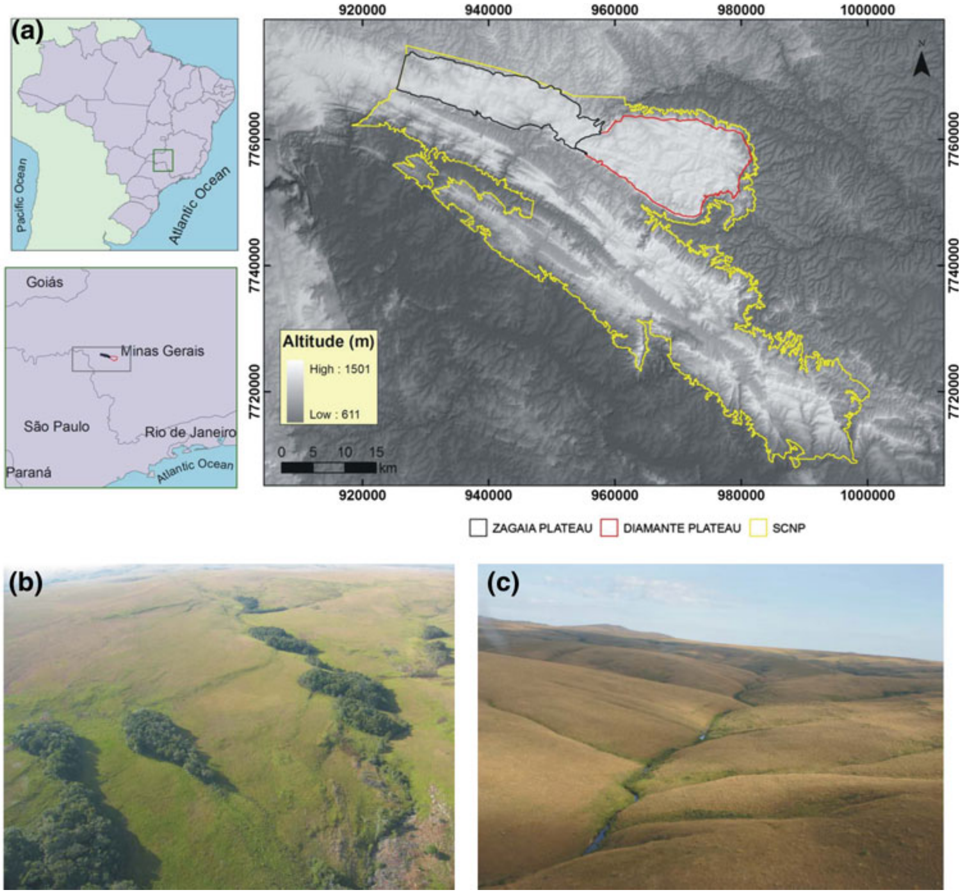


Fig. 32.1 Location map of the Canastra Range, highlighting the Zagaia Plateau (*black line*), Diamante Plateau (*red line*), and the boundary of the Serra da Canastra National Park (*yellow line*) Zagaia Plateau landscape (**a**) and Diamante Plateau (**b**) landscape (**c**)

SCNP is composed of three mountain ranges: Negra, Babilônia, and Canastra. Canastra Range displays a great diversity of soil, geology, climate, and vegetation types and is divided into two plateaus that are known as the Diamante Plateau (DP) and the Zagaia Plateau (ZP) (Fig. 32.1).

Canastra Range (*Serra da Canastra*) is one of the most beautiful sceneries within the morphoclimatic domain of the Cerrados (Brazilian savanna) that contains an area of 1.5–1.8 million km^2 located mainly in Central Brazil, with small areas extending into northeastern Paraguay and eastern Bolivia (Ab'Saber 1970, 1977, 1983). Thus, the Cerrado Region occupies a central position in relation to the other largest biomes in South America, as it has extensive borders with the two largest South American forest blocks (Amazonia and Atlantic Forest) as well as with the two largest South American dry regions (Caatinga and Chaco).

The SCNP has an area of approximately 50,000 ha located in the state of Minas Gerais, with an altitude that ranges from 900 to 1,496 m. This region is a natural water that divides between the São Francisco and Paraná rivers, draining two of the major Brazilian watersheds. SCNP shows a variety of beautiful landscapes, with mountain ranges, hills, valleys, plateaus, and cliffs, which are habitats for important plants and animals of the Cerrado biome, including endemic, rare, and threatened species (Romero and Nakajima 1999; Silva and Silveira 2006). In the park and its vicinity, there are several waterfalls, among which the Casca D'Antas Falls, 186 m high, is the symbol of Canastra Range and one of the most visited in the country. This waterfall, positioned just 20 km downstream from the source, shows the highest topographic amplitude over the entire São Francisco River (Chaves et al. 2009).

In the region around the SCNP, the main economic activity remains being rural with small plantations of coffee, corn, rice, pineapples, bananas, and sugarcane and especially cattle ranching, where milk production for the fabrication of cheese has had a traditional importance. The small towns near the park have developed from villages founded in the middle nineteenth century, having livestock as the main economic activity. Currently, the SCNP reinforces the development of ecotourism projects (both public and private), providing a new economic potential for the region and ensuring environmental sustainability.

The area has a complex geological history, with orogenic events beginning in the Precambrian, followed by cratonic stabilization and tectonic reactivations during the Phanerozoic (Almeida et al. 2000; Brito Neves 1999). The geology comprises a Neoproterozoic orogenic system arising from collision between the Amazon and São Francisco cratons that resulted in the amalgamation of the Rodinia supercontinent at the end of the Neoproterozoic (Almeida 1977). In this chapter, landforms and their relationships with the natural factors of the Canasta Range are presented, on the way to São Francisco River spring.

32.2 Geological and Geomorphological Settings

SCNP region belongs to the Tocantins Tectonic Province, a large Neoproterozoic Brasiliano/Pan-African orogen developed between three major continental blocks represented by the Amazon and São Francisco/Congo cratons and the Paranapanema block, now hidden beneath the Phanerozoic Paraná Basin, in Central Brazil (Pimentel et al. 2001). This tectonic amalgamation of crustal blocks formed part of the West Gondwana assembly (Brito Neves et al. 1999). The tectonic subdivision is defined by land accretion on the western edge of the São Francisco craton that began approximately 900 Ma (Valeriano et al. 2004). The province comprises three large fold belts: Araguaia, Paraguay, and Brasília (Fig. 32.2).

SCNP is included in the Brasilia Fold Belt, a complex fold-and-thrust belt tectonically verging toward São Francisco Craton, with metamorphic grade increasing from east to west, i.e., toward the Amazon Craton (Brito Neves et al. 1999). This fold belt has a length of 1,100 km and is composed of two branches (Brito Neves et al. 1999): NE trending (NBB) and NW trending (SBB) (Valeriano et al. 2000). The SBB shows allochthonous tectonic elements composed by nappes that were thrust eastwards to the border of São Francisco Craton. Thus, the Canasta Range is a part of a set of residual plateaus and mountains of Minas-Goiás, whose alignment of ridges is supported by metamorphic rocks associated with the Brasilia Fold Belt (Ross 2006).

The lithostratigraphy of the study area is constituted by the Canastra Group, an association of psammitic and pelitic metasedimentary rocks frequently containing carbonates and consisting essentially of phyllite and quartzite, metamorphosed in the greenschist facies (chlorite zone) (Silva et al. 2012). The age of deposition of the Canastra Group not was determined (Silva et al. 2012), although U-Pb dating of detrital zircons in the Araxá (Valeriano et al. 2004) and Paracatu regions (Rodrigues et al. 2010) allows one to infer the maximum age of deposition of these rocks for 1,040 Ma. The orogen accretion on the western edge of the São Francisco craton that began around 900 Ma may have a history of activity until the Eocambrian (Valeriano et al. 2004; Rodrigues et al. 2010).

After the Precambrian–Eocambrian transition, the region became a source of sediment for the Paraná intracratonic basin (Soares et al. 1978). NW–SE faults were reactivated mostly as normal and reverse faults during the Phanerozoic. Reactivation of NW–SE trending fault lines during the Cretaceous on the edge of intracratonic Paraná Basin promoted alkaline magmatism (Riccomini et al. 2005) and the formation of mineral deposits such as phosphates, titanium, niobium, rare earth elements (Gomes et al. 1990), and diamonds (Tompkins and Gonzaga 1989; Gonzaga et al. 1994). The Canastra Range located in the magmatic province of Alto Parnaíba has a large number of pipes and dykes, which are related to kimberlites and kamafugites (mafurites, ugandites, and katungitos) whose ages range from 83 to 90 Ma (Leonardos and Meyer 1991). Recently, the first Brazilian primary deposit having economic significance (Canastra-1 kimberlite) was discovered in the Canastra Range near the sources of the São Francisco River (Chaves et al. 2008; Menezes and García 2007). The intrusion is made up of two pulses aligned along NE–SE trend, associated with the metasedimentary rocks of the Canastra Group, and is remarkable for an excellent quality of diamonds (Chaves et al. 2008).

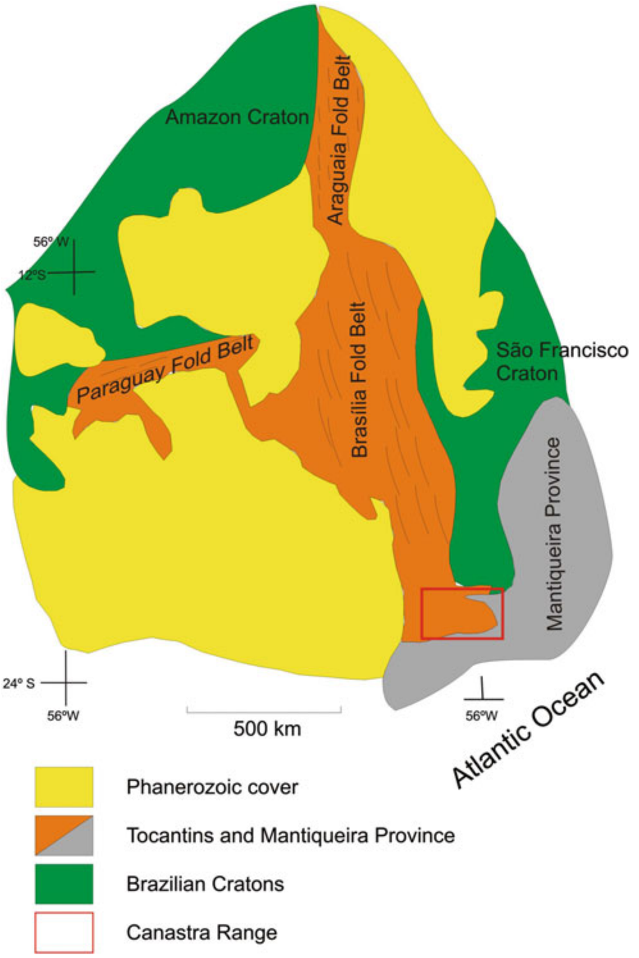


Fig. 32.2 Tectonic outline of Central Brazil, with emphasis on the Tocantins Province (*orange*), locating the Serra da Canastra Range (simplified from Almeida et al. 1981 and adapted from Valeriano et al. (2004))

After the Cretaceous, environmental conditions alternated between longer hot and humid phases interrupted by short, cold, and dry intervals. The most humid and hot period occurred during the Eocene and part of the Oligocene, while during the Middle Miocene and Late Pliocene, warmth and humidity were less pronounced. The driest periods were recorded during the Early Miocene, Late Miocene, and Early Pliocene (more intense), as well as during the Plio-Pleistocene transition (Frakes 1979). These climatic conditions helped the Cenozoic planation surfaces to evolve (Ab'Saber 1970).

Neotectonic studies indicate that the highlands bordering the Paraná Basin are in the state of isostatic adjustment (Braun and Baptista 1978; Grohmann and Riccomini 2012). Thus, episodic uplift allowed for continuous denudation of the region. According to Saadi (1991), the uplift of the Canastra massif would have most likely started between the Aptian and Albian ages (Lower Cretaceous), accelerated in the Late Tertiary in several phases separated by periods of quiescence, when a planation surface developed across the massif in the South American cycle. However, Chaves et al. (2009) followed King (1956) and described the Canastra Range as a part of post-Gondwana planation surface cycle (Pre-Cretaceous).

32.3 Canastra Plateau

The plateau is at about 990–1,500 m above sea level and is bordered by steep cliffs on the southwest and northeast sides, leading to talus slopes that drop down to the plain at 800 m a.s.l. The main rivers leave the plateau over spectacular waterfalls with drops up to 186 m. The landform pattern shows a strong structural control and is characterized by an inverted relief on a synformal structure (Valeriano et al. 1995; Silva et al. 2006) (Fig. 32.3). The escarpments are supported by quartzite layers from the thrust of the Canastra Group over the Bambui Group. Differential weathering, more intense on the carbonate rocks of the Bambui Group, enhanced the appearance of the quartzite layers of the Canastra Group in the topographic surface. The synformal structure hinders drainage and defines different dissection levels among the plateaus, with diverse landforms and associated savanna types (Couto Júnior et al. 2010).

The Canastra Range is divided into two plateaus: ZP and DP. The ZP occurs in concave areas and contains Cambisols, Plinthosols, and Gleysols (IUSS-WRB 2007) as dominant soil types associated with wet grassland, earth mounds (*Murundus*), and riparian forest (Fig. 32.4a, b and Table 32.1).

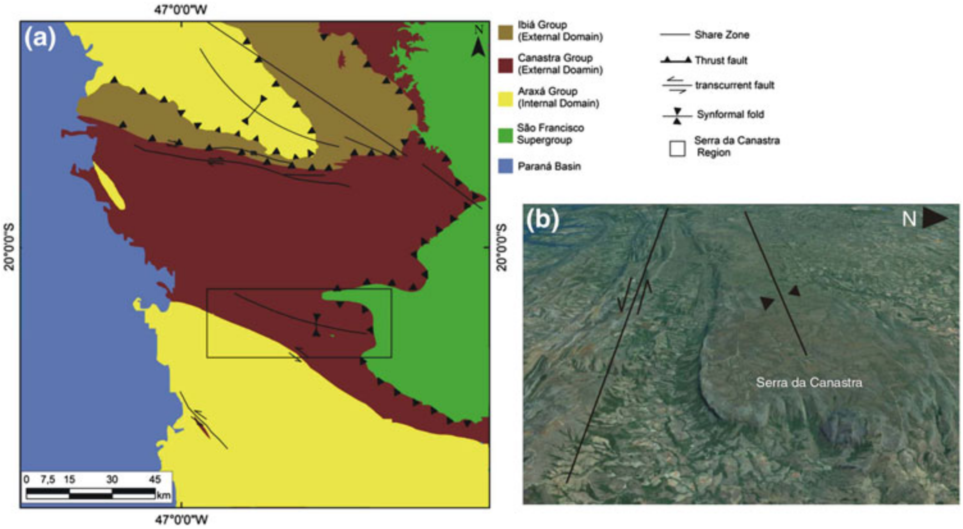


Fig. 32.3 Simplified geological map (**a**) and a Google Earth image in perspective of the Canastra Range presenting the synformal fold and the location of the transcurrent fault (**b**) (Adapted from Valeriano 1999)

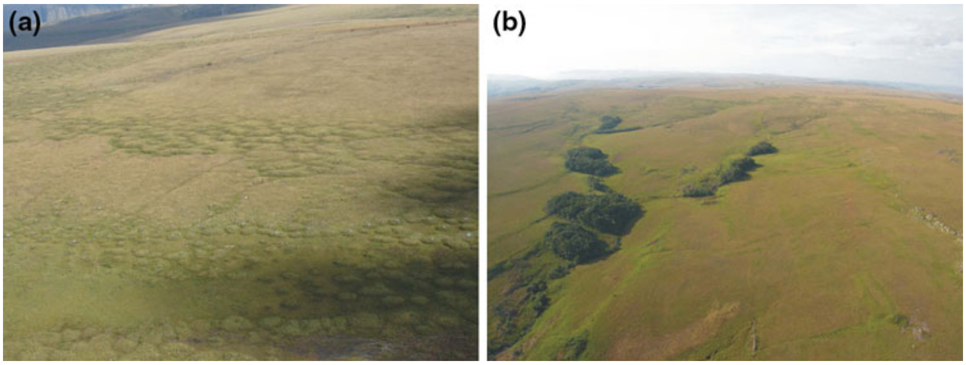


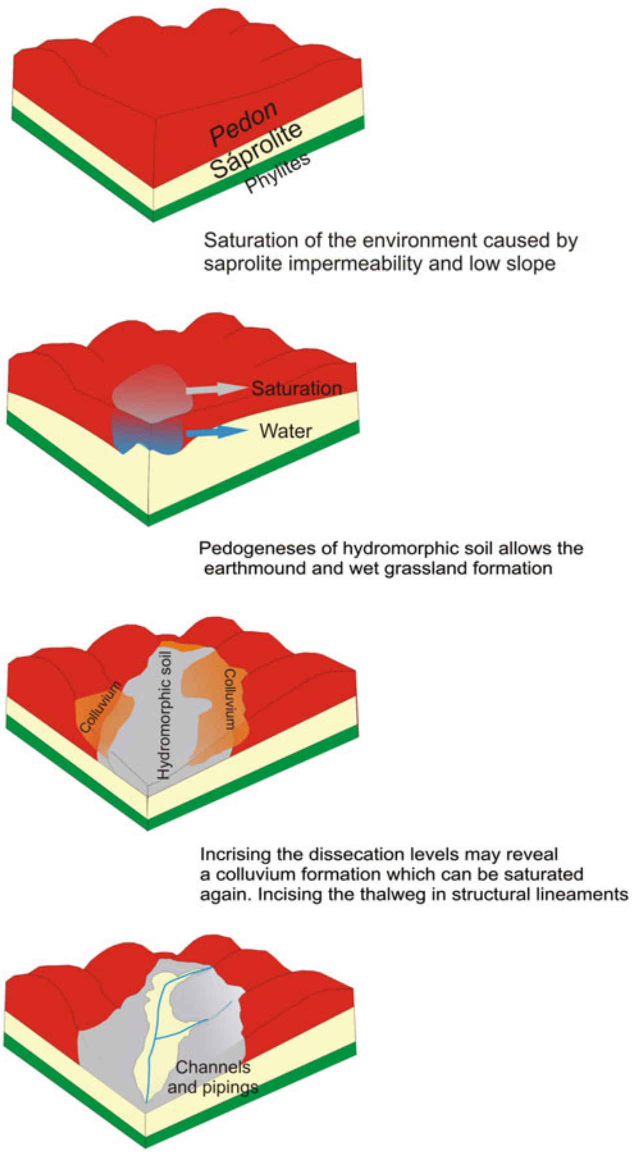
Fig. 32.4 Hydromorphic soil landscape with earth mounds. Mounds intercalated with Cerrado vegetation (**a**) Fragment Riparian forest associated with wet grassland in structural lineament (**b**) rocky outcrops mounds with *Cerrado* outcrops

Table 32.1 Descriptive statistics of slope (S) and elevation (H) showing the minimum (MIN), maximum (MAX), mean and amplitude (AMPL) values, and estimated area of the concave, plain, convex, and saddle features of the Diamond Plateau and the Zagaia Plateau

Diamante Plateau				
	Min	Max	Mean	AMPL
H (m)	988.99	1,494.90	1,332.01	73.53
S (%)	0.13	50.52	9.92	5.68
Zagaia Plateau				
H (m)	1,048.97	1,400.98	1,285.31	61.48
S (%)	0.08	40.96	8.69	4.98
Morphometric features				
	Concave	Saddles	Plain	Convex
DP (area %)	35.34	16.94	5.25	42.47
ZP (area %)	49.21	15.80	7.73	27.37

The DP is more dissected and is typified by convex minor landforms (mounds, hills, and escarpments), containing Leptosols, Cambisols, and Petric Plinthosols, associated with dry grassland and rocky vegetation (Table 32.1). Landform map from SRTM image indicates a balance between the spur (10.07 %) and foot slope (9.09 %) in the ZP, while in the DP foot slopes prevail (14.94 %) (Vasconcelos et al. 2012). On the spurs, *murundus* (earth mounds) occur that are peculiar mound-and-depression microreliefs. These features are formed by a repeated patterns of semi-elliptical mounds, which are raised circular soil mounds or hummocks a few meters in diameter and from a few centimeters to 2 m high (Eiten 1972). These earth mound fields are found in the areas affected semi-permanently waterlogged or those affected by seasonal rainfall and runoff, but having little contact with groundwater (Furley 1986; Araújo Neto et al. 1986). The mound tops contain vegetation, which may be purely herbaceous, but usually contains shrubs and low trees.

The occurrence of thick kaolinitic saprolite with very low iron levels on the plateau is the evidence of deep weathering that has affected the Canastra Range. This impermeable horizon promotes lateral water movement above that level (Bigarella et al. 2007), which can lead to subsurface water concentrations. Thus, this environment causes ground saturation that triggers underground erosion and terrain subsidence. Figure 32.5 shows how the wet grasslands and earth mounds landscapes develop through these processes. Moreover, this landscape may contain colluvial ramps that mainly fill valley heads. The stability of these colluvial deposits is affected by subsurface erosion, which will again saturate the environment with water, thus causing new subsidence (Vasconcelos et al. 2013).



Saturation of the environment caused by saprolite impermeability and low slope

Pedogeneses of hydromorphic soil allows the earthmound and wet grassland formation

Incrising the dissecation levels may reveal a colluvium formation which can be saturated again. Incising the thalweg in structural lineaments

Fig. 32.5 Evolution model of the Canastra Plateau (adapted from Vasconcelos et al. 2013)

Vegetation distribution on the plateau is organized by spatial heterogeneity of the environmental conditions regarding landforms (e.g., elevation, slope, or aspect), soils, and hydrological factors (Couto Júnior et al. 2010). Thus, the vegetation distribution serves as an indicator of geomorphologic processes and landforms. *Cerrado* vegetation demonstrates a variety of structural types ranging from virtually closed forest to open grasslands characterized by decreases in woody plant species density (Eiten 1972; Castro an Kauffman 1998). In the Canastra Plateau, the following physiognomic classes are observed: savanna woodlands (*cerrado stricto sensu*) associated with shrub and grassland (*campo sujo*) (Fig. 32.6b), open grassland (*campo limpo*) (Fig. 32.6d), and rocky savanna (*cerrado rupestre*) (Fig. 32.6c). The *cerrado stricto sensu* occurs in isolated and flat areas and is very often associated with Ferralsols. The *rocky field and rocky outcrops Cerrado* (Fig. 32.6e) occur in

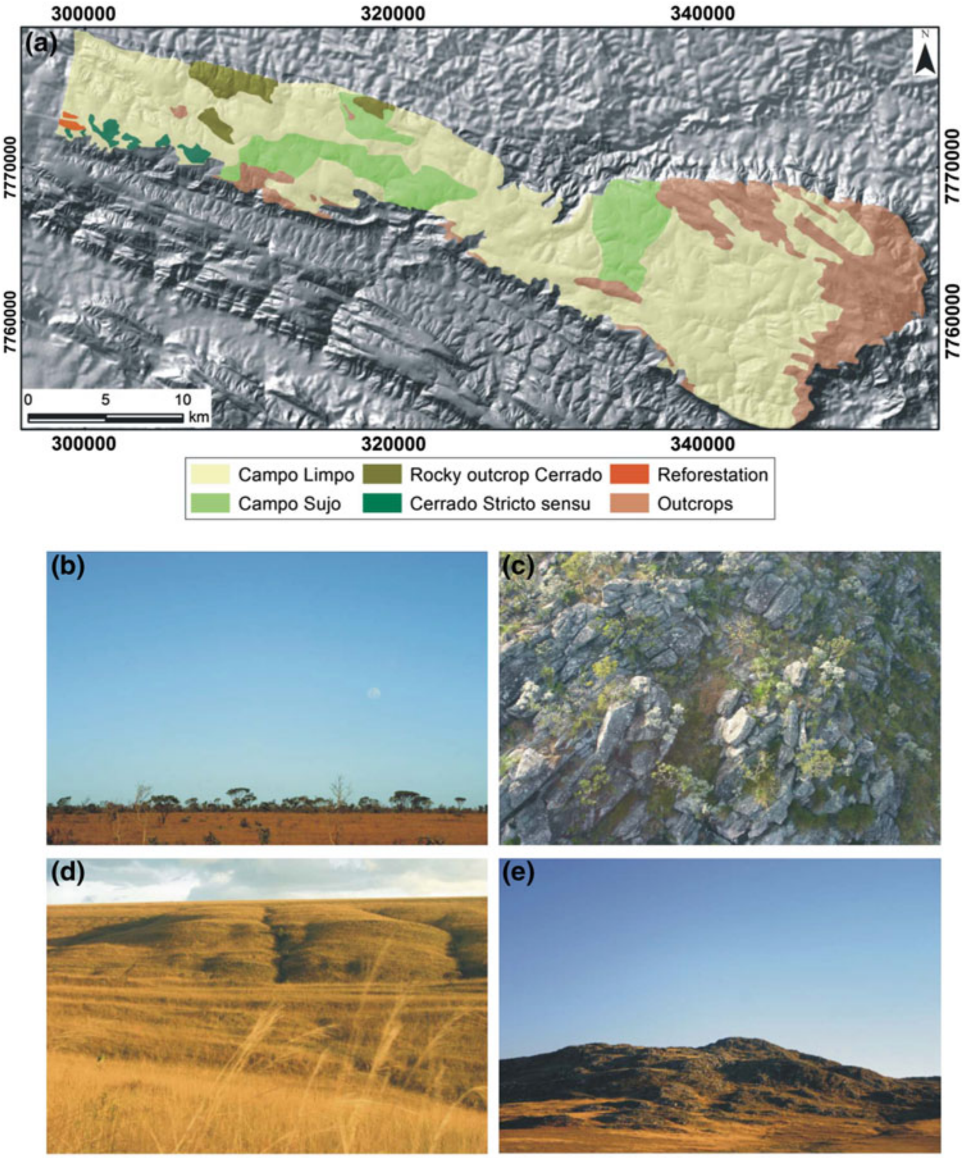


Fig. 32.6 Vegetation map of the Canastra Range (**a**), Cerrado *stricto sensu* and 'Campo Sujo' (**b**), the rocky outcrop of the Cerrado (**c**), the grasslands ('Campo Limpo') (**d**) and the outcrops (**e**) (adapted from Couto Junior et al. 2010)

Table 32.2 Frequency of the phyto-physiognomies of the Cerrados in the Diamante Plateau and the Zagaia Plateau

Phyto-Physiognomies					
Frequency	Outcrops/rocky outcrops cerrado	'Campo limpo'	'Campo sujo'	'Cerrado stricto sensu'	Reforestation
DP (area %)	29.74	60.73	9.33	…	…
ZP (area %)	9.78	67.40	19.66	2.62	0.55

areas with either shallow soil or lack of soil, with bedrock exposed at the plateau edges and escarpments and the plateau tops above 1,300 m (Table 32.2). Typically, the *campo sujo* (environments dominated by shrubs) present greater slope variation and are associated with soils with incipient development. Grasslands cover the largest area and can occur in the wet environment too.

32.4 Escarpment

Escarpments controlled by thrust faults and lithological contacts separate the hilly plateaus and the topographic depressions. The direction of the escarpment follows the direction of foliation (Fig. 32.7). Quartzite layers support the

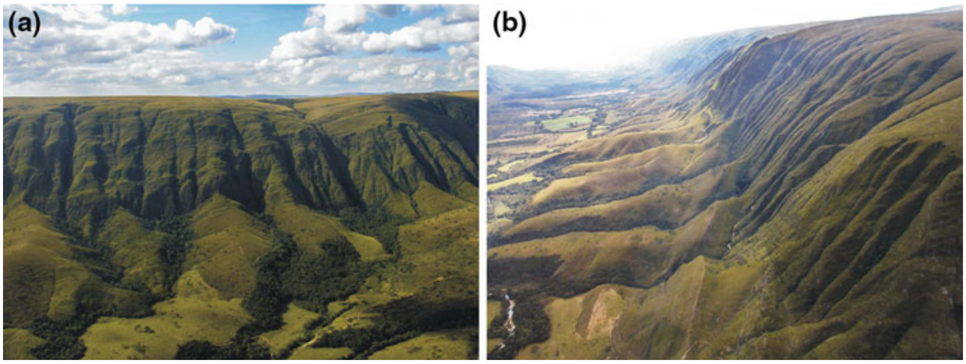


Fig. 32.7 Escarpments of the Canastra Range seen from south to north (**a**) and from east to west (**b**)

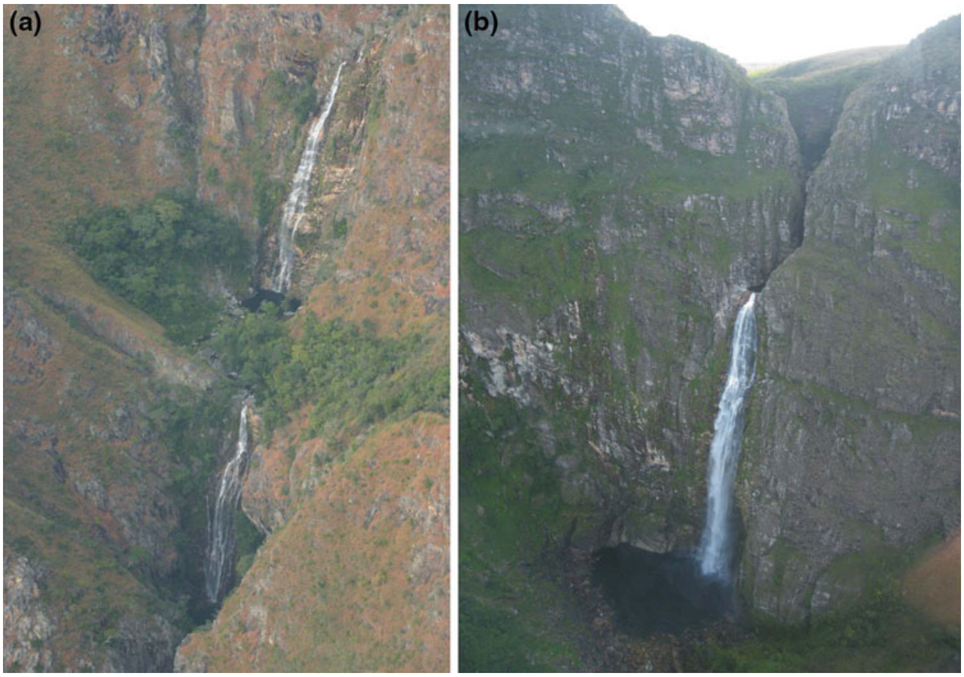


Fig. 32.8 Antônio Ricardo waterfalls (**a**), the Casca D'Antas Waterfall (**b**)

highest sections of the face of the escarpments. The slope profile between the top of the plateaus and the footslope is stepped, associated with interbedded sandy and pelitic levels. Differential weathering is more efficient along fracture zones and in clay levels, while sandy materials are more resistant. The high density of subvertical fractures contributes to an increasing rate of slope retreat within the escarpments.

Quartzites typically appear along the plateau edges, controlling the progress of escarpment retreat and supporting waterfalls. It is ordinary that waterfalls occur in sequences around the escarpment area at different levels, as shown by the Antonio Ricardo waterfall (Fig. 32.8a).

The Casca D'Antas watercourse runs along fractures forming a sequence of waterfalls with the highest drop above 200 m (Fig. 32.8b). The nearly vertical escarpment at the southern edge, where the waterfall plummets, is defined by a large horizontal thrust fault with an approximate NW–SE direction and weak plunge toward the NE. The fault separates the oldest (Canasta Group) and younger geological units (Bambuí Group) (Chaves 2009).

32.5 Conclusion

The Serra da Canasta protects a set of landscapes of rare beauty, with high complexity of geomorphological and geological features. Its vegetation is transitional between Atlantic Forest and *Cerrado* biomes. Thus, this natural park is one of the most visited in Brazil because of its history and natural landscapes. This tropical landscape shows an interaction of tectonic and denudation processes within which intense weathering and lateral water flow lead to different models of landscape evolution.

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Southern Serra do Espinhaço: The Impressive Plateau of Quartzite Ridges

33

Antônio Pereira Magalhães Junior, Luiz Fernando de Paula Barros, and Miguel Fernandes Felippe

Abstract

The Southern Serra do Espinhaço (Serra do Espinhaço Meridional—SdEM) is the meridional portion of the most extensive and continuous Precambrian orogenic belt of the South American Platform. The SdEM is an imposing geomorphological and geological unit and one of the most striking geographical structures of the state of Minas Gerais, southeastern Brazil. The SdEM has an important role in the separation of drainage basins and the individualization of climate, biomes, and landscapes. The result of the long temporal combination of a diverse lithostructural context and morphogenetic agent action, the SdEM stands out for its biological wealth and the scenic beauty of its landscapes, which are marked by quartzite scarps, canyons, and crystalline water rivers with frequent waterfalls. Human occupation, which has been present since prehistoric times but has intensified since the colonial period due to exploration for precious stones, has resulted in a rich historical and cultural asset that enhances its physical environment and makes the SdEM one of the most common tourist destinations in Brazil.

Keywords

Serra do Espinhaço • Plateau • Quartzit ridges • Espinhaço Supergroup

33.1 Presentation

The Serra do Espinhaço (“Rückenknochengebirge”—Eschwege 1822) is the most extensive and continuous Precambrian orogenic belt of the South American Platform. In addition to being an imposing unit of geomorphological and geological interest, the Serra do Espinhaço is one of the most striking geographic structures of the state of Minas Gerais in southeastern Brazil (Fig. 33.1). It acts as a major divide between important drainage basins, biomes, and cultures, but the Espinhaço can also be regarded as a geographic and environmental link that connects the landscapes and their physical, social, and historical elements.

The Serra do Espinhaço stretches over 1,200 km in an approximate N–S direction (Almeida-Abreu and Renger 2002; IBGE 2006), becoming the drainage divide between the watersheds of Eastern Brazil and the São Francisco River Basin, which is one of the largest and most important Brazilian rivers. Despite being referred to as a “serra” (mountain range), the Espinhaço presents a physiographic complexity that would be better defined by the term “planalto” (plateau) as proposed by Saadi (1995), since its longitudinal expanse is more expressive than the alignment of ridges, promoting the spatial configuration of a plateau (as shown by the A–B and C–D profiles and Digital Elevation Model in Fig. 33.1). The contacts between the plateau and the adjacent lower ground are made by impressive rock walls (Fig. 33.2).

From this perspective, the Serra do Espinhaço is arranged as a first-magnitude plateau in the Brazilian relief and displays an irregular morphology as a result of differential

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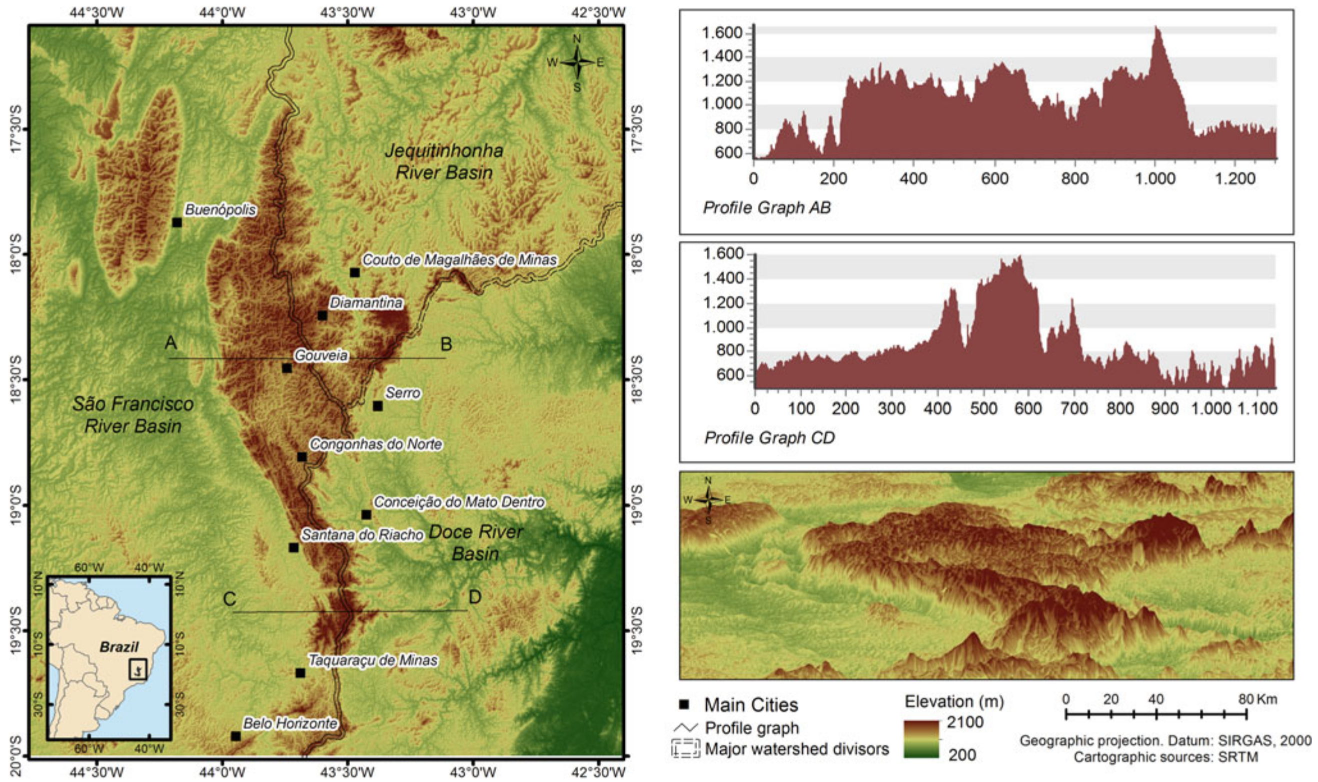

Fig. 33.1 Location and digital elevation model of the southern Serra do Espinhaço and its surroundings

Fig. 33.2 Regional landscape with some of the first walls of the Serra do Espinhaço Meridional—SdEM—Congonhas do Norte region. *Photograph* Ataliba Coelho

exogenous morphodynamic processes in a complex tectonic and lithostructural context. During the Cenozoic, landforming processes under inter-tropical conditions have contributed to shape a wide range of Meso- and Paleoproterozoic metasedimentary rocks, resulting in even more surface diversification of the two large morphotectonic subunits (northern and southern) that compose the Serra do Espinhaço (Saadi 1995).

Fig. 33.3 Diamantina Plateau near the city of Gouveia. According to Saadi (1995), this is a Paleogene planation surface with numerous quartzitic monadnocks, like those in the *upper* part of the photograph. *Photographs* Ataliba Coelho

As a result of the Brazilian Orogeny event, the southern Serra do Espinhaço (SdEM) is set up as a Neoproterozoic mobile belt that has boundaries with the southeastern portion of one of the most known Brazilian cratons (São Francisco craton) and comprises the entire southern portion of the Espinhaço massif until it reaches the Couto de Magalhães Depression (Knauer 2007). This area is excavated by the Jequitinhonha River and its tributaries and is controlled by a NW–SE shear zone. The Northern Serra do Espinhaço (Serra do Espinhaço Setentrional—SdES) is formed by a plateau cut across a Neoproterozoic craton (IBGE 2006) that covers an extensive stretch that crosses the entire state of Bahia in Northeastern Brazil.

According to Saadi (1995), the width of the SdEM is smaller (30 km) at its southern extremity and rapidly increases toward the north, reaching 90 km around near the cities of Gouveia and Diamantina (Fig. 33.1). The average altitude is approximately 1,200 m, and the Pico do Itambé is the highest point, at 2,062 m. The largest topographic relief unity is the Diamantina Plateau (Fig. 33.3), the ceiling of which is at an average altitude of 1,300 m at the municipality with the same name, whereas the Diamantina Plateau average elevation decreases to 900 and 1,200 m around its northern and southern borders.

33.2 The Neoproterozoic Belt

The morphological configuration of the SdEM is a response to its geological characteristics. The tectonic processes that took place in this area created deformed rock masses that have been shaped by long-term denudation processes, left a heritage of beautiful and impressive landscapes. To comprehend the geological and geomorphological origin of the SdEM is a complex task that is still unclear in some aspects.

33.2.1 Geological Origin and Evolution

The geology of the Serra do Espinhaço has attracted researchers since the nineteenth century due to gold and diamonds found in its southern region, discovered in the eighteenth century (Saadi 1995; Knauer 2007; Gontijo 2008). The SdEM has rock sequences with ages between the Archean and Neoproterozoic, but with a predominance of Paleo- to Mesoproterozoic rocks from the Espinhaço Supergroup (Knauer 2007). The geology of the area comprises by Conselheiro Mata, Guinda, and Serro groups that demonstrate the evolution of the Espinhaço Basin as indicated in the Table 33.1 (Almeida-Abreu and Renger 2002).

The Espinhaço geological evolution dates back to rifting starting in the late Paleoproterozoic (ca. 1,752 Ma—Almeida-Abreu and Pflug 1994) that promoted the formation of a taphrogenic basin under semi-continuous crustal extension. More than 5,000 m of predominantly sandy sediments of fluvial, deltaic, shallow marine, and, later, eolian origin accumulated in the basin (Dussin and Dussin 1995). Convergent E–W forces during the Mesoproterozoic (ca. 1,250 Ma—Almeida-Abreu and Pflug 1994) led to the closure of the sedimentary basin and the emergence of the Espinhaço Orogeny in the form of an alpine-type belt (Saadi 1995; Almeida-Abreu 1995). The sedimentation of the Macaúbas Group by glaciogenic processes followed (Almeida-Abreu and Renger 2002; Dussin and Dussin

Table 33.1 Stratigraphy of the Espinhaço Supergroup. (Adapted from Almeida-Abreu and Renger 2002)

	Group	Formation	Lithology	Environment
Espinhaço Supergroup	Conselheiro Mata	Rio Pardo Grande	Metapelites, subordinate metasandstones, dolomites	Low-energy shallow marine, inter- to sub-tidal, with episodic oscillations of the sea level and occasional fluvial and eolian incursions in the marine platform
		Córrego Pereira	Pure to micaceous metasandstones, locally pelites	
		Córrego da Bandeira	Metapelites and metasandstones	
		Córrego dos Borges	Pure to micaceous metasandstones locally quartzitic breccias/conglomerates	
		Santa Rita	Metapelites and subordinate metasandstones	
	Guinda	Galho do Miguel	Pure metasandstones	Eolian
		Sopa-Brumadinho	Metasandstones, polymictic conglomerates, metapelites, and locally quartzitic metabreccias with pelitic matrix. Hematite phyllites and greenschists	Predominantly fluvial, locally prograding into restricted lacustrine troughs. Sporadic eolian reworking
		São João da Chapada	Metasandstones, locally conglomerates and breccias; hematite phyllites	Interlaced fluvial
	Serro	Itapanhocanga	Metapelites, quartzites, and banded iron formations (BIFs); locally dolomites, hematite phyllites, and metarhyolites	Transgressive coastal
		Serra do Sapo	BIFs, metapelites, quartzites, and locally meta-ultramafics	Platform with condensed sections
		Jacém	Quartzites, subordinately metapelites and locally BIFs and meta-ultramafics	Bathyal and abyssal with turbidites
		Alvorada de Minas Ultramafic Suite	Talc schists, tremolite-actinolite schists, chlorite schists; locally BIFs, metapelites, and quartzites	Intra-crustal serpentinite diapirism in thinned crust

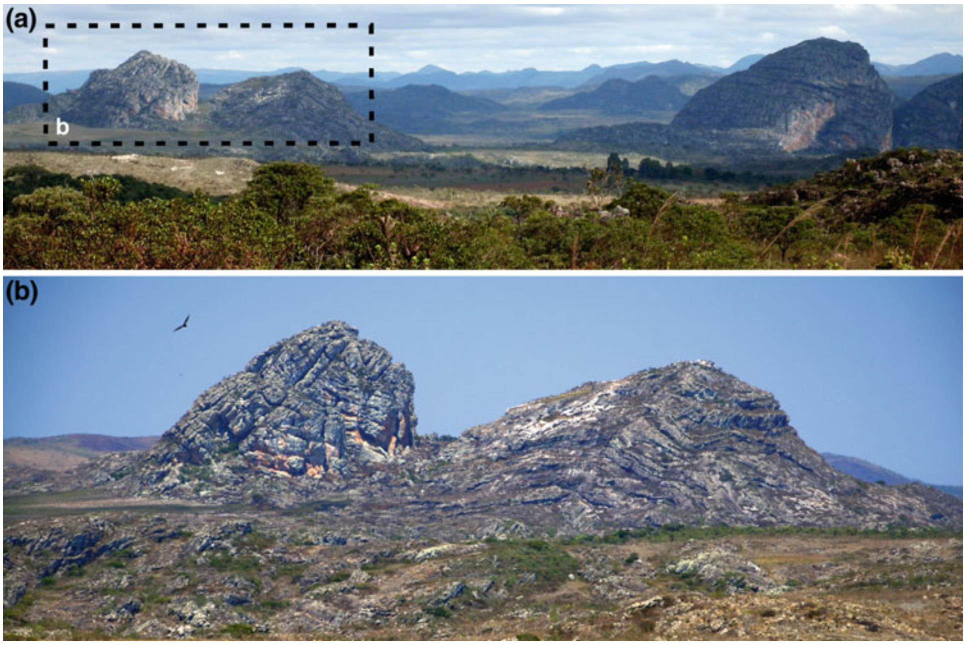

Fig. 33.4 Large morphological expressions of the SdEM folding. Some of mountain forms show inverted folded structures as suspended anticlines—Diamantina region. *Photograph* **a** LFP Barros, **b** Ataliba Coelho

1995). Nowadays, the legacy of the ancient-folded structures can be viewed in the form of inverted synclines or anticlines (Fig. 33.4a, b), showing the efficient work of the exogenous process on the geological framework.

The glacial deposits of the Macaúbas Group have boundaries in the western, northern, and northeastern portions of the SdEM and an age of approximately 1,050 Ma (D'Agrella Filho et al. 1990). In addition, these glacial deposits were cut by igneous rocks with ages of 906 Ma (Machado et al. 1989). In that period, the São Francisco Craton crossed high latitudes (Almeida-Abreu and Renger 2002).

Ancient glacial valleys originated within the SdEM where, at that time, metamorphic and granitic rocks from the crystalline basement cropped out, indicating that the orogenic belt was already well established in the Mesoproterozoic (Almeida-Abreu and Renger 2002). Because the theories about the genesis and evolution of the Espinhaço are conflicting, it should be noted that this model agrees with the ideas of Pflug et al. (1980) and Knauer (1990), but is contrary to those of researchers who argue that the deformation of the Espinhaço Supergroup rocks is of Brazilian age (Upper Proterozoic-Lower Paleozoic—Dussin and Dussin 1995; Uhlein et al. 1995).

Due to the ancient deformational events, the SdEM is structured in *nappes* or thrust sheets, which spread to the west until they reach the western boundaries of the SdEM, as proposed by Almeida-Abreu and Renger (2002). These authors also note that the Serra has a classical W–E profile of collision orogeny, highlighting an increased deformation and degree of metamorphism in the opposite direction to the tectonic vergence and crustal thickening in the internal domain, i.e., the suture-collision zone.

A new crustal strain phase promoted basaltic volcanism in the SdEM in the beginning of the Neoproterozoic (Almeida-Abreu 1995). At the end of the Neoproterozoic, the amalgamation of the Gondwana Supercontinent represented a phase of tectonic reactivation of the SdEM structures, causing thrusting of the units of the Mesoproterozoic orogeny entity (Espinhaço Supergroup) over younger units (Macaúbas and Bambuí groups).

The last major tectonic event that affected the SdEM occurred in the Cretaceous and marked a new episode of crustal extension (Dussin and Dussin 1995). Associated with the fragmentation of the Gondwana paleocontinent and the opening of the South Atlantic Ocean, this event also resulted in several basaltic intrusions cutting the regional lithostratigraphic units.

33.2.2 Megamorphology and Cenozoic Evolution of the SdEM

The southern Serra do Espinhaço is distinguished by different geological, geographical, and environmental attributes, but its imposing landscape is primarily the results of outstanding geomorphology. The high morphological divide appears as an extensive plateau with several internal compartments. The morphology results from a long dissection period associated with the differential geochemical denudation, reflecting the heterogeneity in rock resistance and the important geomorphological role of the fluvial drainage.

Landforms due to dissection are particularly notable in quartzites, with those shaped by erosion being dominant, while formations due to accumulation are limited to restricted plains and fluvial terraces. The few occurrences of formations shaped by dissolution, in turn, correspond to karstic features developed in quartzites, such as Gruta do Salitre (Willems et al. 2008), located near the city of Diamantina. Nevertheless, the quartzite outcrops are marked by abundant alveolar cavities generated by the dissolution of silica (tafoni). The combined action of mechanical and geochemical processes often generates ruiniform quartzitic outcrops.

The SdEM is a sequence of ridges that are preferentially oriented in the SSE–NNW direction in its southern portion and the SSW–NNE direction in its northern portion (Almeida-Abreu 1995; Almeida-Abreu and Renger 2002). The strong structural control upon the main morphological features has influenced the history of fluvial dissection and resulted in landscapes that follow the preferential alignment of the tectonic structures (Saadi 1995). Therefore, sequences of ridges, erosive scarps, and deep valleys appear. One of the most expressive and attractive morphological characteristics of the SdEM is precisely this pattern of alternating ridges and valleys carved along the remnants of ancient-folded thrust structures.

Depressed compartments follow an "*en échelon*" arrangement between the localities of Gouveia and Conceição do Mato Dentro (Saadi 1995). In these depressions, granitoid, metasedimentary, and metavolcanic rocks support a morphology of moderately smooth multiconvex hills. The Gouveia Depression, one of the main morphological units of the region, results from the excavation of Archean gneisses and schists, juxtaposed to the Proterozoic quartzites by thrust and *nappe* tectonics (Almeida-Abreu 1995).

Another striking feature of the SdEM morphology is the significant contrast between the west and east boundaries. The escarpment forming the eastern edge does not exhibit the same regularity and continuity observed along the western edge. It is a discontinuous escarpment, with a height ranging between 100 and 400 m, and often presenting two or more steps and abrupt changes of direction. According to Saadi (1995), this setting appears to result from the combination of the significant variability of rock resistance (quartzites and conglomerates vs. granitoids and schists) and the variability of tectonic structures and their directions. These combinations have produced more efficient retreat along certain tributaries of the left bank Doce River, which deeply penetrates this part of the plateau along the structural windows located between the west-verging thrust fronts.

The escarpment that forms the western edge is the thrust front generated during the Brazilian Orogeny (Saadi et al. 2002). It has an average elevation of 400 m and regular course, and is supported by quartzite packages on the top. This morphotectonic character of the scarp is reinforced by the continuity of the escarpment in the metatillite areas (Saadi 1995). The parallelism of the scarp with the main watercourses is characteristic, while some minor watercourses cut the scarp perpendicularly in stretches with waterfalls, especially at the southern end. Abreu (1982) described the concentration of morphotectonic features in the portion of the Diamantina Plateau drained by the rivers of the São Francisco basin, including scarps with trapezoidal facets, uneven "broken and tilted" planar surfaces, horizontal and vertical block displacements, and debris cones associated with the most fractured sections of the Pardo Pequeno River Basin.

Neotectonic activity at Espinhaço has been proposed in several geomorphological studies, especially in those indicating responses from the drainage network to the regional energy inputs. Field evidence indicates the existence of up to five levels of Quaternary alluvial sequences in the region, in addition to the current floodplains, showing an incision of up to 17 m to the current drainage in the Gouveia Depression. The Pleistocene—Upper Holocene transition is marked by the opening of the valleys, further carving of the troughs (~1 m) and resurgence of gullying processes that cover the entire depression (Saadi 1995). The gullies exert great influence on the morphology and dynamics of the current channels, given the large amount of sediment delivered to the watercourses.

The structural and/or tectonic control of the drainage is expressed by long stretches of almond-shaped plains, controlled by NNW–SSE thrust faults, and short stretches with waterfalls along E–W transcurrent faults at N70 W (Saadi 1991). The canyons and waterfalls make the SdEM a rich tapestry of scenic and tourist attractions generated by the fluvial work. The Travessão Canyon displays relief of hundreds of meters and is one of the most impressive canyons of the SdEM (Saadi 1995). The Peixe Tolo Canyon is another canyon that deserves attention (Fig. 33.5).

Abreu (1982) also described several scenarios of minor fluvial captures in the Diamantina Plateau, which were attributed by him to local faulting and reinterpreted by Saadi (1995) as the local effects of extensive regional faulting. The strong tectonic/lithostructural control is evident in the spectacular waterfalls of the region, such as Cachoeira do Tabuleiro (Fig. 33.6a), which is the highest free-falling waterfall in the State of Minas Gerais and has an approximate height of 170 m, and Cachoeira Grande (Fig. 33.6b) which is about 10 m height and is one of the most visited waterfalls of the region.

The different associations of these three major controllers (tectonic, lithostructure, and fluvial work) are responsible for the complexity of relief configuration in the SdEM. Because of that, several proposals of relief unit mapping were made (Augustin et al. 2011; Rezende and Salgado 2011; Felippe

Fig. 33.5 Peixe Tolo Canyon, near to Conceição do Mato Dentro. *Photograph* Ataliba Coelho

et al. 2012), illustrating its internal morphological diversity and individualization in the context of the plateau. While the SdEM northern portion is marked by the remnants of erosion surfaces in the form of plateaus bordered by rows of erosional ridges and scarps (Augustin et al. 2011), the middle and southern portions contain sequences of ridges and plateaus interspersed by intramontane depressions and dissected slopes of fluvial valleys (Rezende and Salgado 2011; Felippe et al. 2012).

The tilting that affected portions of planation surfaces, the strong resistance of the marginal scarps in different lithologies, fault striation in laterites, different thicknesses of Tertiary sediments in different locations, alignment of lake axes, river captures, and drainages installed in the Paleogenic sediments are all evidence of neotectonics at the Espinhaço (Saadi 1995; Penha et al. 2005; Lana and Castro 2010). The recurrence of some tectonic instability in the region during the Cenozoic illustrates the reflexes of the global tectonics in the entire Brazilian Shield expressed in the reactivation of inherited structures (Saadi 1995).

Some human intervention also has contributed to the formation of the rare landscape beauty observed in the SdEM. Such is the case of the Lapinha Intramontane Depression (Rezende and Salgado 2011) in the municipality of Santana do Riacho, where the Coronel Américo Teixeira Plant dam was built in 1950s (Fig. 33.7a, b). Bordered to the ENE by the Serra do Breu Ridges, this depression covers the western side of the escarpment and the perpendicular valleys of several streams. The fluvial incision along the narrow axis of the depression is facilitated by the weakness of limestones and metapelites. The floor displays smooth slopes and an altitude of approximately 1,100 m. However, the altitude considerably increases near the canyon where the Pedras River crosses the western escarpment of the SdEM and becomes one of the outlets of the drainage system trapped inside the Depression.

33.3 The Key Geographical Divide

Constituting a great hydrographic divide, the Serra do Espinhaço separates the São Francisco River Basin from the basins of central-eastern Brazil and marks a significant altitude difference between the highest surfaces of the continental interior and the lower surfaces in the Atlantic coast (Valadão 2009). In Minas Gerais, the SdEM also plays an important role in the individualization of climate, biomes, and landscape domains.

The unique relationship between the topography, climate, and soils of the southern Serra do Espinhaço has been reported since the nineteenth century by traveling naturalists. Richard Francis Burton and Auguste de Saint-Hilaire depicted the physical, economic, and sociocultural aspects of the southern Serra do Espinhaço in great detail (Lopes et al. 2011). Their works were important means of disseminating information about the Brazilian landscape in Europe and North America, which initiated research on the biogeography of the Serra do Espinhaço.

Fig. 33.6 Examples of waterfalls in the Santana do Riacho region: **a** Cachoeira do Tabuleiro and **b** Cachoeira Grande in the Cipó River. *Photographs* Ataliba Coelho

To the east of the SdEM, the relatively smooth granite-gneiss hills are covered by remnants of semideciduous seasonal forest (Mata Atlântica—Fig. 33.8c) growing in evolved Oxisols and Alfisols (IBGE 2001). This vegetation is favored by the orographic rains that result from the obstruction of Atlantic air masses by the Range. To the west of the SdEM, downwind, there are several savanna vegetation types (Fig. 33.8a) associated with a low-gradient undulating relief of pelitic-carbonatic sedimentary rocks of the Bambuí Group and in thinner soils, such as Alfisols and Inceptsols, which have sometimes evolved from Paleo-oxisols (IBGE 2001). Nowadays, this original vegetation cover appears as fragmented remnants under human influence (Fig. 33.8b).

In addition to the predominant vegetation types in the edges of the SdEM, the internal sectors comprise the high-altitude rocky field biome ("Campos rupestres"—Fig. 33.8d). These fields have vegetation that is unique in the world, occurring at elevations above 900 m, in rocky outcrops or in sandy, fine, or gravelly soil that is shallow, acidic, and poor in nutrients and organic matter and has low water-retention capacity (IEF 2005). This biome is also conditioned by the regional mesothermal climate (Neves et al. 2005), which is strongly influenced by orographic factors, thereby enabling annual rainfall and temperature averages ranging from 1,250 to 1,550 mm and 18 to 19 °C, respectively. The outer zones, in comparison, display a significantly higher annual average temperature.

The high-altitude rocky fields contain a moderately continuous herbaceous stratum and small sclerophyllous evergreen shrubs and subshrubs, concentrating several endemic species of plants and animals (Stattersfield et al. 1998; Vasconcelos 1999, 2008; Vasconcelos and D'Angelo-Neto 2007). The *Velloziaceae* and *Bromeliaceae* families stand

Fig. 33.7 Coronel Américo Teixeira Plant Dam at Lapinha da Serra, near to Santana do Riacho: **a** geomorphological context of the dam; **b** detail of the hills bordering the dam. *Photograph* Ataliba Coelho

out due to their large number of species that only occur in the Serra do Espinhaço (Versieux et al. 2008; Garcia and Diniz 2003). The continuity of the high-altitude rocky fields in the Espinhaço range is only interrupted by the presence of patches of savanna and gallery and hillside forests, in addition to forest islands (capões de matas; Giulietti et al. 1987). These forest patches are often associated with outcrops of basic and metabasic intrusive rocks that influence thicker weathering mantles.

Based on its varied geological and geomorphological setting and its geographical position in the South American continent, the SdEM provides the conditions for setting up a complex environmental mosaic that ensures the ecological support for the establishment of a singular biota (Ab'Sáber 2003). The high endemism recorded in literature led to the United Nations Educational, Scientific and Cultural Organization (UNESCO) recognition of the Serra do Espinhaço Biosphere Reserve (Gontijo 2008). Part of the explanation for the peculiarity of the regional biota is related to the existence of an ecotone, or area of ecological tension between the savanna, the steppe-savanna and the seasonal semideciduous forest. In this context, the distinct formations overlap and communicate, generating a unique floristic identity that is often marked by endemism (IBGE 2004).

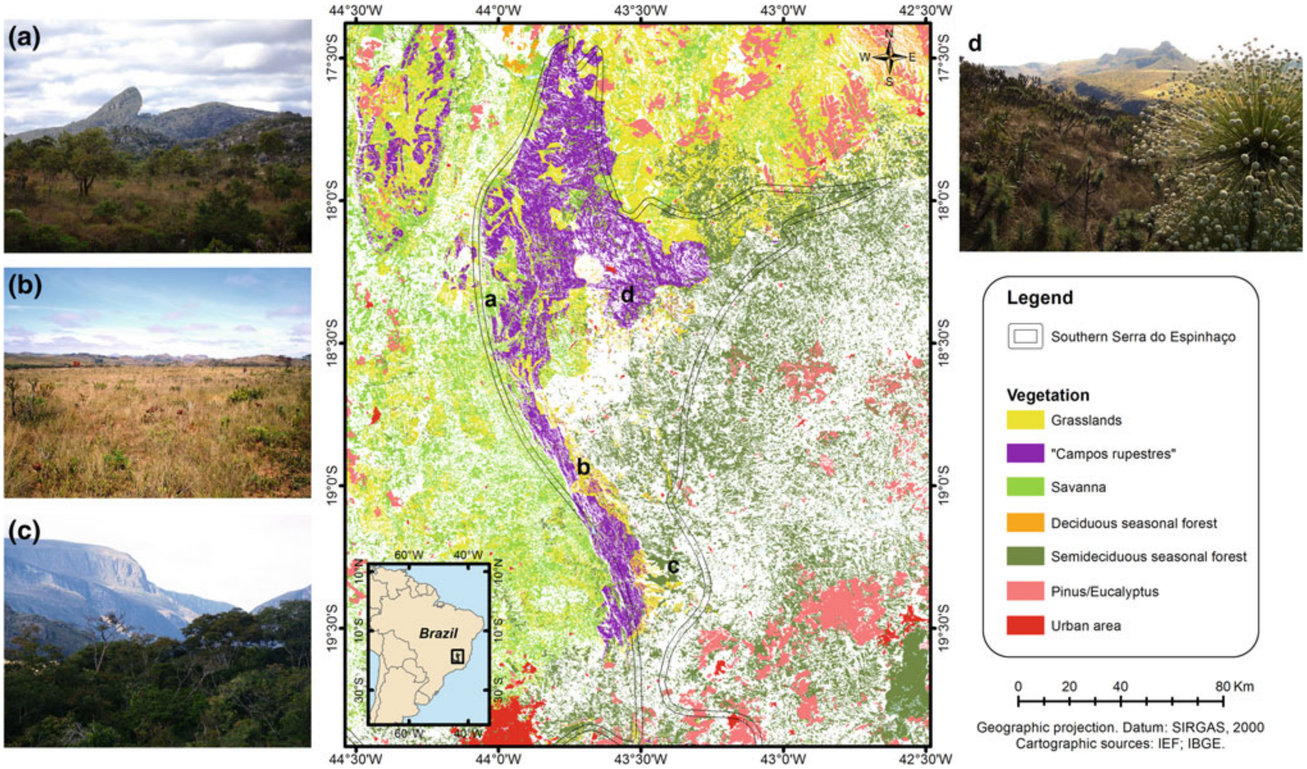

Fig. 33.8 Remnant vegetation in the SdEM and surrounding areas: **a** typical Brazilian Savanna vegetation in the west border of the SdEM; **b** grasslands changed by human influence; **c** fragment of semideciduous seasonal forest nearby a quartzitic ridge; **d** high-altitude vegetation occurring in shallow soils, known as "Campos rupestres"

According to Menezes and Giulietti (2000), the high rate of endemism of the local flora is also related to the age of its isolation and unique climate conditions. Several conservation units throughout the SdEM are of great importance for the preservation of this environmental and scientific potential, such as the Serra do Cipó National Park, the Sempre-Vivas National Park, Biribiri State Park, the Rio Preto State Park, the Pico do Itambé State Park, and the Serra do Intendente State Park.

The SdEM also houses many sites of historical and anthropological interest. Prehistoric records have been identified throughout the SdEM and surroundings (Lagoa Santa sites), which were and still are a great stimulus for further studies and theories about the migration process of man to the Americas. In the mid-1970s, dozens of skeletons from a population with Negroid features were identified in the municipality of Santana do Riacho, which came to be identified as one of the oldest cemeteries in the Americas, aged between 8.2 and 10,000 years BP (IEF 2005). Important records of the indigenous occupation of Mongolian origin have also been verified through archeological sites with rupestrian paintings identified as "Tradição Planalto," beginning at least 7,000 years BP (Prous 1992).

Since the eighteenth century, the human occupation of the SdEM has intensified due to the discovery of alluvial gold and diamonds. Important mining settlements were established, resulting in cities such as Diamantina, Serro, and Conceição do Mato Dentro. At that moment, these cities had a primary importance to the urban network structure. Immigrants arrived and new pathways to food and services were opened, creating other urban centers along the routes. In the climax of this process, the diamond district was linked to Villa Rica and Rio de Janeiro (the two most important Brazilian cities in the eighteenth century) by a road known as "Estrada Real" ("Royal Road"). Currently, this road is one of the most popular tourist routes of Minas Gerais State.

The decline of prospecting in the late eighteenth century sealed the end of an era of intense wealth generation. Nevertheless, that prosperity is still visible in the architecture of the historic towns (Diamantina, Serro, and Conceição do Mato Dentro), which are recognized by UNESCO as World Heritage Sites. Nowadays, this colonial legacy is part of the touristic circuit of Minas Gerais that involves the natural beauties of the SdEM and the architectural heritage of the gold mining period. However, the region has been seen recently as a new frontier for enterprises of mining iron ore, despite its low content. Unfortunately, these large projects may endanger the local biological richness, and the landscape beauty.

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Itatim Geomorphological Site: Largest Concentration of Inselbergs in Brazil

34

Geraldo Marcelo Pereira Lima and Luiz César Corrêa-Gomes

Abstract

Itatim geomorphological site (IGS) in central-eastern Brazil is prominent among inselberg terrains worldwide due to the quantity and variety of shapes (castles, bornhardts, inselgebergs, castle koppies, and tors), formed from the Miocene. Factors that have played a role in the origin of Itatim inselbergs include: (i) the presence of younger intrusions within an ancient bedrock; (ii) location in shear and other tectonic contact zones where high- and low-strain areas are juxtaposed; (iii) mineralogical differences between the inselbergs and the surrounding rocks; (iv) regional uplift followed by tectonic stability in the past tens of millions of years; and (v) arid and semiarid climates exerting influence in the most recent geological past into the present.

Keywords

Itatim geomorphological site • Inselbergs • Structural geomorphology • Plutonic rock • Erosion surfaces

34.1 Introduction

Inselbergs are a special class of residual landforms with landscape configuration marked by a contrast between prominent elevations (height > 100 m) and the surrounding plains. It was first coined by Wilhelm Bornhardt, a German naturalist traveling in Namib Desert at the turn of the nineteenth century, to emphasize visual similarities between steep-sided hills dotting an otherwise flat savanna and islands rising from the sea (Bornhardt 1900). They are typically built of igneous rocks (Bornhardt 1900; Johnson 1932; Dresch 1962; Kesel 1973; Lima et al. 2009), but metamorphic and occasionally sedimentary rocks may support inselbergs too. Brazil has one of the largest concentrations of inselbergs in the world. They are preferentially distributed in the northeast regions of the country, in Bahia, Ceará, Paraíba, and Rio Grande do Norte states. Other inselbergs are located outside the semiarid domain of Brazil, including the states of Espírito Santo, Rio de Janeiro, and Amazonas, which are all in sub-humid to humid regions. In the east-central portion of the State of Bahia (Fig. 34.1), an area of approximately 1,000 km^2 known as Itatim geomorphological site (IGS) is located, prominent among inselberg landscapes given the quantity, variety of shapes, and scenic beauty of these landforms (Fig. 34.2).

The Itatim area is characterized by pronounced climatic variability, with frequent periods of water scarcity. Rainfall patterns vary across IGS, but the whole region receives less than 600 mm rainfall per year (with six dry months), typically between September and February. The average annual temperature in the region exceeds 26 °C. However, the temperature variation from sunlight during the day and cooling at night can be 35–16 °C, respectively. Moreover, rock surfaces can be warmed by insolation to up to twice the ambient air temperature, which significantly accelerates rock exfoliation.

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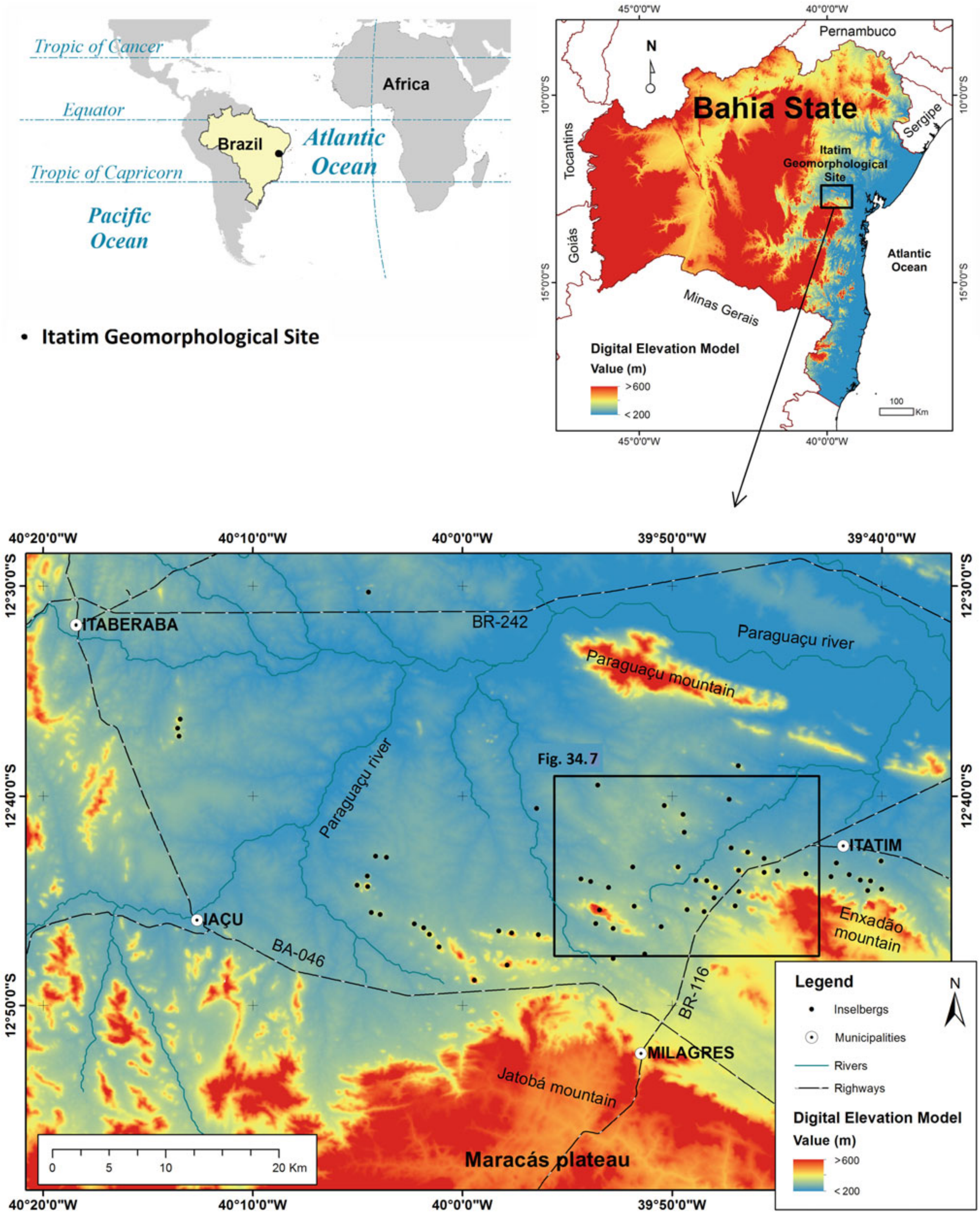


Fig. 34.1 Location at Itatim geomorphological site in the Bahia State *Rectangle* locates 3D-diagram block in the Fig. 34.7

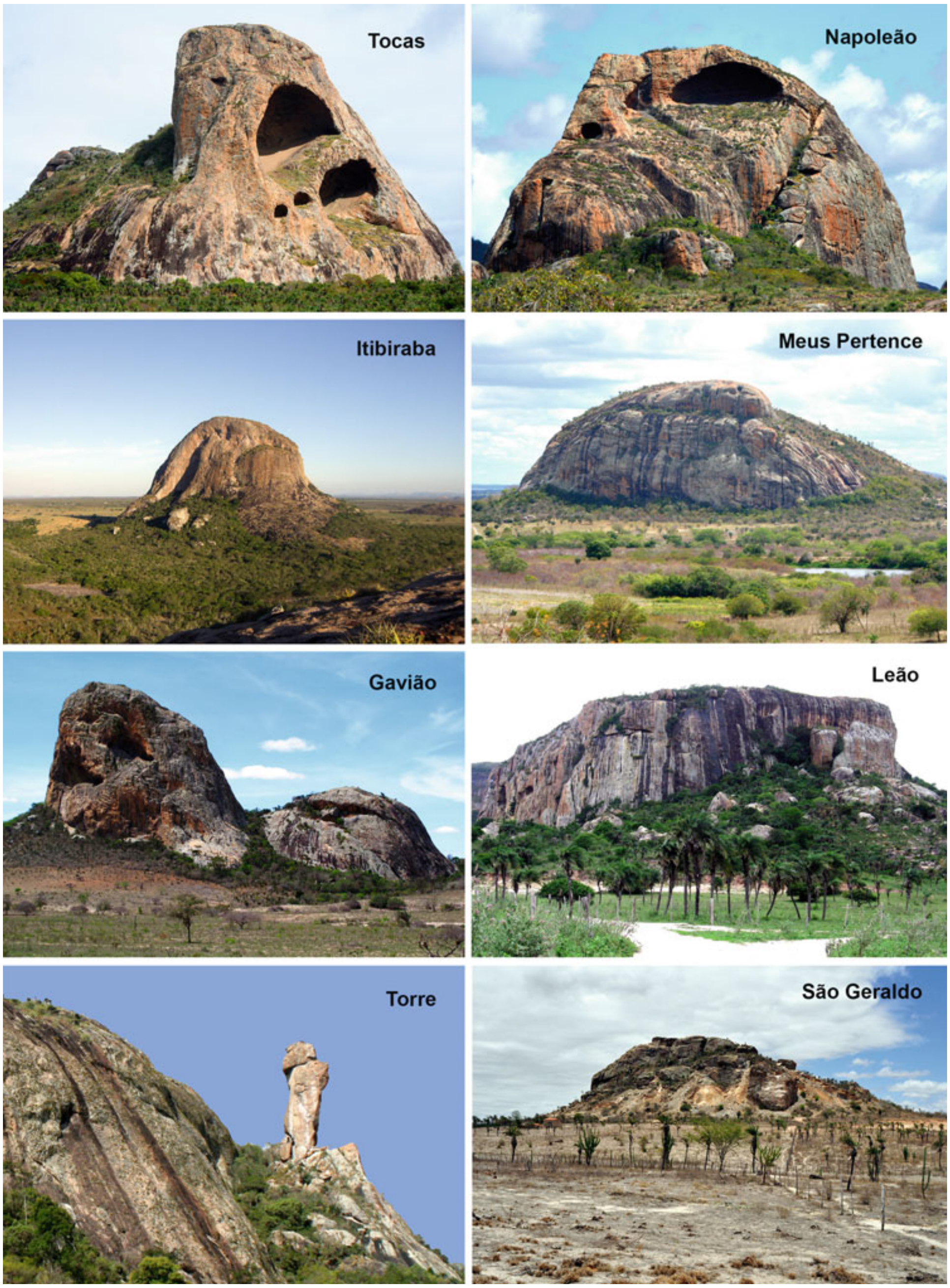


Fig. 34.2 Some Inselbergs at the Itatim geomorphological site

From a geoecological perspective, an inselberg is a sensitive microhabitat. Sometimes, it comprises a thin layer of soil and a particular microclimate at its surface, which are conditions tolerated by a few organisms, such as Bromeliaceae (*Encholirium spectabil* and *Tillandsia* sp) and Cactaceae (*Melocactus* sp), some of which are endemic to IGS region, given the inhospitable conditions in their steep cliffs. However, tree-size vegetation may grow in fractures. Thus, inselbergs are regarded as seed banks because they can repopulate a part of the surrounding original flora when they are swept by strong and frequent gusts of wind. Furthermore, the seeds can be dispersed by animals, including insects, birds, small mammals, and reptiles, which seek shelter and food in the rock surface.

34.2 Geomorphological Settings

The vertical contrast between an extensive erosion surface and the tops of inselbergs at IGS is a key indicator of major base level changes. In general, inselbergs are between 100 and 200 m high (see Fig. 34.2), which is a striking feature

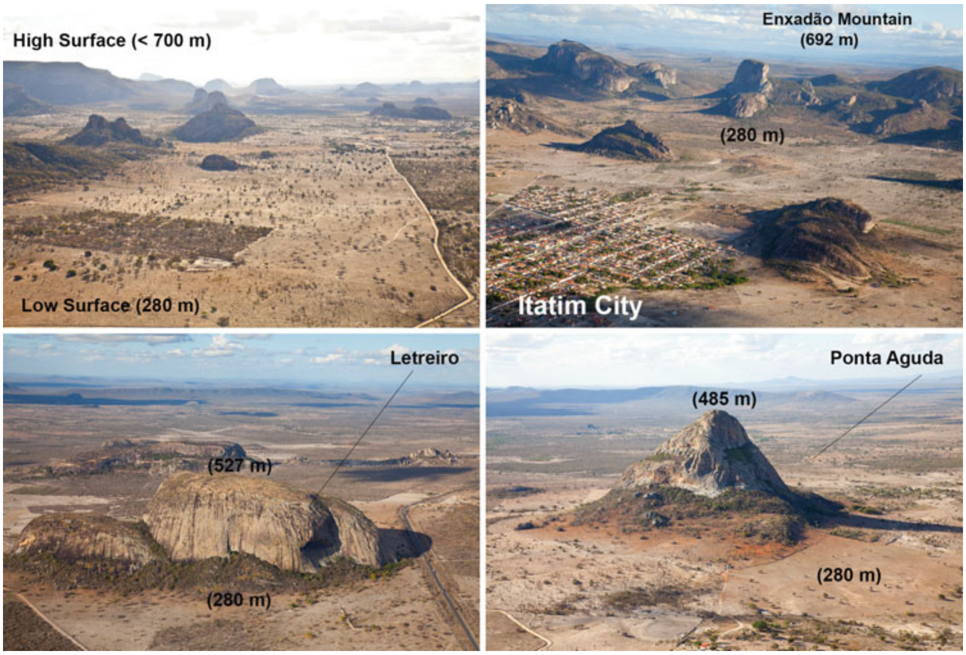


Fig. 34.3 Main elevations at the Itatim. Low surface represent current base level in the region

of the inselberg population (Fig. 34.3). The current base level in the region is ~300 m asl. on average, ranging from 280 to 320 m. Were the erosion surfaces of the crystalline basement produced by surface processes typical for arid environments or their presence reflects strong structural control?

Horizontal and sub-horizontal stress-relief fractures are created in each rock package in the shallow lithosphere and crucially influence the formation of flat base levels in crystalline basement environments. The visual effect of terrain flatness is primarily from the sandy cover on pediments, which covers approximately 80 % of IGS area and corresponds to the "Pediment Association" aggradation zone (Cooke 1970). Lithological properties of this quartz-rich sandy material may be linked to the phaneritic texture of the crystalline rock in the Itatim Shear Zone.

The piedmont junction between the low-elevation surface and hillslopes of inselbergs is sharp and steep, with an angle that ranges from 50° to 90°. At the base of inselbergs and in its surrounding, big boulders of decametric size commonly occur. The main mountains are known as Paraguaçu (799 m) in the north and Jatobá (809 m) in the south (see Fig. 34.1) and are apparently the relief compartments of the greatest resistance against weathering and erosion. The central part of this area corresponds to a shear zone and rock resistance is reduced, which is demonstrated by the Enxadão (692 m) and other, less elevated inselbergs (Fig. 34.3).

The regional denudation history of Itatim may be traced back to the Permian (295 Ma), wherein approximately 3–5.6 km of rock have been eroded away. Denudation appears to have occurred in phase-wise manner, via the three well-marked episodes of enhanced surface lowering: Permian–Early Jurassic (300–180 Ma), Late Jurassic–Early Cretaceous (150–120 Ma), and Neogene (<30 Ma) alternating with periods of stability. Denudation intensified from the Miocene onward, with exhumation of metamorphic rocks that form the inselbergs, with the minimum and maximum rates ranging from 30 to 150 m M year^{-1}, respectively (Lima et al. 2012) with periods of stability again.

Japsen et al. (2012) reported that the low surface corresponds to the Paraguaçu Surface, but the highest surface is Maracás Plateau and is also the Velhas Surface (see Fig. 34.3) described by King (1956). Peulvast and Sales (2005) further identified two levels of erosion of regional extent in the Brazilian northeast region with inselbergs, including a surface at 300 m, the Sertaneja Surface, and a discontinuous plateau at an altitude higher than 750 m, which corresponds to Chapada do Araripe and the Borborema Plateau and analogous between the Paraguaçu and Velhas surfaces at IGS.

34.3 Types of Inselbergs in Itatim Geomorphological Site

The shapes of inselbergs at Itatim are drawn before the massive bedrock compartments reach the surface. The contours follow the spatial arrangement of fractures and joints, magmatic foliation, and deformation structures. Depending

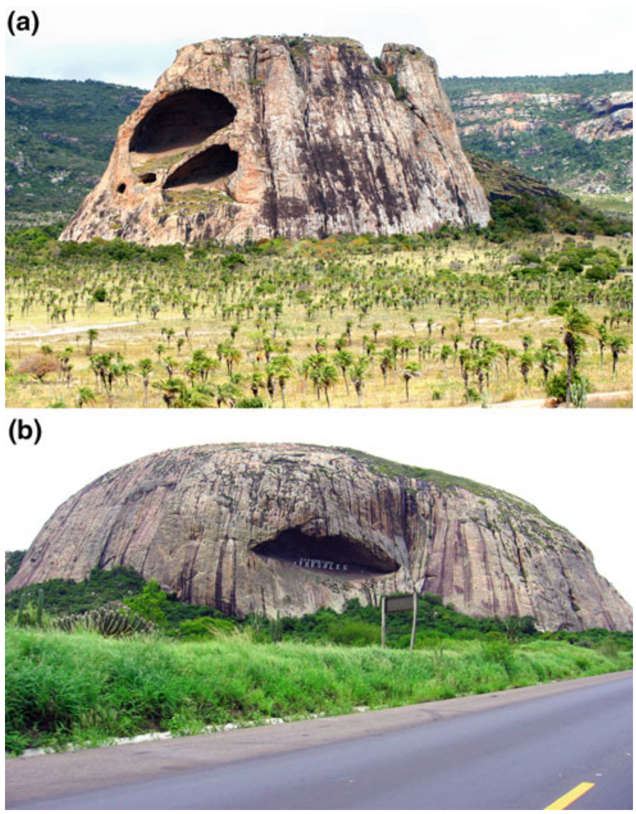


Fig. 34.4 Types of castles (**a**) and bornhardts (**b**) found at Itatim geomorphological site. The cavities (tafoni) observed in inselbergs are controlled by magmatic foliations, horizontal fractures, and spheroidal exfoliation

on the shape and outline, a few major morphological types of inselbergs may be distinguished.

Castles—These inselbergs are the most imposing and scenically beautiful. They are typically controlled by vertical and subvertical fractures. Their steep walls can reach a 90° angle relative to the planation surface (Fig. 34.4a).

Bornhardts—These are domes with rounded surfaces. They may resemble turtlebacks or whalebacks and are elliptically elongated (Fig. 34.4b). The bornhardt incipient archetype is initiated in the subsurface, following the shape of a plutonic intrusion, flow foliations formed during intrusion, or the pattern of arched joints. When close to the surface and exposed to atmospheric influences, the intrusion is subject to lithostatic stress-relief and peeling or exfoliation surfaces consistent with the primary foliation planes may develop. Bornhardts may be more than one kilometer long and are the most common inselbergs in the region.

'**Inselgebirge**' ('inselbergs groups' in German)—These formations comprise two or three elevations close to one another, but as a group, they are as isolated as the inselbergs proper. In general, the base level decrease between individual massive compartments was insufficient to isolate them and there connecting hillslopes still exist. A large concentration of groups of inselbergs is west of IGS (Fig. 34.5a), and as they become true inselbergs due to further surface lowering, the current number of inselbergs in the area may double.

Castle koppies—These inselbergs, if compared with bornhardts, are much lower residual hills. They are typically <100 m high and consist of stacked angular blocks, with well-marked edges and rock walls (Fig. 34.5b). Their advanced disintegration likely reflects a higher density of fractures and, hence, more efficient water infiltration into the rock and weathering (Twidale 1981).

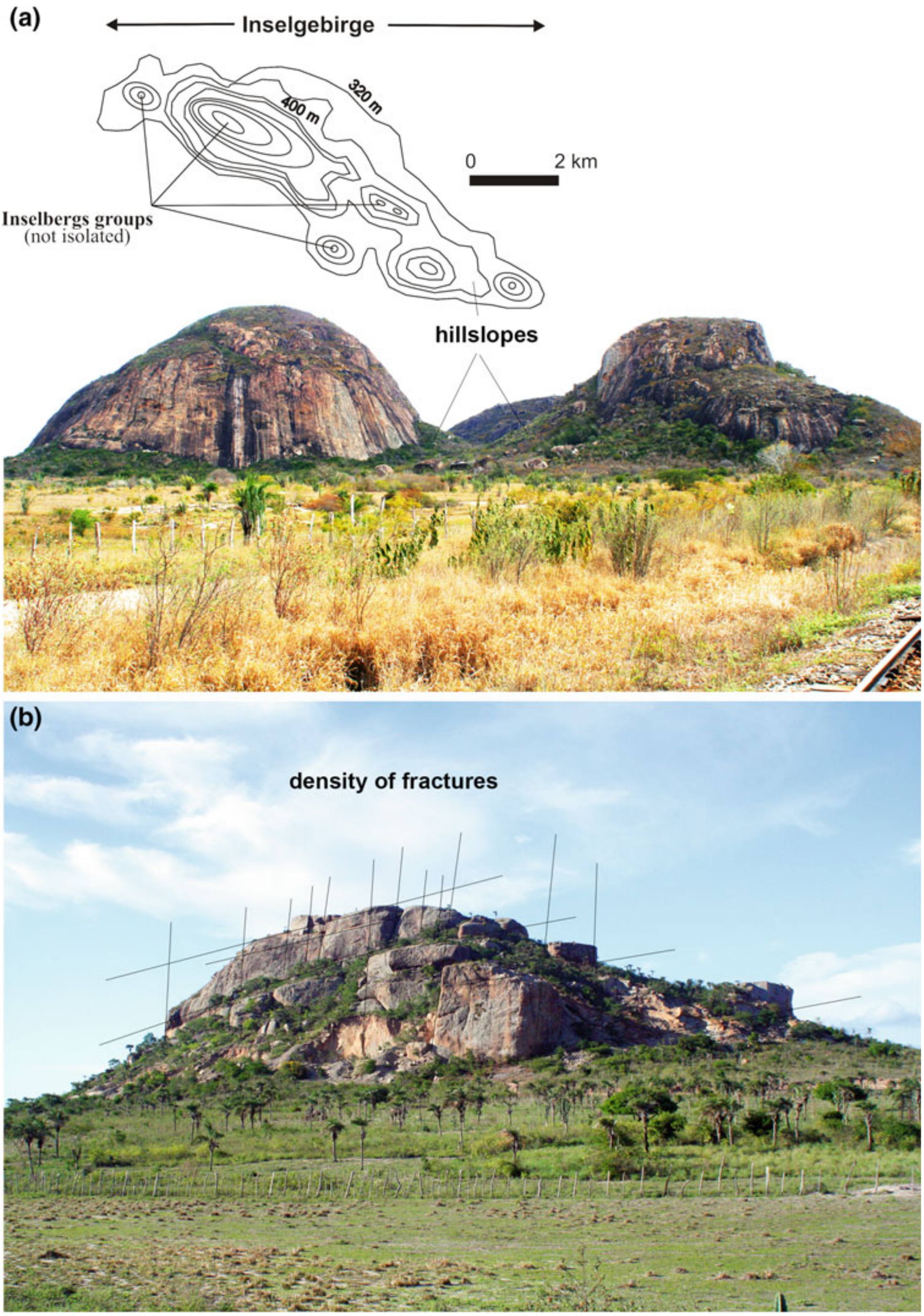
34.4 Structural and Mineralogical Control in Inselberg Formation

Freise (1938) was a pioneer in morphological and petrographic studies of inselbergs in northeast Brazil and hypothesized that their resistance resulted from their granite–gneiss composition. He also showed structural control effects on inselbergs, demonstrating their alignment with the regional tectonic stress orientation.

At Itatim, the following factors may be recognized as responsible for the origin of inselbergs: (i) Intrusions are hundreds of millions of years younger than rocks underlying plain areas and when exposed, they tend to be more resistant to erosion; (ii) shear and/or other tectonic contact zones are high-strain areas, where weathering and erosion may act with particular efficacy; by contrast, the intervening low-strain areas are eroded less and give rise to inselbergs and other residual landforms; (iii) mineralogical differences between inselbergs and the surrounding rocks, now eroded; (iv) regional uplift followed by tectonic stability during the past tens of millions of years; and (v) the influence of arid and semiarid climates in the recent geological past and up to the present.

Small- and large-scale structures formed during collision, shear zones, and younger intrusions have had a remarkable effect on inselbergs development, especially at Itatim. Such structures were formed between 2.1 and 2.0 Ga during collision and collapse of a mountain range between two crustal

Fig. 34.5 'Inselgebirge' (**a**) and a castle koppie (**b**) found at Itatim geomorphological site



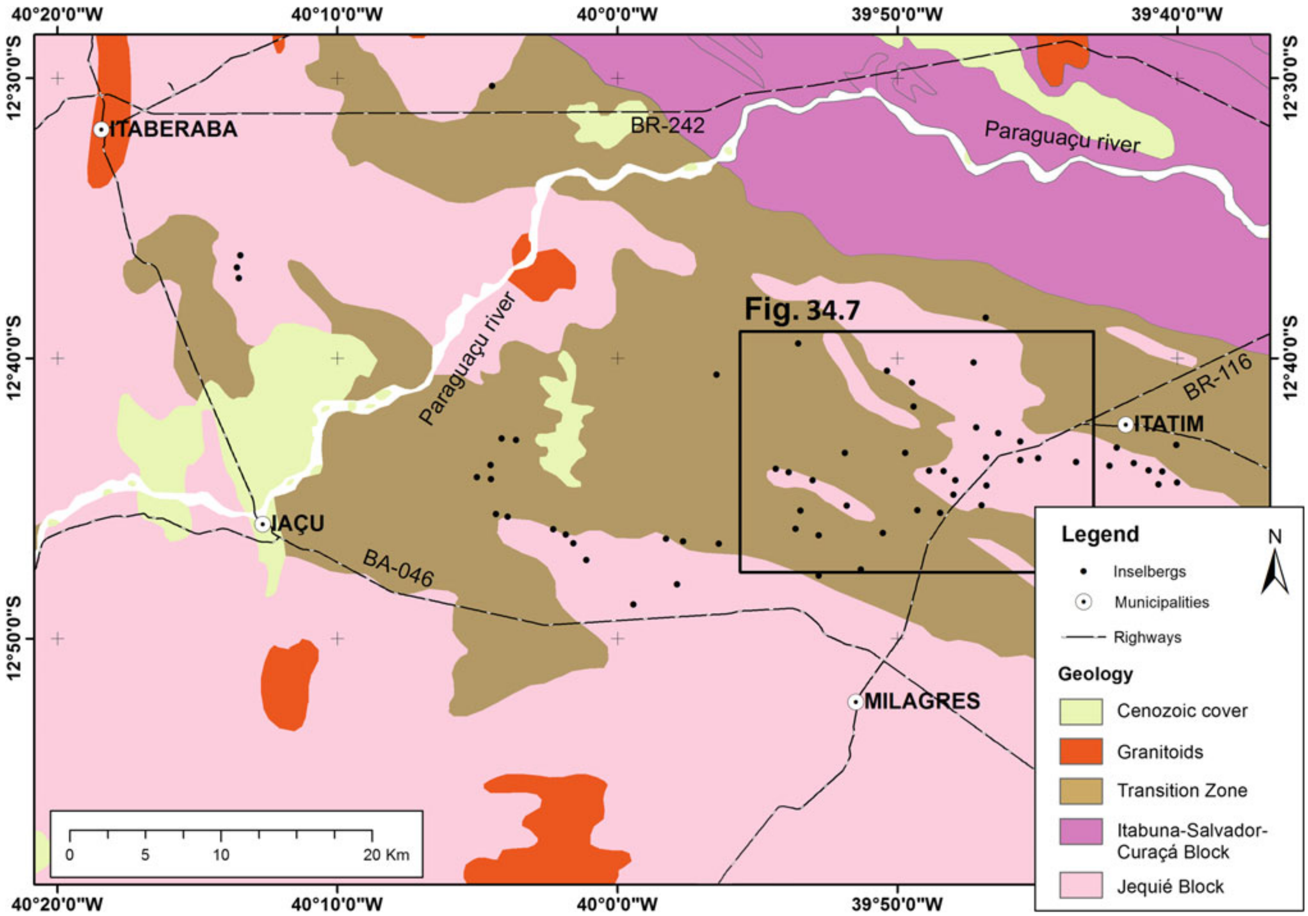


Fig. 34.6 Simplified geological map of Itatim. The *rectangle* locates 3D-diagram block in the Fig. 34.7

blocks (Corrêa-Gomes et al. 2012), the Jequié and Itabuna-Salvador-Curaçá blocks (Fig. 34.6), formed 2.7 Ga years ago (Barbosa and Sabaté 2003; Barbosa 1997). The rocks that currently crop out and build the inselbergs have granodioritic to tonalitic composition and consist in approximately 30 % of quartz (Fig. 34.7). They were formed at the depth of tens of kilometers, which is consistent with the granulite and amphibolite facies in the deep root of the Paleoproterozoic orogen.

Virtually, all ductile structures were reused during the formation of stress-relief fractures as the rock masses approached the topographic surface through denudation. The cumulative control of these structures and events is clearly demonstrated in the following geometric shapes of inselbergs: (i) The vertical shear bands (S_{n+1}) trending WNW–ESE (110–120°) control the outlines of inselbergs as valleys have been excavated along high-strain areas and elevations survived along low-strain areas and/or bands with more mafic or felsic mineralogical compositions; (ii) the upper slopes of inselbergs are typically parallel to sub-horizontal mineral banding (S_n), magmatic foliation (S_0), and low-angle foliation planes (S_{n+3}); and (iii) the N30° and N150° vertical shear zones (S_{n+2}) represent cross-sectional inselberg contours (Fig. 34.8).

Field analysis of regional and local structures at Itatim shows a succession of events that indicates a continued rise in the crustal level (Santiago 2010; Corrêa-Gomes et al. 2012). Foliation and sub-horizontal mineral banding (S_n) were formed at the beginning of the collision and materialized as reverse shear zones with tectonic vergence from NW

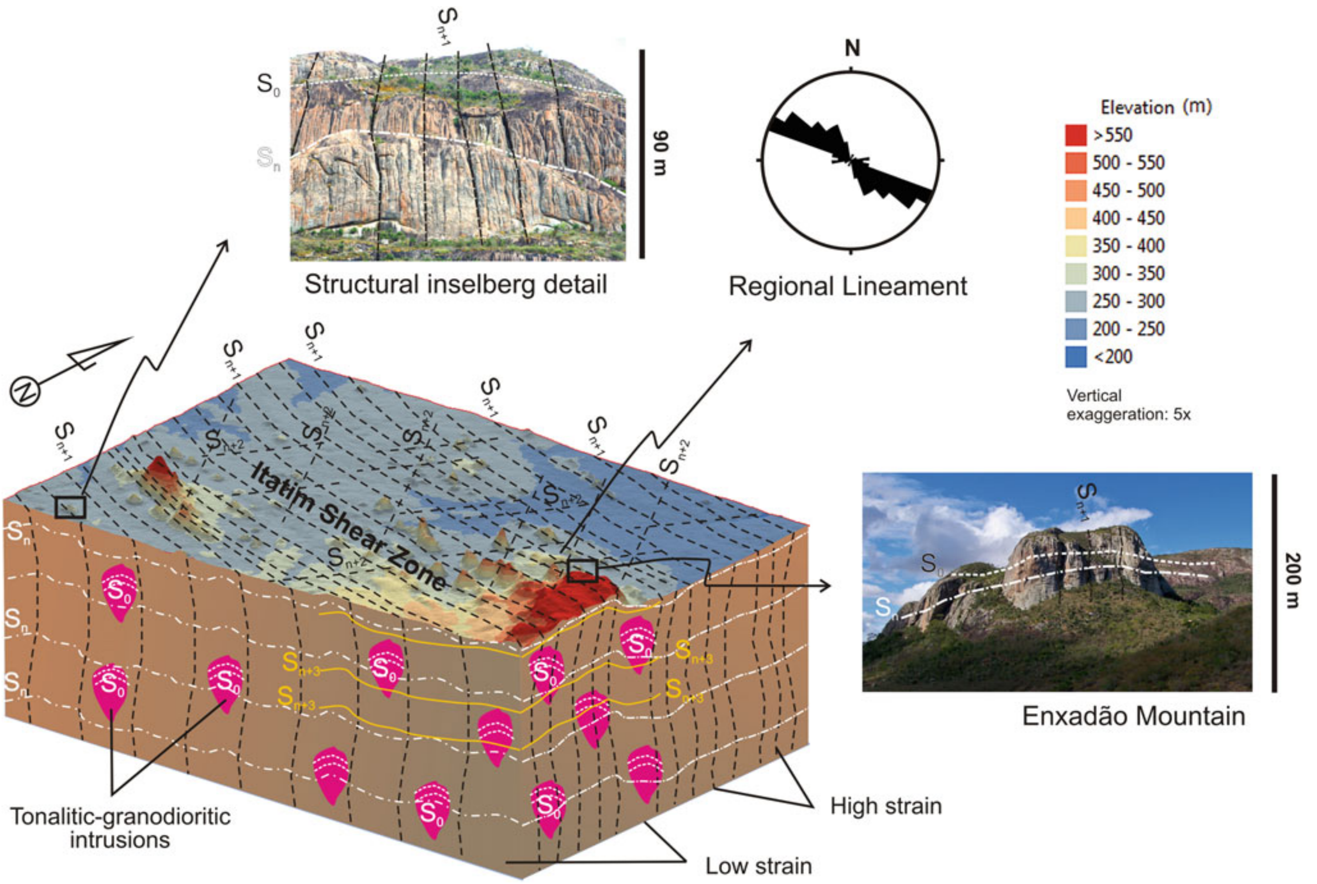


Fig. 34.7 Main structural lineaments (*black lines*) drawn over terrain model and the corresponding rose diagram of their frequencies at the Itatim geomorphological site

to SE. In the next event, the foliation was transposed by dextral N110–120° vertical shear bands (S_{n+1}), which represent the primary current regional trend in inselberg orientation. A third event generated a pair of vertical conjugate shear zones: the N30° sinistral and N150° dextral (S_{n+2}) zones. Finally, the last event generated low-angle N–S foliation (S_{n+3}) linked to the orogenic collapse and an E–W regional extension.

Morphometric analysis of inselbergs at Itatim shows that the structures and mineralogical composition are primary factors controlling differential erosion and the different sizes of individual hills, with weathering as a secondary factor. The spacing between the fractures exposed within inselbergs is metric and decametric, vertically and horizontally, respectively. On a smaller scale, spheroidal exfoliation acts upon the rocks, giving rise to onion-like appearance of outcrops.

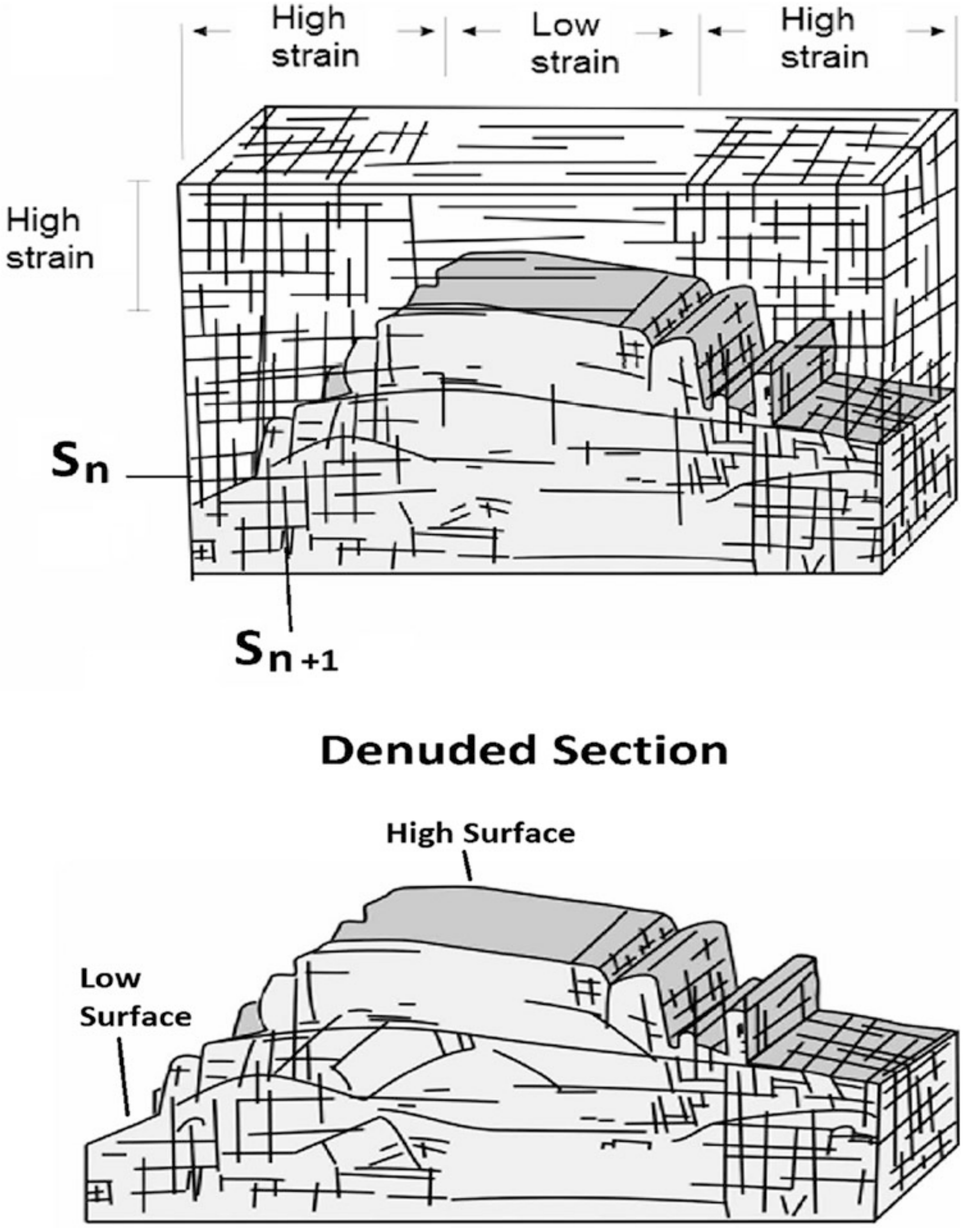


Fig. 34.8 Structural control on inselbergs evolution at the Itatim geomorphological site

34.5 Conclusion

Inselbergs, fairly common in Brazil, are not only exceptionally magnificent natural monuments that rip the ground toward the sky, contributing thereby to the unique scenic beauty of the landscape. They also have a key scientific and ecological value and emphasize the spiritual value of the landscape. Cave paintings found in these inselbergs are the evidence of the early human occupation of the region, which could have been used as a “geographic position system” because of landscape configuration marked by a contrast between a prominent elevation and the surrounding plain. This area was occupied again only after European colonization, from the eighteenth century onward. However, the major environmental challenge at Itatim is associated with poor social conditions of the population living in the surroundings. Due to ongoing quarrying, some of these stone giants may eventually become cobblestones or be reduced to gravel. Even though the inselbergs are protected by law, numerous quarries clandestinely attract hundreds of men, women, and even children to meet the livelihood of their families. Nevertheless, as for now, towering bornhardts, castle koppies, and tors can be found at Itatim, in a stunning setting worthy of the great movie scenes. This is how the visitor feels when confronted with such nature monuments.

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35 Pancas: The Kingdom of Bornhardts

César Augusto Chicarino Varajão and Fernando Flecha de Alkmim

Abstract

Underlain by Neoproterzoic granitic rocks, the region around the town of Pancas, located in the Espirito Santo State, eastern Brazil, comprises a spectacular landscape dominated by bornhardts of various shapes. Sugarloafs, turtlebacks, domes and pinnacles separated by long and rectilinear valleys occupy an area of ca. 17,400 ha, which was declared natural monument by the Brazilian government in 2008. The development of the bornhardt province seems to involve the following stages: (i) nucleation of a system of vertical and widely spaced joints in the granitic bedrock at sometime in the Late Neoproterozoic, (ii) intensive weathering along the joints probably during the Eocene and (iii) uplift and subsequent erosion between the Late Miocene and the Pliocene, thereby leading to the exhumation of the bornhardts.

Keywords

Bornhardt • Pancas • Pontões capixabas • Espirito santo state • Brazil

> *Bornhardts, or granite-gneiss inselbergs, have attracted attention from geomorphologists… they sometimes confer upon the landscape a truly awful and mysterious appearance as though the observer had descended upon another planet.*
>
> *—(King 1948, p. 83).*

35.1 Introduction

Bornhardts are common landforms in the vast area of the southeastern Brazilian states of Rio de Janeiro and Espírito Santo (Fig. 35.1). Underlain mainly by Neoproterozoic gneissic and granitic rocks, this region encompasses, among other geomorphologic provinces, the Serra do Mar (the coastal range), whose most famous manifestation is the Pão de Açúcar (Sugarloaf) of Rio de Janeiro.

The region around the town of Pancas in northern Espírito Santo is one of the most spectacular landscapes of Brazil and is characterised by a high concentration of bornhardts of various shapes (Figs. 35.2 and 35.3), separated by long and straight valleys partially covered by remnants of the Atlantic forest. Extending over an area of 17,443.43 ha, Pancas and its surroundings were declared a Natural Monument in 2008. Presently managed by the Chico Mendes Institute for the Conservation of the Biodiversity (ICMBio) of the National Environment Department, the Pancas bornhardt province is currently called the Monumento Natural dos Pontões Capixabas.

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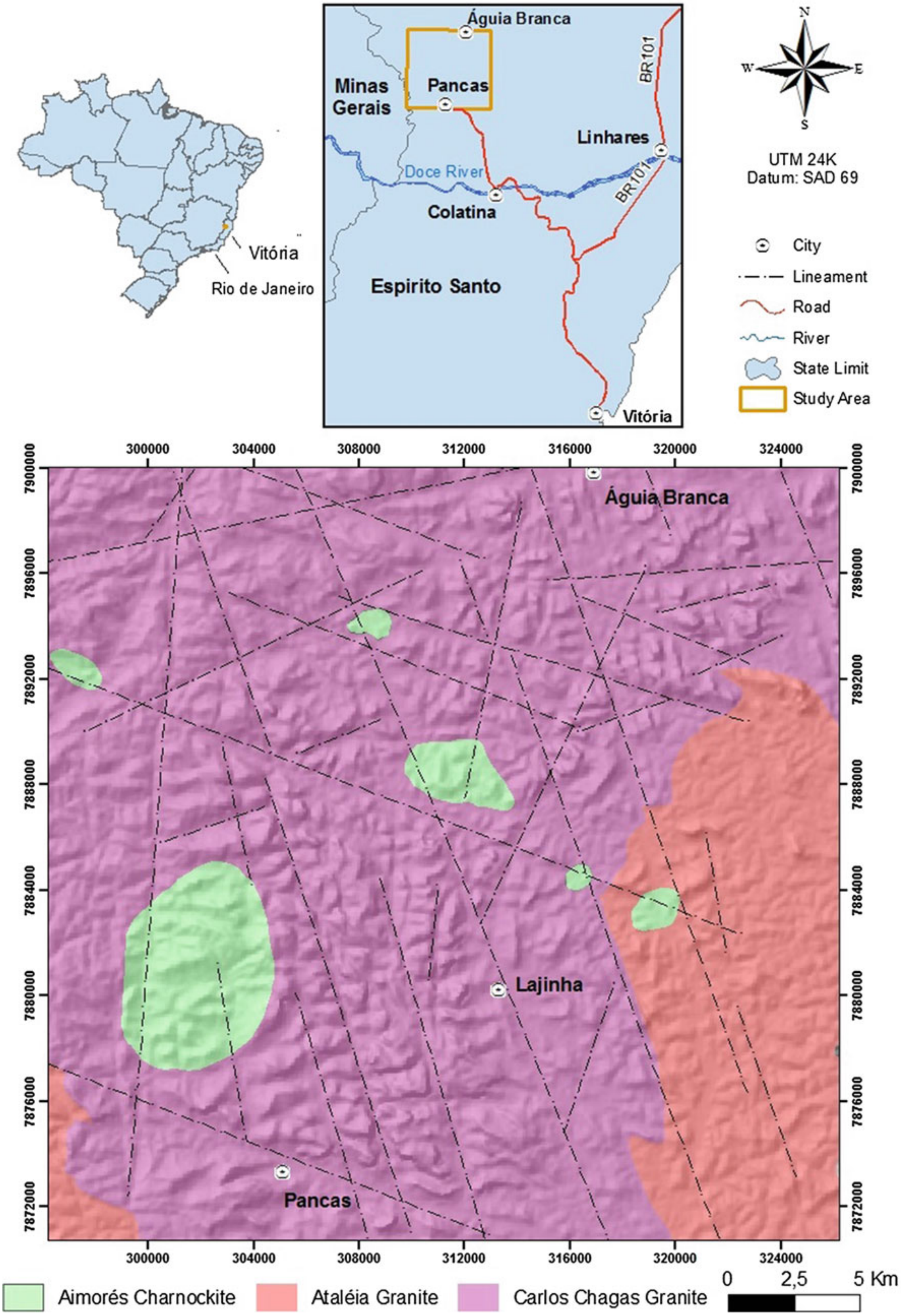

Fig. 35.1 Simplified geologic map of the Pancas bornhardt province (modified from Baltazar and da Silva 2009)

Fig. 35.2 The town of Pancas at the entrance of the bornhardt kingdom, viewed from the southwest

Fig. 35.3 The “many brothers” (after King 1956), a set of bornhardts near the town of Águia Branca

The regional climate is tropical humid with dry winter (Aw). The annual precipitation is greater than 1,400 mm, and the mean annual temperature is 23 °C. Coffee has always been the main agricultural activity. After the huge crisis of the 1960s, which culminated in the eradication of more than 50 % of the crops, this culture was reactivated in the 1980s and became part of the second most important area of Brazilian coffee production. Eucalyptus plantations for cellulose production started in the 1970s.

35.2 Bornhardt: Term and Concept

The term “*bornhardt*” was introduced in the literature by Willis (1934), in honour of the German geologist Wilhelm Bornhardt, who had in turn proposed the term “*Inselberg*” (island mountain) to refer to the massive rounded domes, sharp pinnacles and smooth turtlebacks made up of gneissic rocks (Bornhardt 1900) that abruptly rise above the lowlands of the west African savannahs. As noted by Twidale (2002, p. 44), "*in a masterly and succinct outline of a two-stage theory of inselberg landscape development*", Falconer (1911, p. 246) stated, "*A plane surface of granite gneiss subjected to long-continued weathering at the base level, would be decomposed to unequal depths, mainly according to composition and texture of the rocks. When elevation and erosion ensued, the weathered crust would be removed, and an irregular surface would be produced from which the more resistant rocks would project. Those rocks which had offered the great resistance to chemical weathering beneath the surface would upon exposure naturally assume that configuration of surface…In this way would arise the characteristic domes and turtle-backs*". Later, the term inselberg was used to refer to similar landforms in a variety of terrains, regardless of the dominant rock type or climate.

Willis (1934, p. 124) was precise and strict in his concept of bornhardts. Accordingly, bornhardts are forms that show "*bare surfaces, dome like summits, precipitous sides becoming steeper toward the base, an absence of talus, alluvial cone soil, and close adjustment of form to internal structure*". Furthermore, he postulated that weathering acting upon of a particular rock type (i.e. granite and gneiss) in a peculiar structural setting and then tectonic uplift and erosion are the processes that lead to the isolation of a bornhardt (Willis 1934, 1936).

The Falconer–Willis model was preceded by various attempts to unravel the development of bornhardts. Hassenfratz (1791) described all intermediary phases between a block of fresh granite and the resulting mass of deep weathered and friable saprolite in the Massif Central of France. Branner (1896) emphasised the abrupt transition between cohesive fresh rock and friable weathered granitoids, as well as the role played by landslides in the generation of the Rio de Janeiro bornhardts. King (1948, p. 84) emphasised the role of tectonic structures in the development of the bornhardts and noticed that "*the distribution of bornhardts is governed by the patterns of sub-rectangular joint system*". Following the same line of thought, Birot (1958) argued that the inselbergs correspond to the nuclei of rock not affected by a fracture system. After these works, the Falconer–Willis theory on the origin of bornhardts became widely accepted and currently viewed as one of the foundations of the two-stage model of landform and landscape development (see, for instance, Büdel 1957; Ollier 1960; Cotton 1961; Twidale 1964; Thomas 1965, 1989a, b, 1994).

The studies mentioned above led to the conclusion that bornhardts are landforms generated in the subsurface and later uplifted and cleaned up by erosion, which is surprising at first glance. Furthermore, as coincidently suggested by their name, bornhardts correspond to hard rock masses that escaped intensive subsurface weathering and have been able to resist subsequent erosion. Thus, as elements of the landscape, they are witness of an intricate concurrence of geological materials and processes.

35.3 Pancas Bornhardt Province

Geologically, the Pancas bornhardt province is located in the crystalline core of the Araçuaí orogen, which represents a branch of the Brasiliano/PanAfrican orogenic system developed during the amalgamation of west Gondwana by the end of the Neoproterozoic and beginning of the Palaeozoic (Pedrosa-Soares et al. 2001; Alkmim et al. 2006) (see Chap. 2). The internal sector of the Araçuaí orogen is dominated by high-grade gneisses and five distinct generations of granitoids emplaced between 625 and 490 Ma (Pedrosa-Soares et al. 2001, 2011).

The Pancas bornhardt province is underlain by the 575-Ma-old Carlos Chagas and Ataleia granites, locally intruded by 520- to 490-Ma-old charnockite plutons (Fig. 35.1) (Gradim et al. 2006; Pedrosa-Soares et al. 2006; Baltazar and da Silva 2009). The foliated Carlos Chagas leucogranite, the dominant unit in the province, is composed of very large (up to 15 cm long) K-feldspar crystals embedded in a matrix composed of plagioclase, quartz and garnet (Pedrosa-Soares et al. 2006; Roncato 2009).

Throughout the whole province, the granitic bedrock is cut by a system of long and widely spaced joints, which preferentially strike NNW, N–S, WNW and NE. This N15° W-striking family of joints defines a ca. 200-km-long and 40-km-wide fracture zone known as the Colatina Lineament, a NNW-trending joints which straddles the crystalline core of the Araçuaí orogen from Vitória, on the coast of Espírito Santo State, until the border with Minas Gerais State. In addition, the Colatina Lineament also includes an equally oriented mafic dyke swarm dated at 134 Ma (Silva and Ferrari 1976; Silva et al. 1987; Novais et al. 2004; Valente et al. 2009).

Three distinct morphological domains can be recognised in the Pancas province (Fig. 35.4a). Domain I, on the west, is characterised by a rough topography, in which steep-sided hills with up to 300 m height and maximum elevations between 800 and 850 m above sea level, forms a continuous ridge capped by a 30-m-thick weathering profile (Fig. 35.5). Domain I is not affected by the Colatina Lineament (Fig. 35.4a). Domain II, which is located in the centre of the province, is composed of bornhardts in a variety of shapes as follows: sugarloafs, domes, turtlebacks and pinnacles ("pontões") (Fig. 35.6). Close to each other and separated by narrow rectilinear valleys, the bornhardts are bare, exposing fresh granitic rocks. However, some of them exhibit a thin soil cap at the very top. The maximum elevations of the

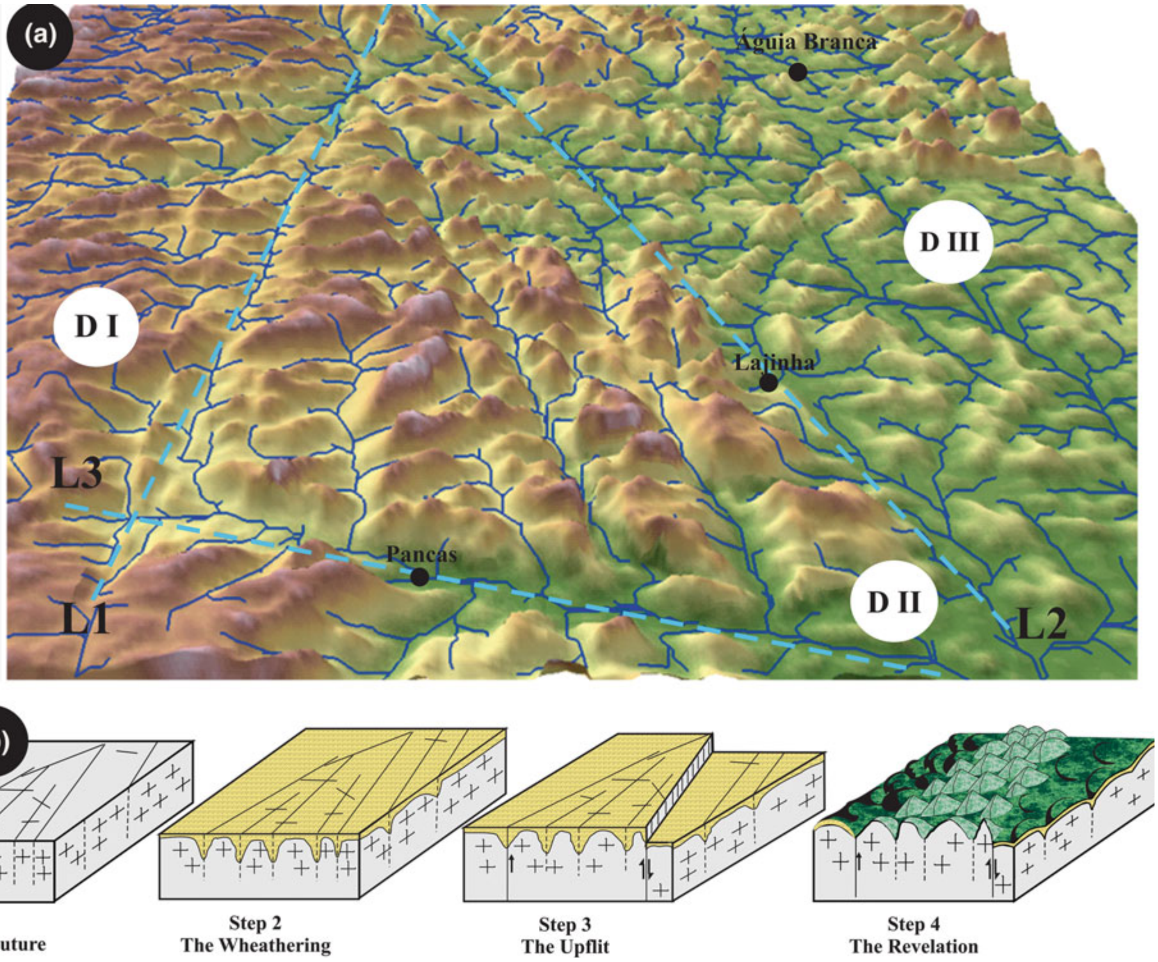

Fig. 35.4 **a** Digital elevation model (DEM) of the Pancas bornhardt province showing the domains *D I*, *D II* and *D III* as well as the main lineaments (*L1* Alto Mutum Preto; *L2* Lajinha; *L3* Pancas). **b** A four-stage model for development of Pancas province (see text for explanation)

Fig. 35.5 The highlands of domain I viewed from west with the bornhardts of domain II and a roadcut outcrop of an weathering profile typical of domain I

Fig. 35.6 Panorama of domain II bornhardts viewed from the south

Fig. 35.7 View from lowland smooth hills, domain III, towards the bornhardts, domain II and the weathering profile at Lajinha district

bornhardts vary between 800 and 900 m above sea level with up to 300 m height. The boundary between domains I and II is given by the Boa Esperança river valley, which follows the NS-trending Alto Mutum Preto lineament (Fig. 35.4a) and represents the local base level (320 m). The boundary to domain III, marked by the N15° W-striking Lajinha lineament, is also abrupt (Fig. 35.4a). Domain III encompasses the eastern portion of the province, marked by a smooth topographic relief, with maximum elevations between 300 and 400 m and gentle slopes, with up to 150 m height (Fig. 35.7). The weathering mantles show an average thickness of 30 m. The local base level at an altitude of 100 m is reached along the Pancas river valley.

35.4 Birth and Evolution of the Kingdom

Detailed studies concerning the generation of Pancas bornhardts have not yet been performed. However, their development history might have started with the regional uplift of the eastern Brazilian margin associated with the break-up of west Gondwana and the consequent generation of the South Atlantic in the Early Cretaceous. The nucleation of the NNW-trending Colatina Lineament (Novais et al. 2004) and simultaneous reactivation of preexistent (Neoproterozoic) joint sets also occurred during the Early Cretaceous (Fig. 35.4b Step 1).

According to Tardy et al. (1991), the weathering mantle experienced a vigorous development all around the Earth's tropical zone, during the Late Palaeocene and reached its climax in the beginning of the Eocene at ca. 55 Ma. The weathering front, preferentially following the boundaries of the cells defined by crossing joints, might have propagated into the granitic substratum of Pancas province during this period. The domes of fresh rock then became progressively isolated within the joint cells, thereby leading to the generation of embryonic bornhardts at depths (Fig. 35.4b Step 2).

Currently referred to as the Tertiary reactivation, a renewed episode of extensional tectonics affected the Brazilian Atlantic margin from the Late Eocene to the beginnings of the Miocene. This event led to the reactivation of preexistent tectonic structures and the development of a system of rift basins in southeastern Brazil (Almeida 1976; Riccomini et al. 2004; Zalán and de Oliveira 2005). A normal displacement along the Laginha lineament caused the downward motion of the block represented by the morphological Domain III, most likely in the course of the Tertiary reactivation (Fig. 35.4b Step 3).

Following the Tertiary reactivation, a long period of erosion started under arid conditions in the Late Miocene, persisting until the Pliocene (Zachos et al. 2001). The Palaeogene extension and the subsequent Neogene erosion are recorded in Brazilian passive margin basins by thick packages of siliciclastic sediments. In the Espírito Santo basin, located along the continental margin at the same latitude of the Pancas province, a 2,500-m-thick succession of terrigenous sediments accumulated during the Neogene (França et al. 2007). In the Pancas area, the central portion of the province (Domain II) was exposed to the erosional front (Fig. 35.4b Step 4). The exposition of the unweathered nuclei of joint-bound cells could thus have started at some time by the beginning of the Neogene, revealing in this way a spectacular landscape: the kingdom of bornhardts (Fig. 35.6).

Recent tectonic motions also seem to have contributed to the final sculpture of the bornhardts in the Pancas region. As previously mentioned, the hilltops in the western portion of the province (Domain I) are approximately at the same elevation as the bornhardts summits in the central sector of the province (Domain II). Moreover, these landforms in both Domain I and Domain III are capped by a 30-m-thick saprolite, which no longer exists in Domain II. Therefore, a vertical displacement of at least 30 m must have been accommodated along the Mutum Preto lineament that marks the boundary between Domains I and II. In addition, seismic activity along both the Alto Mutum Preto and Laginha lineaments is often reported by local inhabitants and the Brazilian seismologic observatories.

35.5 Final Remarks

The region around the town of Pancas in northern Espirito Santo can be regarded as the kingdom of the bornhardts not only due to the abundance, diversity and scenic beauty of its landforms but also because it constitutes an exceptional natural laboratory (Fig. 35.8). How could we realise that such an astonishing landscape was sculptured at depths? The contrasting attributes of its domains provide the geoscientist and the public in general with key features and materials to understand the origin of bornhardts and geomorphologic processes in a broad sense. However, further investigations in the Pancas region are required to better constrain the time frame and the details of the kingdom history.

Fig. 35.8 View of the Pedra da Agulha ("the needle rock") when approaching the city of Pancas (approximately 250 m height)

Acknowledgments Field work in the Pancas region was conducted in connection with a research project of the Rede de Estudos Geotectônicos (Geotectonic Studies Network) supported by PETROBRAS. The authors are also grateful to Pedro Borgo Cypriano, a Pancas citizen, who kindly provided the pictures reproduced in Figs. 35.2, 35.5, 35.7a and 35.8.

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36 The Guanabara Bay, a Giant Body of Water Surrounded by Mountains in the Rio de Janeiro Metropolitan Area

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Abstract

The Guanabara Bay in Rio de Janeiro is one of the most important Brazilian morphological features, both in terms of its geological and geomorphological evolution as well as considering its historical importance to the development of Brazil. The existing morphological contrast, varying from mountain escarpments, hills, fluvial, and marine coastal plains, beaches, and lagoons, results from a complex evolution that imprinted in the landscape an intriguing diverse morphology which constitutes a highly attractive touristic natural scenario that is well known internationally. Its geological and geomorphological history is related to the Paleogene extensional faults and alkaline magmatism within the Guanabara Graben that was filled by Cenozoic continental and/or fluviomarine sediments. In this landscape, the use of natural resources has constrained human occupation for more than 500 years. It was only in the 2000s that improved environmental consciousness promoted measures toward minimizing environmental degradation processes.

Keywords

Guanabara Bay • Geological and geomorphological evolution • Landuse and occupation processes in Rio de Janeiro • Environmental questions

36.1 Introduction

The Guanabara Bay is located in the central portion of the metropolitan region of Rio de Janeiro (RMRJ) and is intrinsically linked to the area that surrounds it, from where it receives a high volume of water, sediments, and wastes. The bay and its surroundings have an area of approximately 4,200 km^2 (Pinheiro 2005) and constitute one of the most important natural and cultural highlights of Brazil.

The boundaries of the Guanabara terrains, which extend in the east–west direction, are provided by the Serra do Mar to the north and the coastal massifs and the sea to the south. This area consists of a contrasting topography (Fig. 36.1a), where smooth morphological features, such as rounded hills and large floodplains, are in abrupt contact with steep hillslopes of the mountainous terrains. The Guanabara Bay entrance has a width of 1,600 m between the cities of Rio de Janeiro and Niteroi, with ancient fortifications on its flanks (Fig. 36.1) Approximately in the middle of this opening stands a stone slab (Slab Island), used since the settlers as support to the defense of the bay, the Slab Fort (ITT 2009).

The magnificence of the landscape and the exuberant nature were repeatedly and enthusiastically highlighted by travelers, painters, poets, scholars, and many anonymous

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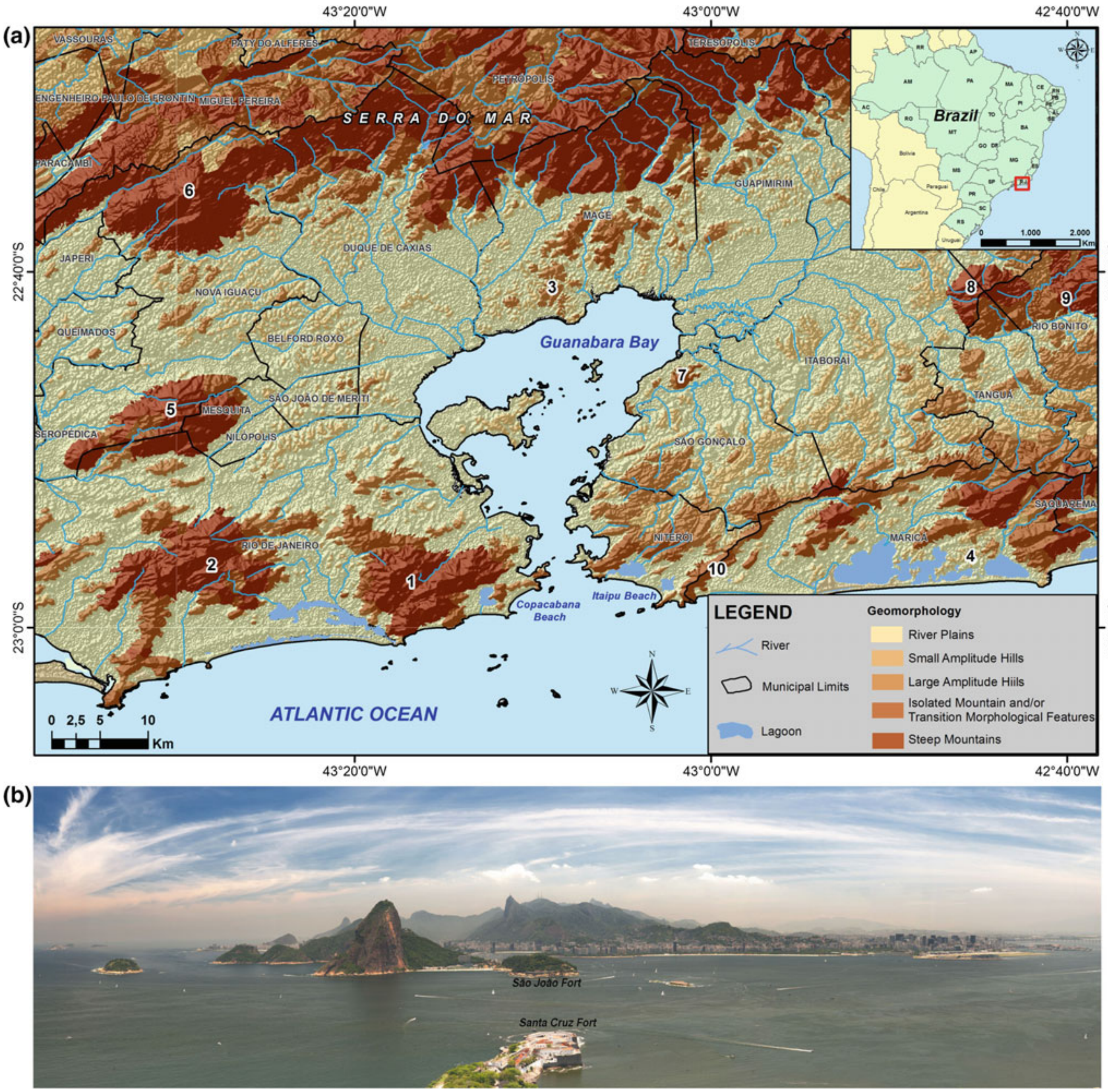

Fig. 36.1 **a** General map showing the coastal massifs and lowlands around the Guanabara Bay (after Silva 2002). *Coastal Massifs*: *1* Tijuca; *2* Pedra Branca; *3* Suruí; *4* Região dos Lagos; *10* Tiririca. *Alkaline Massifs*: *5* Mendanha; *6* Tinguá; *7* Itaúna; *8* Tanguá-Rio Bonito; *9* Sambê. *a* São João Fort; *b* Santa Cruz Fort. **b** Panoramic view of the Guanabara Bay entrance, looking toward Rio de Janeiro city from Niteroi, attesting the strategic location of the forts of Santa Cruz, in Niteroi, and São João, in Rio de Janeiro, both located at the entrance of the bay with Slab Fort in more central position (*Photo* Estaky 2013)

admirers. A good example is Henry Chamberlain (1802–1858) who was an officer in the British Royal Artillery by profession, as well as a painter and designer. He arrived in Brazil in 1819 following his father who was the General Consul of England and for two years painted landscapes and people and customs of the Brazilian colony and empire (Fig. 36.2).

The national and international prominence of the Guanabara Bay is not only because of its scenic beauty, but also due to the availability of vast natural resources which provided the first inhabitants with large amounts of available food, derived from the richness of their ecosystems: bay waters, rivers, mangroves, and forests, as well as the availability of extensive farmlands. The Guanabara Bay was an

Fig. 36.2 "**O Lazareto**" by Henry Chamberlain (1822) portrays lepers gathered in a region around the Guanabara Bay to avoid contagion with healthy people. The picture also shows the waters of the bay and a portion of the Serra do Mar escarpment in the background, with emphasis on the God's Finger peak. Picture courtesy of David Coimbra (2008)

area of greed and contention by rival indigenous groups before the arrival of European settlers (Itt 2009). At that time, the coastal massifs and the hills that stand above the fluviomarine lowlands were used as strategic sites of defense.

However, the flatlands in the city of Rio de Janeiro were narrow and bordered by hills that surrounded the initially urbanized areas. It was in one of these elevations, the Cara de Cão Hill, that the first nucleus of occupancy was established in the first quarter of the sixteenth century for strategic reasons to control production and defense (Amador 2012). The lower portions of these Quaternary lowlands, basically constituted by sandy–clay sedimentary terrains, swamps, bogs, marshes, and ponds, were unfavorable areas to urban settlement. Only after the drainage, the swamps, and mangroves as well as the implementation of many landfills on ponds, marshes, wetlands, and coastal lowlands, the occupation process could have started (Abreu 2006; Serra and Serra 2012). However, the landscape did not surrender entirely because of the steep topography that witnessed the opulence of such an acclaimed pristine scenery (Amador 2012).

36.2 The Guanabara Terrains

The extensive fluviomarine lowlands, or coastal plains, are situated just above sea level, and in many places, they are wetlands intermixed with marshy depressions and soil-mantled convex hills that reach altitudes about 200 m. As we get closer to the Serra do Mar, these hills become more and more frequent, showing narrower valleys between them, attesting to intense dissection processes along the escarpment that bounds the northern and northeastern border of the Guanabara basin (Fig. 36.3a, b).

The coastal massifs are isolated hills and mountains located parallel to the coast showing altitudes between 500 and 1,000 m asl. In the eastern portion of the bay, the mountains associated with the Serra da Tiririca stand out with elevations between 200 and 410 m asl and the Sambé with the maximum altitude of 610 m asl. On the other side, in the western portion, three major massifs can easily be distinguished in the landscape: the Gericinó-Mendanha (974 m), the Pedra Branca (1,024 m), and the Tijuca (1,021 m), these last ones closer to the coast (Fig. 36.1). Many gneissic and granitic hills are found in the metropolitan region of Rio de Janeiro (RMRJ) (Fernandes et al. 2010) and are great tourist attraction, like the hills of Leme, Urubus, Babilônia, Cara de Cão, Viúva, Outeiro da Glória, Pão de Açúcar (Sugar Loaf), and Gávea. The granitic–gneissic hills and massifs characterize the surroundings of the Guanabara Bay and contribute to the scenic beauty of the city (Fig. 36.4).

The high relief contrast of the massifs is achieved by a combination of structural and lithological constraints (Fernandes et al. 2010). The Sugar Loaf profile (Fig. 36.4) is controlled by the folding of two gneisses with different weathering susceptibilities. A biotitic gneiss is isolated in a hinge of synclinal fold, with limbs constituted by the more resistant granitic gneiss. The final erosional form is a double

Fig. 36.3 Fluviomarine lowlands of the lower middle portions of the Suruí (**a**) and Guapi-Açu (**b**) rivers that drain toward the Guanabara Bay, in contrast to the presence of hills and mountains of different elevations while we get closer to the Serra do Mar escarpment (locally known as Serra dos Órgãos), in the background (*Photo* Silva 2009, 2010)

Fig. 36.4 Panoramic view of the coastal massifs that surround the Guanabara Bay waters. In the foreground stands out the massifs of Niteroi city, while in the background, the impressive massifs of Rio de Janeiro city can be distinguished, like the Sugar Loaf and Corcovado hills (*Photo* Estaky 2006)

granitic gneiss hill separated by a narrow valley occupied by biotite gneiss in the hinge of the fold. In the Sugar Loaf and the Gávea hill, post-tectonic granite dikes and sills produce granitic caps at their top and flanks, controlling the final geometry and erosional resistance.

Many of these hills plunge directly into the sea forming steep rocky cliffs interrupted by the combination of tectonic and unloading fractures, continuously reworked by the waves, providing a distinctive aspect to the city (Fernandes et al. 2010). During the colonial period (sixteenth to nineteenth centuries), the hills and rocky cliffs offered an efficient natural defense barrier to the squadrons looking for shelter from storms and enemies within the bay (Pinheiro 2005) (Fig. 36.5).

The magnificent Serra do Mar (Fig. 36.6) that isolates the fluviomarine coastal plains from the inland plateau reaches the maximum altitude of 2,316 m asl at the three peaks point located on the limit between the municipalities of Teresópolis and Nova Friburgo. The escarpment of the Serra do Mar is crossed by a remarkable drainage system that flows in torrents along the hillslopes constituted of bare rock and/or thin soils, forming rapids and waterfalls surrounded by a luxurious, dense rain forest. One of the most impressive geomorphological features of the Serra do Mar is a series of

Fig. 36.5 Panoramic view of the Guanabara Bay highlighting its southern limit, on the right, and many hills associated with the coastal massifs that outcrop on the surroundings (*Photo* Silva 2006)

Fig. 36.6 Panoramic photograph of the Guanabara Bay and a portion of the Paquetá Island in the foreground, showing the impressive topographic barrier of the Serra do Mar at the bottom, locally called the Organ Mountains due to the similarities with the organ tubes (*Photograph* Silva 2007)

high peaks aligned along a straight divisor. The most evident peaks are the God's Finger (1,692 m) and the Escalavrado (1,490 m). In the divisor, a thick post-tectonic granitic dike sustains the ridge crest. In addition, a set of fractures that intercepts the ridge at right angles produces narrow valleys, creating towers and steep peaks (Fernandes et al. 2010).

The different terrains of the Guanabara region were developed in gneissic and granitic rocks (Fig. 36.7b) generated between 790 and 480 Ma by collisional processes between lithospheric plates during the formation of the Gondwana supercontinent, between the Neoproterozoic and the Early Paleozoic (Heilbron et al. 2008; Tupinambá et al. 2012). The older gneissic rocks were derived from sedimentary (paragneisses) and metaigneous (pre-collisional orthogneisses) rocks, dating from 790 to 630 Ma. Between 600 and 560 Ma, the collision and metamorphism climax caused an extensive melting of rocks that produced syn-collisional leucogneisses and late-collisional gneisses. The tectonic collapse of the orogen formed at the time caused the intrusion of post-collisional Cambro-Ordovician granites (530–480 Ma).

In the Early Cretaceous (127–130 Ma), the crystalline basement was intruded by a multitude of basic tholeiitic dykes that preceded the Gondwana breakup and the opening of the South Atlantic Ocean. During the Paleogene, extensional tectonics led to the occurrence of major block faulting

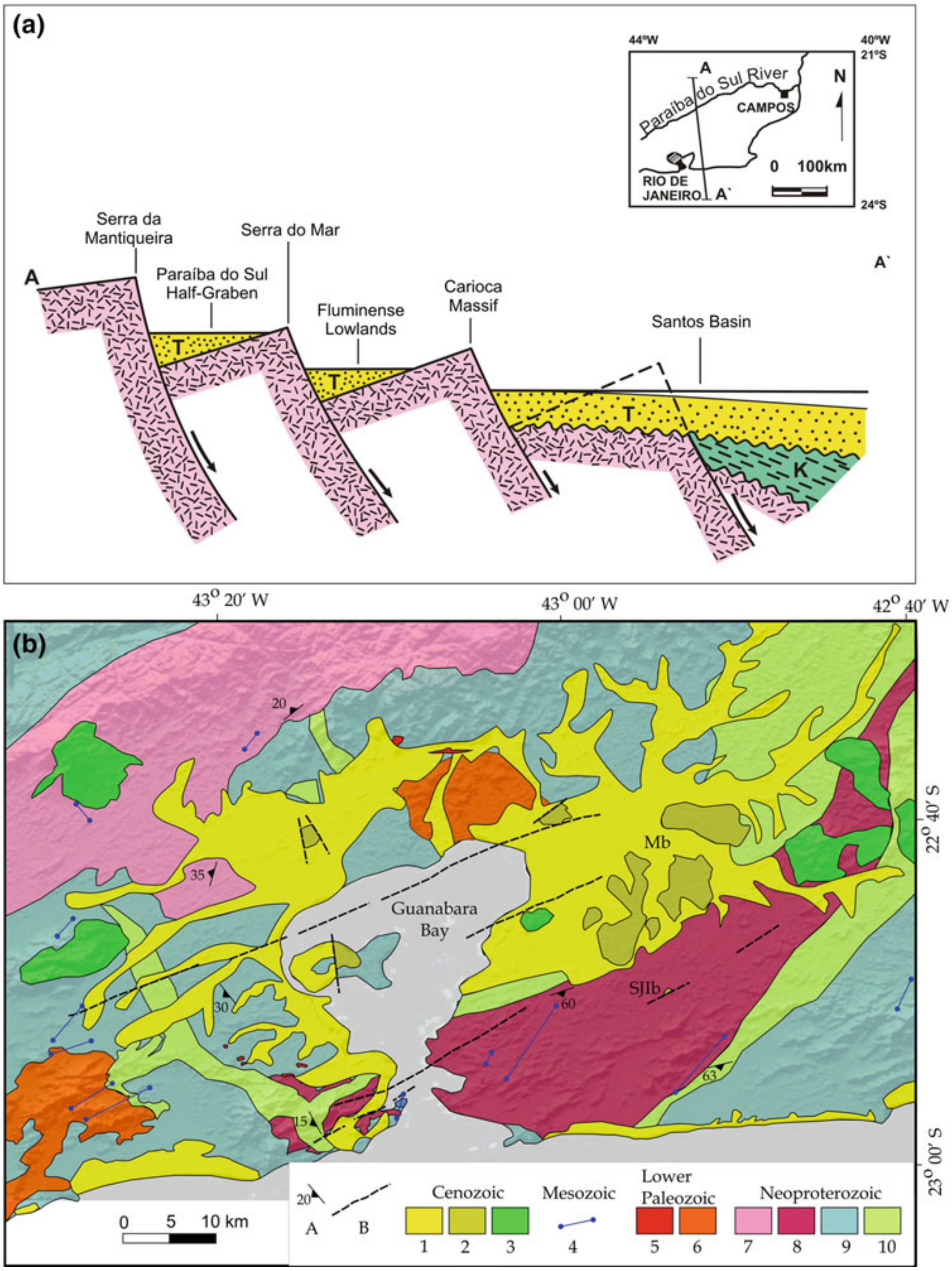

Fig. 36.7 **a** Schematic geological profile from the Serra da Mantiqueira to the Coastal Massifs (*A*–*A*′) in the vicinity of the Guanabara Bay (modified from Asmus and Ferrari 1978), *T* Tertiary, *K* Cretaceous; *B* Geological Map of the Guanabara Bay (redrawn from Ferrari 1990, Silva and Silva 2001, Valeriano et al. 2012, digital terrain model from Miranda 2005). *Cenozoic*: *1* Fluvial and marine sediments, Holocene, *2* Macacu Formation, Paleogene, *3* Alkaline igneous intrusions. *Mb* Macacu Basin; *SJIb* São José do Itaboraí Basin; *Mesozoic*: *4* Diabase dikes; Lower Paleozoic: *5* Ordovician Granite plutons; *6* Cambrian Granite plutons; *Neoproterozoic*: *7* Late-collisional gneissic granitoids; *8* Syn-collisional leucogneisses; *9* Pre-collisional gneissic tonalites; *10* Metasedimentary rocks (paragneisses). *Geological structures*: *A* gneissic foliation, *B* Normal faults, lower block in the southeast

associated with alkaline magmatism, which produced the major tectonic feature of the Guanabara Graben (Fig. 36.7a, b) of ENE–WSW orientation. The alkaline magmatism, dating from 70 to 50 Ma, was a shallow event recorded by subvolcanic and intrusive bodies that stand out in the landscape, such as the massifs of Mendanha, Tinguá, Itaúna, and Tanguá-Rio Bonito (Fig. 36.1).

The Guanabara Graben was partially filled by Cenozoic deposits in two rift basins: São José de Itaboraí and Macacu (Fig. 36.7b). São José de Itaboraí is a small basin approximately 1.5 km long by 500 m wide, limited by a border fault in the ENE direction. This basin was filled by a sequence of approximately 150 m of Paleocene sediments, predominantly carbonatic, which extends to 10 m below the present sea level (Ruellan 1944; Riccomini et al. 2004).

The continental sedimentary sequence of the Macacu basin is constituted by a succession of poorly consolidated and unfossiliferous lenses and thin layers of sandstones and shales of fluvial and lacustrine origin (Macacu Formation), dating from the Eocene to Oligocene (Riccomini et al. 2004). Quaternary deposits recorded in the basin show alternating marine, fluviomarine, fluvial, and colluvial material. The marine deposits are found at different terrace levels above the current sea level: one at a higher position about 6 m high (4,300 ± 150 years BP) and another one at a lower position at about 3 m high (3,000–3,600 years BP), as well as build sand barrier ridges that close some coastal lagoons.

The fluviomarine sequence is constituted by Holocene fluvial and regressive marine deposits, originated in tidal flat and coastal progradation environments inside an estuarine system. The alluvial deposits filled the topographic depressions eroded by the major river systems of the Guanabara basin, generating a fairly regular flat topography of variable altitude, depending on the level of fluvial dissection that took place in the drainage basin, while the colluvium is found overlying the weathered crystalline basement in the convex rounded hills and the morphological tableland features of Macacu formation (Amador 2012).

Several rivers and creeks that drain toward the Guanabara Bay, contributing with an approximate total daily discharge of about 11 million m^3, are installed over flat areas of the Guanabara lowlands. This drainage system is relatively young since it was restructured during the phases of uplift and formation of the Serra do Mar and the coastal massifs. Therefore, even before the anthropogenic activities of the nineteenth and twentieth centuries, the drainage network of the Guanabara basin had already undergone changes in geometry, slope, flow regime, and sediment load carried by the river, resulting from climatic oscillations and sea-level changes. In the lowland areas, the rivers carry huge discharges due to the significant contribution of the upstream drainage network, with the occurrence of extensive floodplains that surround the many hills and mountains. In the lower segments of the main rivers, on the low-gradient floodplains, the channels are shallow and form wide meanders until reaching the bay, creating estuaries subject to strong tidal action, with the presence of mangroves (Pinheiro 2005).

36.3 The Guanabara Bay Surrounding Areas and Their Evolutionary Processes

The Guanabara Bay, which has a water surface area of about 400 km^2, is classified by Muehe et al. (2006) as a compartment on the Brazilian coast dissected along major faults that cut the coastal massifs. For Ruellan, this depression corresponded to ancient river valleys that were drowned by the Holocene marine transgression (Ruellan 1944). The Guanabara Bay has a very irregular bottom topography, marked by ancient valleys that are now partially or completely buried by the estuarine sedimentation (Amador 2012). The extensive sedimentation inside the estuary toward the continent resulted in a thin sedimentary filling, forming extensive plains that may be flooded many times during the year.

The sea-level fluctuations played a major role in the landscape evolution of the Guanabara Bay. Different paleogeographic scenarios were presented by Amador (2012). In the first scenario, proposed for the Last Ice Age between 20,000 and 18,000 years BP, sea level was 130 m below the current position. At that time, the sediment discharge derived from the Serra do Mar and from the coastal Massifs escarpments filled the paleovalleys, carved during the previous interglacial period, with a fluvial system composed by wide and shallow channels of braided rivers. The main channel of the old Guanabara River was quite wide and occupied almost the entire distance between the Pão de Açúcar (Sugar Loaf) hill in Rio de Janeiro and Jurujuba in Niteroi city. Evidences of ancient river channels are present at the innermost portions of the bay (Amador 2012).

The Guanabara Transgression event (Amador 2012) did not occur continuously, but was interrupted by rapid regression pulses that left paleoshorelines which are submerged in the current continental shelf. Between 8,000 and 10,000 years BP, a sea-level stabilization between 40 and 50 m below the current position caused the erosion of Pleistocene deposits at the base of the mountains, leading to the sedimentation in downstream sectors. The area of the current Guanabara Bay was limited to an estuary, and probably some lagoons and marshes established in the lowland.

After the Guanabara Transgression, the coastal area has undergone further small-amplitude oscillations, reaching the maximum level by 5,600 years ago, between 3 and 4 m above the current level. This highest level then dropped to the current position, and coastal ridges at a relative elevation of 8–14 m (older) and 5–7 m (most recent) were built. These features were responsible for closing of the existing lagoons along the internal portions of the coast, which were fed by river channels descending from the costal massifs.

The continuous evolution of the drainage network and the convergence of streams, from the Holocene to the present time, created marshes and swamps responsible for the clogging of ancient lagoons and the generation of extensive fluviomarine plains. The shallow groundwater position inhibits surface and subsurface water drainage, generating the swampy landscape that typically characterizes the lowlands that surround the Guanabara Bay. Therefore, at the same time that sandy beaches were formed in the areas close to the ocean, in the interior portions of the Guanabara Bay, waterfront extensive mangroves (Fig. 36.8) were present at the mouths of numerous rivers (Muehe et al. 2006; Muehe and Rosman 2011).

Figure 36.8a shows the Guanabara Bay bathymetry in 2001, with an average depth of 3 m in the innermost portions of the bay, ranging from 5 to 20 m deep at the President Costa e Silva Bridge (Rio-Niteroi bridge), and an average depth of 35 m along the channel at the entrance of the bay. In a future perspective, Muehe and Rosman (2011) predict,

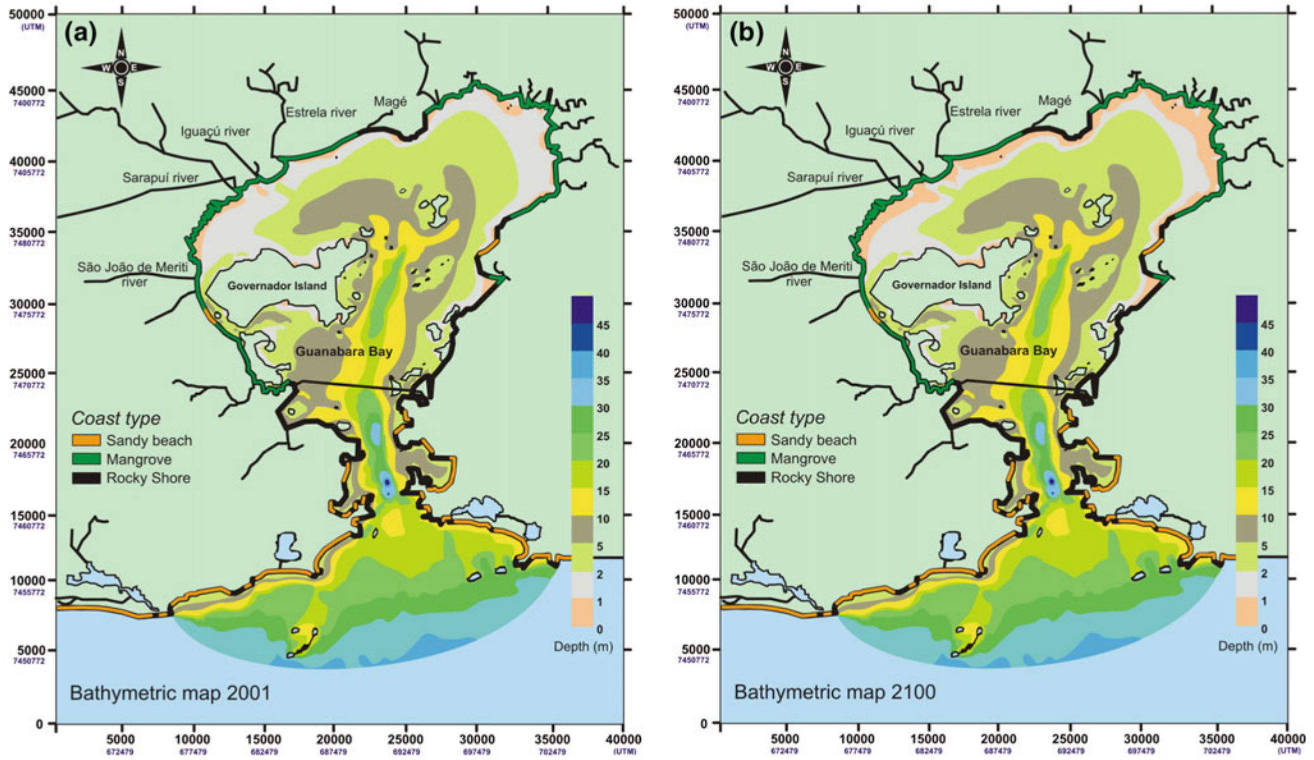

Fig. 36.8 Litoral partitions of the Guanabara Bay and surroundings, according to the classification of Muehe et al. (2006): sandy beaches, mangroves, and/or rocky coasts. The maps also show estimates of changes in water depth (bathymetry): **a** 2001, **b** Estimates for 2100 based on predictions of sedimentation rates inside the bay (modified from Muehe and Rosman 2011)

using computer simulations (Fig. 36.8b), that in the year 2100, the innermost part of the bay, near the outlet of the main river courses, would be submitted to intense sedimentation, reducing water depth and altering the internal circulation inside the bay, further degrading the environmental conditions.

Based on the mechanisms controlling its evolution, the Guanabara Bay can be classified as a drowned river valley, i.e., a river mouth with an estuarine shape, where the coastal water body is semi-enclosed or protected from the direct action of the waves, and having smooth bottom slopes with water depths gradually increasing toward the entrance of the bay (Amador 2012). This author, however, points out that the geometry of the bay suggests a more complex origin than a simple river drowning, arguing that the paleodrainage network consisted of two basins separated by a structural high, still noted by the topographic elevations located close to the city of Magé, where a rocky coastline can be observed, represented by the black dash around Guanabara Bay (Fig. 36.8). These topographic elevations and the rocky coast can be projected in the bottom of the bay toward the crystalline basement areas of the Governador, Paqueta, and Itaoca islands, among others that structurally divide the bay.

36.4 Occupation History and Environmental Issues

The Guanabara Bay is directly associated with the occupation and corresponding spreading of the Rio de Janeiro Metropolitan Region (RJMR), which played a major role since the colonial times, since the city of Rio de Janeiro hosted the capital of Brazil from 1763 to 1960 and was the most populous city during most of this period (Abreu 2006). This significance is associated with a long history of use and occupation, where the surroundings of the Guanabara Bay took part in the political and economic development, both at the local and the national scales. Therefore, the bay is not simply a static landscape, but rather an active and testimonial player of the events and interventions that have occurred over these centuries of occupation (Pinheiro 2005).

On January 1, 1502, the ships commanded by Amerigo Vespucci crossed the coastal bar of Rio de Janeiro, unveiling to the world one of the most beautiful natural geomorphological scenarios on Earth, the Guanabara Bay, enclosed by spits, inlets, beaches, and a magnificent tropical forest (Amador 2012)—Table 36.1. Studies concerned with the oldest records of human occupation in the area comprised an investigation of

Table 36.1 Major historical events and environmental interventions in the Guanabara Bay and its surroundings

Year	Historical event	Environmental situation/intervention
1502	Amerigo Vespucci arrives in Rio de Janeiro, penetrating inland by the waters of the Guanabara Bay	Came across one of the most beautiful sceneries in the world, with a supreme natural richness with indigenous occupation
1565	Beginning the extraction of natural resources and the establishment of an urban nucleus, projected to protect the Portuguese colony	Period of the first interventions with marked reduction of marine resources and indiscriminate extraction of vegetation cover (especially Pau Brazil) and animals in the areas surrounding the Guanabara Bay
1701–1771	Expansion of agricultural activities inland and growth of surrounding areas because the use of the port to export the gold from Minas Gerais, as well as for trading of goods and slaves	Large areas were deforested and burned, causing sedimentation and reduction of fluvial discharge. Many plantations of coffee and other crops were installed in the Tijuca Massif hillslopes, leading to the destruction of many water sources that supply the city
1763–1960	Changing the capital of Brazil from Salvador to Rio de Janeiro	Expansion of the occupation in the surroundings of the Guanabara Bay due to the arrival of the Portuguese court and other migrants. Many ancient agricultural areas were occupied, lagoons were destroyed by landfills, and the Castelo hill was dismantled, resulting in a noticeable degradation process, as well as sedimentation and pollution of rivers draining to the bay. In 1861, by a pioneering initiative of Dom Pedro II, started the reforestation of the Atlantic Forest in the Tijuca Massif which was removed for planting coffee
1960/…	Changing the capital of Brazil from Rio de Janeiro to Brasília	The city of Rio de Janeiro goes through a long phase of agricultural and industrial deterioration. The waters of the bay become destination of sewage and wastes
Beginning of the 2000s	Economic industrial recovery (oil, shipyards, steel…)	Period with a greater focus on reducing environmental degradation and pollution of the waters of the bay
By the year 2010	Announcement of the World Cup 2014 in Brazil and the 2016 Olympics in Rio de Janeiro	Major concern in externalizing to the world, as a foreign policy, the interest in development and sustainable growth

the many shell-mounds observed along the coastal areas, located at strategic points of the ancient estuary as well as close to lagoons, river channels, mangroves, salt marshes, and forests, places where drinking water was available.

This form of occupation was associated with a period of environmental changes in which there was a significant growth of marine resources. This phase, the “climatic optimum,” occurred between 6,000 and 5,000 years BP, when a rise of both temperature and sea level was registered. Around 3,000 years BP, a decrease in these marine resources, basic for the formation of the shell-mounds, was compensated in the diet by collecting plants and hunting small animals and fishery (Amador 1992).

The occupation of these coastal settlements remained until about 1,000 years BP, making them important markers of sea-level variations in past times. Some shell-mounds were found about 5 km inland from the Guanabara Bay shore due to events of marine transgressions, when the ecological zones were pushed inland, rocky outcrops became islands, and the human occupation took refuge in topographically higher areas.

During marine regressions events that took place during the Holocene, indigenous people returned to ancient habitats, colonizing dried mangroves or fixed dunes (Prous 1992). According to Serra and Serra (2012), this prehistoric population maintained a fairly harmonious relationship with available natural resources.

At the beginning of the Portuguese occupation in 1565, the first major local interventions were carried out, including the creation of an urban nucleus that tried to promote the definition of property rights and those associated with natural resources, as well as ensuring the security of the colony to potential invaders (Table 36.1). During the subsequent years, there was a direct intervention on the Atlantic Forest due to the trade of the tree Pau-Brasil with the Indians, which also took place along the entire Brazilian coast, extending from Rio Grande do Norte to São Paulo states. This extractive activity destroyed a significant part of the rain forest that covered the coastal hills and mountains surrounding the Guanabara Bay and lasted until the nineteenth century.

During the seventeenth century, the agricultural penetration which demanded huge portions of land resulted in deforestation and burning done by black and Indian slave labor, with pronounced loss of local biodiversity, besides the reduction in the number and volume of fluvial routes, causing erosion and loss of soil fertility as well as silting up of rivers, lakes, and bogs. With the discovery of gold in Minas Gerais at the end of the seventeenth century, a progressive occupation of the colony interior occurred having Rio de Janeiro as a radiating focus, which generated a significant growth of the occupied area around the bay. The new route, which directly connected the mines to the coast, was called the Royal Road. The road brought to Rio de Janeiro gold and diamonds, whereas food products, luxury articles, and free and slave workers were send to the mines. All these activities made the crown to transfer the government center to the city, transforming it into the most important one in the colony, while its port became the most dynamic one among the existing ones along the coast.

At the end of the eighteenth century, with the reduction of gold production, a good portion of the population which lived in the city had to look for alternatives for their survival, with the agropastoral activity being the one which offered good perspectives for development. Crops like rice and sugar took larger and larger spaces. However, it was coffee that became in a short time the main product in the list of exports. Native of Abexim lands, introduced in the Amazon region and cultivated commercially in the Tijuca Massif, coffee passed from a backyard culture in the nineteenth century to the most important product in the Brazilian economy. Occupying vast areas in the valleys surrounding the Guanabara Bay and reaching the hillsides of the Tijuca Massif, the rubiaceae ended up almost eliminating the hydric sources which filled up the city. Before this problem, the imperial government expropriated farms and ranches to reforest the hillsides of the Tijuca Massif which correspond to the elevations closer to the bay shore and that nowadays is the world's largest urban forest, constituting Tijuca National Park, which is part of the view that attracts visitors arriving in Rio de Janeiro.

The agricultural activities degraded many areas around the Guanabara Bay, and the introduction of animal species such as cattle, horses, pigs, and chickens demanded the deforestation of new areas toward the lowlands, especially in the western portions of the Guanabara basin (Serra and Serra 2012), increasing erosion rates and siltation in small creeks and river channels, as well as the sedimentation of the Guanabara Bay.

Two important events triggered major transformations in the landscape of the Guanabara Bay area: the transfer of the capital from Salvador (Bahia State) to Rio de Janeiro (1763) and the arrival of the court and thousands of Portuguese migrants following the change of the headquarters of the Portuguese monarchy (early nineteenth century). The human presence started to imprint profound modifications in the landscape, which after the mid-nineteenth century suddenly changed, with urban expansion over former farmland areas playing a major role in land degradation, sedimentation, and pollution of the bay waters (Serra and Serra 2012).

The economic and population growth required new portions of land, and thus, after 1850, the area around the Guanabara Bay went through a new and no less important period of expansion. In this period, the mapping of all mangrove areas started, with the purpose of constructing drainage channel systems in the lowlands and landfilling waterlogged areas to continue the expansion process of the central area of the city, which at that time was still inadequate to new buildings (Abreu 2006).

During the second half of the twentieth century, most expansion took place toward the fluviomarine lowlands which had been occupied by new residences, attracted by the industrial development over old areas of orange and sugarcane plantations, as well as over areas of ceramic extraction used for the construction industry. During the 1960s, with the relocation of the capital to Brasília (Table 36.1), the city went through a long phase of agricultural and industrial decline. Only in recent years, an economic recovery has occurred, due to a significant industrial expansion in area, associated with the installation of oil refineries, shipyards, steel mills, metallurgical, and petrochemical industries, among others, which have a greater concern to mitigate mechanisms of environmental degradation and pollution, trying to maintain the integrity of one of the most important areas of the country, and that has a central part in disseminating a positive image of Brazil abroad.

Recently, with the announcement of the World Cup 2014 in Brazil and the 2016 Olympic Games in Rio de Janeiro (Table 36.1), with the intensification of the country exposition in the international media, a great interest in the development and sustainable growth exists, aiming at improvement of the country image that was degraded by 500 years of a history of misuse and lack of suitable management.

The best way to make Rio de Janeiro a city really integrated with its natural environment and wonderful for all its visitors and residents would be the implementation of an effective cleaning program in the rivers, all the way up to their headwaters, and the prevention of new trash and sewage entrance in the channels, rather than installing nets of waste containment in the main river mouths, with the spending of millions in river treatment units (RTU). It is estimated that, without interruptions in the ongoing remediation programs, the waters will only be clean in about thirty years. Therefore, the history of the Guanabara Bay is far from reaching a final stop, either in terms of the natural process or those associated with the human action (Hees 2013).

36.5 Final Remarks and Future Perspectives

As one of the most important natural and cultural attractions of Brazil, the Guanabara Bay will always be relevant to the country. In the same way, the governmental actions should always pursue the maintenance of its physical and environmental natural characteristics, as well as the well-being and quality of life of the inhabitants residing on its surroundings. Although a great part of the morphology in the bay area has been modified by processes of settlement and urban development for centuries, today the morphological contrast between the coastal massifs that gently dip into its waters, beaches, and estuaries, and some mangroves that still resist all degradation processes, are natural attractions that continue to fascinate Brazilians and foreigners.

Regarding specifically the waters of the bay, they are partially renewed by the interaction with the ocean waters resulting from daily tide variations. However, being the ultimate recipient of all wastewater generated by industrial establishments sited on the surrounding lowlands and along the 55 rivers and creeks located in its drainage basin, it is urgent to implement effective programs and environmental projects that will improve the environmental conditions and maintain the existing morphological beauty.

Regardless the long record of abuse and misuse discussed above, the Guanabara Bay still is, like many other tropical estuaries, an important area for nursery, feeding, and protection for various living resources. Despite the current poor environmental condition, the Guanabara Bay still has an intense commercial fishing activity and important biota. Besides, its scenic splendor still emerges as a major attraction for the tourist economy.

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