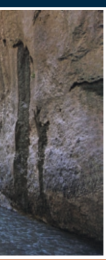
Geoheritage, Geoparks and Geotourism

Khaoula Baadi *Editor*





Geoheritage of the Middle Atlas (Morocco)

Springer

Geoheritage, Geoparks and Geotourism

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Spectacular geo-morphological landscapes and regions with special geological features or mining sites are becoming increasingly recognized as critical areas to protect and conserve for the unique geoscientific aspects they represent and as places to enjoy and learn about the science and history of our planet. More and more national and international stakeholders are engaged in projects related to "Geoheritage", "Geo-conservation", "Geoparks" and "Geotourism"; and are positively influencing the general perception of modern Earth Sciences. Most notably, "Geoparks" have proven to be excellent tools to educate the public about Earth Sciences; and they are also important areas for recreation and significant sustainable economic development through geotourism. In order to develop further the understanding of Earth Sciences in general and to elucidate the importance of Earth Sciences for Society, the "Geoheritage, Geoparks and Geotourism Conservation and Management Series" has been launched together with its sister "GeoGuides" series. Projects developed in partnership with UNESCO, World Heritage and Global Geoparks Networks, IUGS and IGU, as well as with the 'Earth Science Matters' Foundation will be considered for publication. This series aims to provide a place for in-depth presentations of developmental and management issues related to Geoheritage and Geotourism in existing and potential Geoparks. Individually authored monographs as well as edited volumes and conference proceedings are welcome; and this book series is considered to be complementary to the Springer-Journal "Geoheritage".

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Editor
Khaoula Baadi
Faculty of Sciences Dhar El Mahraz
Sidi Mohamed Ben Abdellah University
Fez, Morocco

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Preface

The Middle Atlas, an intracontinental chain, has the particularity of showing fields covering several geological periods from the Ordovician to the Present. The exceptional quality of the outcrops makes it easy to read the geological events recorded in the sediments and structures. At the scale of all Morocco, it is the only region that offers three marine sedimentary cycles of Alpine age and different obediences (Tethysian, Atlantic and Atlantic-Mediterranean). This chain shows a great geological diversity and numerous geological testimonies that offer lithostratigraphic, paleontological, paleogeographical, structural, hydrological, karstological and volcanic data.

This book is a condensed summary of a broad spectrum of the geological heritage of the Middle Atlas. It has the particularity of proposing an in-depth synthesis and a critical review of the geoheritage of the region. This book is an important contribution and will remain a fundamental resource not only for geoheritage experts but also for the wider geoscientific community.

It will serve the geoscience community with sufficient depth of content for any expert wishing to acquire a broad multidisciplinary or even transdisciplinary knowledge. Its publication will also play an important role in the geoeducation of the region with the aim of providing an easy to follow educational compendium on the geological aspects of the Middle Atlas chain from a multidisciplinary perspective.

This book is of specific interest not only to the geoheritage and geodiversity research community, but also to local authorities. The editor, authors and co-authors propose different legislative initiatives to preserve and protect the natural heritage and offer new perspectives and recommendations to protect and conserve the geological heritage.

Its presentation is excellent, especially in the way it exposes the little-known geoheritage of the Middle Atlas chain. To all those who aspire to the discovery of the geological heritage of this region, I recommend this book which is, to my knowledge, the first complete study of the geological richness of the Middle Atlas.

Abdellah Sabaoui
Faculty of Sciences Dhar El Mahraz
Sidi Mohamed Ben Abdellah University
Fez, Morocco

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- Eighteenth authors and co-authors from 5 countries (Cameroon, France, Morocco, New Zealand, Portugal) provided the texts for the 7 parts and 15 chapters
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- Aaron Schiller (Springer) and Moses Herbert who coordinated the submission process with great enthusiasm

All these people are thanked for their very valuable contribution. Our thanks go to the local inhabitants of the Middle Atlas who have contributed with their help on the ground to the exploration of the region. This book is dedicated to them.

Fez, Morocco — Khaoula Baadi

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About the Contributors

Ayad Akasbi is a professor at the Faculty of Sciences, Moulay Ismaïl University (Meknes, Morocco). He is a specialist in cartography, sedimentology and geodynamics of basins. His work focuses on the stratigraphic and sedimentological study of the Dogger of the Northern Middle Atlas (Morocco) and especially studies on the Toarcian and Bajocian. One of his works, the participation in the realization of several geological maps of the Middle Atlas, as map of Berkine, Boulemane and Imouzzer Marmoucha. ay.akasbi@yahoo.fr

Hamid Amhoud is a professor at the Faculty of Sciences, Moulay Ismaïl University (Meknes, Morocco). He is a specialist in paleontology and biostratigraphy. His work is focused on micropaleontological, biostratigraphic and paleogeographical studies of the Atlas chain. His skills are focused on the study of the microfauna of the Jurassic and the Cretaceous foraminifera. He has participated in the realization of maps at different scales in different regions of Morocco. amhoudhamid@yahoo.fr

Abdelmounji Amine is a doctor in volcanic geomorphology and petrography at the Ben M'sick Faculty of Sciences of the Hassan II University of Casablanca. His research work focuses on the establishment of the Middle Atlas volcanic landscape through the reconstruction of the geological and heritage history of the region. abdelmounji@gmail.com

Mustapha Amzil is a PhD student in Geosciences and geoheritage at the Ben M'sick Faculty of Sciences of the Hassan II University of Casablanca. Its projects focus on 3D Reality Capture solutions and new perspectives for Moroccan geological heritage. He is an expert in 3D mapping, laser scanning and applied geomatics in geology, surveying, mines and heritage. amzilmustapha01@gmail.com

Khaoula Baadi is a doctor in geosciences and natural development at the at the Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University (Fez, Morocco). She works in several teaching schools in Canada. Her work focuses on the theme of geology and geoheritage. Among her works is the elaboration of a systematic inventory of all the geosites of the Middle Atlas (Morocco). She is a member of several associations and federations protecting and promoting the Moroccan geological heritage. She is also a reviewer in various international journals. khaoulabaadi@gmail.com

Hicham Benani is a PhD student in karstology within the department of geology at the Faculty of Sciences, Mohammed V University, Rabat, Morocco. He works on the inventory of karstic cavities, and he has a geotourism association which reveals the underground riches of the Middle Atlas to the general public. hicham.benani@um5r.ac.ma

Larbi Boudad is a professor at Mohammed V University (Morocco), Faculty of Sciences and currently head of the geology department. He is a specialist in the geology of superficial formations and also working on the archaeological and geological heritage of Morocco. He is responsible for several national and international projects and a member of several evaluation and expertise commissions for national or international projects. l.boudad@um5r.ac.ma

Hassan El Arabi is a professor at the Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University (Fez, Morocco). He is a specialist in sedimentology. His work is centred on the study of Jurassic carbonate deposits of the Middle Atlas. Other works of his research focus on Jurassic reef sedimentation and sequence stratigraphy in the Middle Atlas. elarabihassan2001@yahoo.fr

Bernard Lebreton is a biospeleologist, member of the technical council of the Scientific Commission of the French Federation of Speleology (FFS). He is in charge of the supervision of biospeology internships. He has participated in several scientific expeditions abroad as a hydrobiologist and specialist in subterranean biodiversity. bernard.lebreton.bl@gmail.com

Ayoub Nehili is a PhD student at the Faculty of Human Sciences, Moulay Slimane University (Beni Mellal, Morocco). He works on the karst geoheritage of Tazekka National Park (TNP), and his work focuses on the field of underground topography. He is a member of several national associations. nehili@hotmail.com

Károly Németh is an adjunct professor in Geology at Massey University, New Zealand, and a senior researcher at the Institute of Earth Physics and Space Science, Hungary. He is a visiting research scientist at the Saudi Geological Survey in Jeddah, Saudi Arabia. He is also the Chairperson of the Geoconservation Trust Aotearoa, New Zealand. He has also been appointed as an affiliated researcher of the Instituto Nazionale di Geofisica e Vulcanologia at Bologna, Italy. His expertise includes sedimentology, volcanology and geoheritage. He spent most of his research carrier on various projects targeted monogenetic volcanic fields. He is also a member of several geoscientific committees.

Mostafa Oukassou is a professor of Earth Sciences at the Ben M'sick Faculty of Sciences of the Hassan II University of Casablanca. His research focuses on the geological and geodynamic evolution of the northern part of the West African craton from thermochronological and structural investigations of the Moroccan Anti-Atlas belt. He is also interested in the paleontology and ichnology of vertebrates and invertebrates in the Jurassic-Cretaceous red beds of the Moroccan Atlas belt, and its relations with sedimentology, stratigraphy sequence and paleoecology. mostafa.oukassou@gmail.com

Abdellah Oumou is a PhD student in Geomatics and Geo-environment at the Faculty of Sciences, Moulay Ismaïl University (Meknes, Morocco). He is working on topics focusing on the use of hyperspectral images in monitoring evapotranspiration and soil degradation and also on the application of modeling and geospatial tools to water and environment. a.oumou@edu.umi.ac.ma

Lalla Amina Ouzzaouit is a professor at the Faculty of Sciences, Mohammed V University of Rabat. She is a specialist in geology, geothermal energy and environmental issues. Her research work is centred on the field of geothermal energy modeling. She participates in the organization of several national congresses in the theme that is always related to geosciences. She is also a member of several associations such as the Moroccan Association of Geosciences (AMG), the International Geothermal Association (IGA) and the National Association of Speleologists of Morocco “Moroccans explorers”. Amina.ouzzaouit@fsr.um5.ac

Paulo Pereira has BSc in Geography (2000) and PhD in Geology (2007) at the University of Minho (Portugal). Since 2011 in the Earth Sciences Department of the University of Minho teaching, he is supervising and doing research on topics related with geomorphology, geodiversity and geoheritage. He is the Portuguese representative member of ProGEO (International Association for the Conservation of Geological Heritage), member of the European Federation of the Geologists (EFG) Panel of Experts on Geological Heritage and member of the IUCN WCPA Geoheritage Specialist Group. paolo@dct.uminho.pt

Abdellah Sabaoui is a professor at the Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University (Fez, Morocco). His research projects go towards cartography, stratigraphy and structure. His work has guided the unveiling of the geological richness of the Middle Atlas through his innumerable geological maps. He is also interested in geoheritage and its protection. abdellahsabaoui@gmail.com

Ghislain Zangmo Tefogoum is a professor at the University of Maroua (Cameroon) of geoheritage, geotourism, volcanic risks and mass movement. He is the creator of the informal Camerooonian Association of Geomorphologists (CAG) and is a member of several associations that aim to promote geoheritage and reviewer in various journals. zangmotefogoum@gmail.com

Brahim Tekiout is a professor at the Faculty of Sciences Dhar El Mahraz, University of Sidi Mohamed Ben Abdellah (Fez, Morocco). He is a specialist in geology, geochemistry and petrology. His work has specifically focused on the Anti-Atlas. Among these works, the study of several deposits with manganese mineralization and others.

Contributors

Ayad Akasbi Faculty of Sciences, Moulay Ismail University, Meknes, Morocco

Hamid Amhoud Faculty of Sciences, Moulay Ismail University, Meknes, Morocco

Abdelmounji Amine University of Hassan II, Casablanca, Morocco

Mustapha Amzil Faculty of Sciences Ben M'sick, Hassan II University of Casablanca, Casablanca, Morocco

Khaoula Baadi Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, Fez, Morocco

Hicham Benani Mohammed V University, Faculty of Sciences, Rabat, Morocco

Larbi Boudad Mohammed V University, Faculty of Sciences, Rabat, Morocco

Hassan El Arabi Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, Fez, Morocco

Bernard Lebreton French Speleology Federation, Lyon, France

Ayoub Nehili Sultan Moulay Slimane University, Faculty of Letters and Human Sciences, Beni Mellal, Morocco

Károly Németh Volcanic Risk Solutions, Massey University, Palmerston North, New Zealand

Institute of Earth Physics and Space Science, Sopron, Hungary

Saudi Geological Survey, Jeddah, Kingdom of Saudi Arabia

Instituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy

Mostafa Oukassou Faculty of Sciences Ben M'sick, Hassan II University of Casablanca, Casablanca, Morocco

Abdellah Oumou Faculty of Sciences, Moulay Ismail University, Meknes, Morocco

Lalla Amina Ouzzaouit Mohammed V University, Faculty of Sciences, Rabat, Morocco

Paulo Pereira University of Minho, Braga, Portugal

Abdellah Sabaoui Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, Fez, Morocco

Ghislain Zangmo Tefogoum Faculty of Sciences, University of Maroua, Maroua, Cameroon

Brahim Tekiout Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, Fez, Morocco

Part I

Introduction

Geoheritage: A Growing Research Topic in Morocco and the Middle Atlas

1

Khaoula Baadi

Abstract

Morocco is one of the most advanced African countries in terms of research on geological heritage. Several initiatives are underway, including the famous Middle Atlas chain, which has received special attention through several inventory initiatives. This chain bears witness to geological phenomena and processes and to a geoheritage of exceptional value. This chapter provides an overview of all the key initiatives that have contributed to the inventory, promotion and preservation of the region's geoheritage.

Keywords

Geoheritage · Inventory · Middle Atlas · Morocco

1.1 Geological and Geoheritage Richness of the Middle Atlas

The Middle Atlas, with an area of 23,000 km^2, an element of the Atlas domain to which the High Atlas and the western and eastern Mesetas also belong, constitutes an intracontinental chain whose mountainous and structural buildings are essentially elongated in the NE-SW direction. It is longitudinally subdivided by the North Middle Atlas Fault (NMAF) into two structural domains: the subtabular Causse, subhorizontal, and the folded Middle Atlas.

The Middle Atlas conceals a rich and varied geological heritage. It is a chain with one of the greatest geological diversities in Morocco. It recorded part of the geological history of Morocco through its geology, its morphology, its springs, its rivers, its lakes, its caves and its volcanoes. The geoheritage characteristics of the Middle Atlas chain present emblematic examples of a rich geological heritage ranging from the Ordovician to the present. These characteristics are often of national or even international interest.

Several initiatives have been developed regarding the geological heritage of the Middle Atlas (Fröhlich et al. 1998; El Khalki and Akdim 2001; Malaki 2006; De Waele and Melis 2009; Eddif et al. 2017; Hili and El Khalki 2017; Ait Omar et al. 2019; Eddif et al. 2018; Amine et al. 2019; Mounir et al. 2019; Oukassou et al. 2019; Amari and Hamoud 2020; Baadi 2021; Baadi et al. 2020, 2021a, b).

The region conceals a typical lithostratigraphy and sedimentology, considered as witnesses, at different spatial and temporal scales, of the stratigraphic, sedimentological and paleogeographic history of the Middle Atlas chain.

The paleontology (vertebrates) of the Middle Atlas, compared to other Middle Jurassic localities (England, USA, Portugal), presents the greatest paleontological diversity (Hadri and Pérez-Lorente 2012). Some sites have local and global singularities. The richest areas of the entire Middle Atlas chain, in terms of their wealth of ichnofossils and dinosaur bones, are those of El Mers, Boulemane, Imouzzer Marmoucha and Oulad Ali. Even today, several discoveries of dinosaur tracks in the chain are made.

The Middle Atlas, considered to be Morocco's "water tower" par excellence, is the richest Moroccan mountain chain in surface and underground water resources. It largely contributes to the supply of water essential for the socioeconomic development of the surrounding plains. Indeed, on the one hand, in these plains, many rivers find their birth in the Middle Atlas; on the other hand, the underground water tables are fed mainly at the level of the hydrogeological basins of this chain.

The Middle Atlas is a favourable environment for the genesis of karstic formations. It is named the "capital of caves in Morocco". It constitutes a vast karstic domain of 30% of the

K. Baadi (✉)
Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, Fez, Morocco

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surface of the Moroccan territory. This vast karst domain offers important sources of information on the characteristics and varieties of karst.

1.2 National Initiatives for Geoheritage Development in Morocco

Geoheritage focuses on the diversity of minerals, rocks and fossils, as well as landforms and other geomorphological features that illustrate the present and past effects of climate and earth forces (McBriar 1995). It represents the abiotic part of the natural heritage and is one of the concepts related to the preservation of Earth science features, such as landforms, natural exposures of rocks and sites where geological features can be examined. It is now recognized that the Earth's history is embedded in the materials and surface of our globe, and that with its destruction this archive (or geoarchive) will be lost for future generations, thereby losing baseline data and valuable information whether already discovered or still unknown (Brocx and Semeniuk 2007). Geoheritage is often made up of exceptional geosites. The latter constitute a delimited space offering the possibility of observing geological elements and/or phenomena of interest for the understanding of Earth sciences (De Wever et al. 2006).

Morocco, by its position, between the European and African plates, at the northern end of the West African craton, has an important geodiversity, covering all the geological domains going from the Archean to the present, this one is linked to the four major structural domains that constitute it. From north to south, follow one another: the Rif, made up of lands carried along the margin of the African plate; the Atlas, intracontinental chain; the Meseta, a region of plains, plateaus and hills constituting the cover of a Paleozoic base; and the Anti Atlas and its Saharan confines.

In recent years, interest in Moroccan geoheritage has been the source of many works leading to a great desire to promote and preserve the history of Earth science. Morocco was among the first African countries considered leaders in the fields of geoheritage and geopark strategies which are an integral part of geoeducation, geotourism, geoconservation, planning and management of the environment and development sustainable. It has instituted national legislation for the protection and preservation of its natural heritage by listing natural sites with biodiversity characteristics. Since then, Morocco has a dozen natural parks, nature reserves, sites of biological and ecological interest (SIBE) and RAMSAR sites. At the international level, Morocco ratified, in 1975, the Convention on the Protection of the World Cultural and Natural Heritage, adopted by UNESCO in 1972. In 1995, he was elected member of the World Heritage Committee and then member of the Center World Heritage in 1996. It now has several laws protecting its natural resources. However, no law is dedicated to the protection of geological heritage. Across the country and over the past 20 years, a large majority of research conducted, particularly at Moroccan universities, has focused on geological heritage. It is for this reason that several universities and national associations have engaged in various initiatives contributing to the enhancement, protection and conservation of geological heritage. Among these initiatives, we can cite the creation of the first association for the protection of Moroccan geological heritage, the APPGM (Association for the Protection of Moroccan Geological Heritage) in 2000. In 2005, the M'Goun Geopark Association (AGM) was created with a view to bringing together many local players and encouraging awareness-raising actions on the interest of geoheritage value.

Subsequently, scientific meetings were organized to share the results of several works on geoheritage, such as the Meetings on the Valorization and Preservation of Paleontological Heritage (RV3P1), which began in Marrakech in 2006. Since then, these meetings biannual meetings take place in different Moroccan cities, and special attention is paid to reflection on the status and enhancement of paleontological, archaeological, mineralogical, etc. collections as well as the legislative aspect relating to the protection of this national heritage. The Moroccan Association of Earth Sciences (AMST), created in 2007, supports in particular the teaching of geosciences and awareness of the importance of geoheritage. Other associations, such as the Association of Teachers of Life and Earth Sciences, created in partnership with the Institute for Research and Development in 2008, carry out traveling exhibitions training more than 1000 participants in a better understanding of the geological history of their region and the preservation of the national geoheritage.

Since 2010, several workshops have been organized in the country, including the international workshop "Geological heritage and sustainable development of the region of Rabat Salé Zemmour Zaer" and the international workshop "Promotion of geoecotourism and scientific mediation in the province of Tiznit".

At the institutional level and within the framework of public policies supporting the diversification of economic activities, the administrative authorities have begun to support geotourism development projects. Many larger local projects, aimed at diversifying the register of tourist practices, are now being deployed. For example, the Ministry of Energy, Mines, Water and the Environment and the National Office of Hydrocarbons and Mines published, in 2011, in the editions of the Moroccan Geological Service, a series of nine discovery guides for the geological and mining heritage of Morocco. In the same year, the first international conference on African and Arab geoparks was held in El Jadida. Finally, the year 2014 saw the birth of the M'Goun Geopark considered as the first geopark labeled by UNESCO in Africa.

In addition to these national initiatives, there are other meetings which are held regularly and which greatly contribute to the emergence of a national culture of enhancement and preservation of geoheritage. For example, the international Conference "The Rise of Animal Life- Promoting Geological Heritage: Challenges and Issues", organized in October 2015, had as objectives the presentation of the latest scientific results, awareness, promotion and the preservation of Moroccan geoheritage, as well as the promotion of museological culture to breathe new life into natural history museums.

Experts in geology, academics and personalities from the associative world, called, in November 2017, in Rabat, to better understand the problem of Moroccan geological heritage in its richness and diversity, but also in its fragility by providing the country with an effective protective device. They were brought together on the occasion of the first national day of geological heritage in Morocco, which had as its theme "Geological heritage as a lever for sustainable development in Morocco". In 2018, in Ouarzazate, the International Congress of Human Capital and Territorial Marketing, Vectors of Sustainable Development in Oasis and Mountain Areas was organized. Geological heritage was among the main areas of discussion.

The second edition of the JNPGM, organized by the APPGM and the Ministry of Energy, Mines and the Environment, was held in 2019, in Rabat. The objective of this edition was to lay the foundations of a draft framework law on the Protection of the Geological Heritage of Morocco (PGM) and to define the methods and concrete solutions to make it a real lever of sustainable development for the regions. Also in 2019, the establishment of the African Geoparks Network (AGN) catalyzed an awareness, at national and continental level, of the need to promote research related to the richness and diversity of the country's geological heritage, but also to increase awareness of its fragility and the need to acquire adequate systems to contribute to its protection. The first Geological and Archaeological Heritage Congress (CPGA), "Inventory, preservation and enhancement", also met in 2019, in Oujda.

In 2020, the 15th Annual Natural Heritage and Sustainable Development Plenary Session highlighted the importance of preserving the national geological heritage. In 2021, the second edition of the National Scientific Congress of Speleology, Geotourism and Valorization of Natural Resources, placed under the theme "Karsts, arts, speleology and development issues", aimed to highlight the importance of natural heritage in general, and karstic in particular, as well as the means of making it a lever for integrated and sustainable territorial development.

Morocco will continue to organize events framing the promotion of the national geological heritage. In 2023, it will host the 10th "International Conference on UNESCO Global Geoparks" in Marrakech. More than 1500 people from 50 nationalities will participate in order to strengthen the channels of collaboration and a better contribution to the preservation and sustainability of geoheritage.

These national days, congresses and conferences were an opportunity to present the key examples of Morocco's geological heritage and a number of national and international best practices for the preservation and enhancement of this non-renewable resource. Morocco stressed the urgency of identifying this heritage, listing it, treating it, enhancing it and preserving it.

1.3 Inventory Initiatives in Morocco and Middle Atlas

Among the initiatives that contribute as an essential step to promote and to protect the geoheritage is the inventory. The inventory of geosites is in fact one of the key steps in the preservation of geoheritage through obtaining an exhaustive list of sites revealing the geoheritage value of the country.

In recent years, Morocco has experienced several inventory attempts in different regions of the country. Among these initiatives, there are those dealing with all types of geosites (Fröhlich et al. 1998; De Waele et al. 2005; Malaki 2006; Ezaidi et al. 2007, 2015; El Wartiti et al. 2008, 2016; Errami et al. 2008; De Waele and Melis 2009; Beraaouz et al. 2010; Lefebvre et al. 2010; Beraaouz 2011; El Hadi et al. 2011a, b; Albab et al. 2013; Nahraoui 2014, 2016; Tahouri et al. 2016; Beraaouz et al. 2017; Arrad et al. 2018, 2020; Bouzekraaoui et al. 2017, 2018; Khoukhouchi et al. 2018; Ait Omar et al. 2019; Amine et al. 2019; Aoulad-Sidi-Mhend et al. 2019; Beraaouz et al. 2019; Berred et al. 2019, 2020; Khouraiss et al. 2019; Baadi et al. 2020; Lahmidi et al. 2020; Mehdioui et al. 2020; Mirari et al. 2020; Salhi et al. 2020; Berred and Berred 2021) or particular geosites (Malaki 2006; Fedan 2014; Mounir et al. 2019; Baadi et al. 2021a, b).

The Middle Atlas is one of the regions of Morocco that have experienced several attempts to inventory and assess its geoheritage (Fröhlich et al. 1998; El Khalki and Akdim 2001; De Waele et al. 2005; Malaki 2006; De Waele and Melis 2009; Eddif et al. 2017, 2018; Hili and El Khalki 2017; Mounir et al. 2019; Oukassou et al. 2019; Amari and Hamoud 2020; Baadi 2021; Baadi et al. 2020, a, b; Hili 2020).

Research on geoheritage in the Middle Atlas has focused on certain areas more than others. Work on the lithostratigraphic and sedimentological heritage still remains modest (Baadi 2021). This heritage is in most cases accompanied by a rich fossiliferous content, some paleontological sites of which have undergone more detailed studies (Hadri and Pérez-Lorente 2012; Marinheiro et al. 2014; Maidment et al. 2020, 2021; Baadi 2021). Research on water heritage, for its part, is numerous and concerns both the inventory of wetlands (Chillasse et al. 2001), springs, waterfalls and lakes (Malaki 2006; Baadi 2021). Regarding the karstic heritage, in 1981, around 300 underground cavities were inventoried and identified by the Hydraulic Service of the Ministry of Equipment. Today, this number is increasing significantly thanks to the work of various associations and federations as well as the work of several researchers. Most of these works have focused on the inventory of karst (De Waele and Melis 2009; Hili and El Khalki 2017; Mounir et al. 2019; Baadi et al. 2021b). Work aimed at volcanic heritage, for their part, has been mainly concentrated on the volcanism of the Azrou-timahdite Plateau (Malaki 2006; De Waele and Melis 2009; Eddif et al. 2017, 2018; Amine et al. 2019; Baadi et al. 2021a).

1.4 Objectives of the Book

Geological heritage is widely studied in European and North American countries, but it is much less studied in Africa in general. On the other hand, Morocco is among the African countries that is a leader in terms of geoheritage research.

The Middle Atlas chain is extremely rich and diversified. Outcrops, well exposed, of various natures and ages, contain evidence of phenomena and geological processes of exceptional value. Given their heritage importance, the geoheritage of the Middle Atlas provide information through which we can decipher the history of the Earth and understand its evolution.

Despite the development of fundamental geological research in the Middle Atlas and its remarkable and non-renewable wealth, it should be noted that the region has not benefited from an exhaustive study of the broad spectrum of all types of geoheritage, with the aim of lead to its enhancement, and indirectly, to its protection, especially since the legal statutes that would ensure its sustainability are absent.

The proposed book is of current interest within the community of geoheritage and geodiversity researchers and also local authorities. On the other hand, there is no such condensed book of the broad spectrum of geological heritage dedicated to the Middle Atlas. There are individual and fragmentary scientific publications in various national and international peer-reviewed articles, but no such book has yet been published. The book presents an in-depth synthesis and critical review of the geoheritage of the Middle Atlas region which will be a significant contribution and will remain a fundamental resource not only for geoheritage experts but in the wider geoscience community. It aims to serve the geoscientific community with a content deep enough for any expert wishing to acquire a broad multidisciplinary or even transdisciplinary knowledge.

It presents the state of the art of Moroccan geoheritage and more specifically that of the Middle Atlas, the conceptual issues of Middle Atlas geoheritage, the methodology used for the selection, inventory, assessment and valuation of geosites, and finally the presentation of different geosites in different disciplines with a view to meeting the following scientific needs:

(i) Present a study of the lithostratigraphic and sedimentological heritage as witness geosites, at different spatial and temporal scales, of the stratigraphic, sedimentological and paleogeographic history of the Middle Atlas chain.
(ii) Take stock of the discoveries of vertebrate paleontological sites in the region in order to propose conservation plans.
(iii) Reveal the water and fluvial wealth of the Middle Atlas as "water tower of Morocco".
(iv) Inventory the surface and underground karstic heritage of the region, an irreversible heritage on an African scale.
(v) Assess volcanic geosites indicative of strombolian, phreatomagmatic and Hawaiian activities in the chain.
(vi) Introduce different legislative initiatives aimed at preserving and protecting the natural heritage and propose new perspectives and recommendations protecting and conserving the geological heritage.

The publication of this book also plays an important role in the geo-education of the region for the purpose of obtaining an easy-to-follow educational compendium in the geological aspects of the Middle Atlas chain from a multidisciplinary perspective. This will likely resonate throughout the geoscience community far beyond the region described in the book. It is, therefore, intended for readers belonging to the following groups of people:

(i) Any researcher who is planning geological research in the area and needs a general summary of what to expect from a multi-faceted geoscience perspective.
(ii) Geoheritage experts who seek ideas and strategies assessing geoheritage values by shaping their own research.
(iii) Local and foreign geoeducators who are looking for a sufficiently in-depth compendium on the subject of geoheritage.
(iv) Specialists, including volcano scientists, geomorphologists, geodiversity researchers, hydrogeologists, or

regional geology experts, seek base anchor resources to support their own research.

(v) The general public who can use the book as a potential guide for their planned geotourism activity.

1.5 Organization of the Book

This book is organized into seven parts:

The first part presents all the initiatives carried out to retrace the evolution of the concept of geoheritage in Morocco and the Middle Atlas by representing the objectives and the organization of the book.

The second part, composed of four chapters, deals with the lithostratigraphic and sedimentological history of the Middle Atlas through geosites tracing the geodynamic evolution of this chain from the Paleozoic to the present. The first chapter, by Khaoula Baadi, Abdellah Sabaoui, Brahim Tekiout and Hassan El Arabi, focuses on the specificities of the lithostratigraphic and sedimentological geosites from the Paleozoic to the Lower and Middle Lias with the presentation of the main geosites of the region. Chapter 2, by Ayad Akasbi, Hamid Amhoud, Abdellah Sabaoui and Abdellah Oumou, proposes a lithostratigraphic study of the Toarcian geoheritage of the Middle-Atlasic chain through its Brown and Ammonitico-Rosso levels. The third chapter, by Khaoula Baadi, Abdellah Sabaoui and Bernard Lebreton, presents a unique site in the region, the Jbel Serhla site, by its litostratigraphic, sedimentological and paleogeographic characteristics by revealing a deposit of bones at the edge of a cave. The fourth chapter, by Khaoula Baadi and Abdellah Sabaoui, traces the Cenozoic history of the Middle-Atlasic chain through its Paleogene, Miocene and Plio-Quaternary geosites.

The third part, made up of two chapters, presents the most important fossiliferous deposits of vertebrates with the reconstruction of their paleogeographic history. The fifth chapter, by Khaoula Baadi, presents a systematic inventory with an assessment of the paleontological geosites of vertebrates by exposing the threats leading to the deterioration of this heritage. The sixth chapter, by Mustapha Amzil and Mostafa Oukassou, presents a new perspective for the enhancement of geoheritage through the presentation of a 3D virtual tour of a paleontological site “Anchrif” of national rarity.

The fourth part, made up of two chapters, reveals the wealth of hydric and fluvial heritage and recommends strategies for the conservation of water resources in the region, considered to be the water tower of the country. The seventh chapter, by Khaoula Baadi, Bernard Lebreton and Paulo Pereira, reveals the water wealth of the Middle Atlas by exposing the various climatic and human constraints pushing on these resources. The eighth chapter, by Khaoula Baadi, discloses the fluvial potential of the region, considered as an essential element for the socioeconomic development of the country.

The fifth part, composed of three chapters, presents two karst complexes, superficial and subterranean, via an inventory of exo- and endokarst sites and a detailed karst study, followed by a presentation of subterranean biodiversity. The ninth chapter, by Khaoula Baadi and Bernard Lebreton, presents the geological characteristics of the exo- and exokarst. The tenth chapter, by Hicham Benani and his co-authors, presents scientific and heritage characteristics of the Chaâra cave by revealing the discovery of a Teleosauridae Crocodylomorph. The eleventh chapter, by Bernard Lebreton, introduces an inventory of the subterranean biodiversity of the Middle Atlas karst.

The sixth part, composed of two chapters, presents the largest and youngest volcanic field in Morocco and reveals a wide range of edifices and volcanic products covering approximately 1000 km^2 of the region. The twelfth chapter, by Khaoula Baadi and Károly Németh, offers a presentation of a diversity of volcanic landscapes marking Moroccan geological history. The thirteenth chapter, by Khaoula Baadi, Ghislain Zangmo Tefogoum and Abdelmounji Amine, shows the geotouristic characteristics holding the volcanic field of the Azrou-Timahdite Plateau.

The last part is devoted to taking stock of the various initiatives implemented in different regions of Morocco in order to propose a national inventory, based on objective criteria, which will make it possible to group together all the works of Morocco and to put them into a project for the future for the first time, which will allow to inventory the Moroccan geological heritage. Recommendations and proposals in the concept of regional and national geoheritage will also be proposed.

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Part II

Lithostratigraphic and Sedimentological Heritage

2 Paleozoic-Lower and Middle Lias Lithostratigraphic and Sedimentological Geosites of the Middle Atlas (Morocco): Inventory and Valorization

Khaoula Baadi, Abdellah Sabaoui, Brahim Tekiout, and Hassan El Arabi

Abstract

The Middle Atlas offers an exceptional outcrops diversity facilitating the reading of the geological history of this chain from the Ordovician to the present by recording part of the geological history of Morocco. It conceals a rich and varied lithostratigraphic and sedimentological geoheritage. This heritage presents geological characteristics of exceptional quality. It is illustrated in nearly 50 lithostratigraphic and sedimentological sites inventoried. Among these geosites, five sites are studied offering an example of both Hercynian and Alpine orogenies. It is (i) a Palaeozoic site (Kandar geosite) presented by schists outcrop, sandstones and pelites reflecting a Hercynian orogenic cycle; (ii) a Triassic site (Geosite of El Ghar) corresponding to sandstone-conglomeratic levels and lower red clays, basalts and upper red clays from the Middle to Upper Triassic and (iii) and the third and last one is represented by Lower and Middle Liassic sites (geosites of Jbel Lakraâ, Tizi Bou Zaâbel and Koudiat Ech Chham) marked by limestone and dolomitic limestone.

Keywords

Geoheritage · Lithostratigraphic and sedimentological geosites · Inventory · Middle Atlas

2.1 Introduction

Since the beginning of the twentieth century, several lithostratigraphic, sedimentological and paleontological studies were carried out on the Middle Atlas chain. These studies revealed the history of the Hercynian substratum and Meso-Cenozoic cover of this chain. Paleozoic studies concern the Tazzeka massif and the various inliers (Termier 1936; Morin 1948; Choubert and Faure-Muret 1967; Morin 1973; Hoepffner 1987; Amaouine 1989; Chalot-Prat 1990; Charrière 1990; Gharmane et al. 2021). Other studies have focused on the Triassic-Jurassic terrains which make up most of the outcrops in the Middle Atlas (Termier 1936; Colo 1961, 1962; Choubert and Faure-Muret 1967; Robillard 1978; Laadila 1982; Nassili 1982; Baudelot and Charrière 1983; El Arabi 1987, 2001; Ouarhache 1987; Fedan 1988; Benshili 1989; Baudelot et al. 1990; Charrière 1990; Akasbi 1993; Benjelloun 1995; Laadila 1996; Sabaoui 1998; Juidette 2000).

The geological outcrops of the Middle Atlas offer an exceptional diversity making it easy to read the geological history of the region from the Ordovician until now. Despite the numerous studies carried out in the region and the rich diversity of geological outcrops, the region is devoid of exhaustive work that deals with lithostratigraphic and sedimentological heritage (Baadi 2021).

This chapter presents the most important lithostratigraphic and sedimentological sites of the Paleozoic, Triassic and Lower and Middle Liassic by providing an explanatory study of their importance.

2.2 Diversity of Geological Outcrops

The geological outcrops of the Middle Atlas are made up of deposits ranging from the Ordovician to the present. Most of these terrains are of Triassic and Jurassic age. Paleozoic outcrops, structured during the Hercynian orogeny, outcrop at the level of the Tazzeka massif and the inliers of El Menzel, Bsabis, Bhalil, Kandar and El Hajeb. The Triassic and

K. Baadi (✉) · A. Sabaoui · B. Tekiout · H. El Arabi
Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, Fez, Morocco

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Jurassic outcrops, which are part of the Alpine cycle, are deformed in the folded Middle Atlas "Middle Atlasic trough" while they remained subhorizontal in the Subtabular Causse area "Tabular Middle Atlas" (Fig. 2.1).

2.2.1 Paleozoic

Paleozoic outcrops in the Middle Atlas appear only at buttonholes inliers. The most important outcrop of the Middle Atlas chain is that of the Tazzeka massif (Fig. 2.1). It is characterized by land consisting mainly of shales, sandstones and pelites. Their age ranges from Ordovician to Middle Devonian. While the most complete series of Paleozoic terrains is found at the Kandar inlier (Fig. 2.2).

2.2.2 Trias

The Triassic outcrops, mainly clay-salt and basaltic, are very rarely fossiliferous. They show a thick serie ranging from a few meters (Fig. 2.3a) to a few hundred meters. These deposits are qualified sedimentologically as margino-littoral, laguno-lacustrine to continental. They outcrop on the edges of the Tazzeka massif and the others buttonholes, along the major tectonic accidents and also in

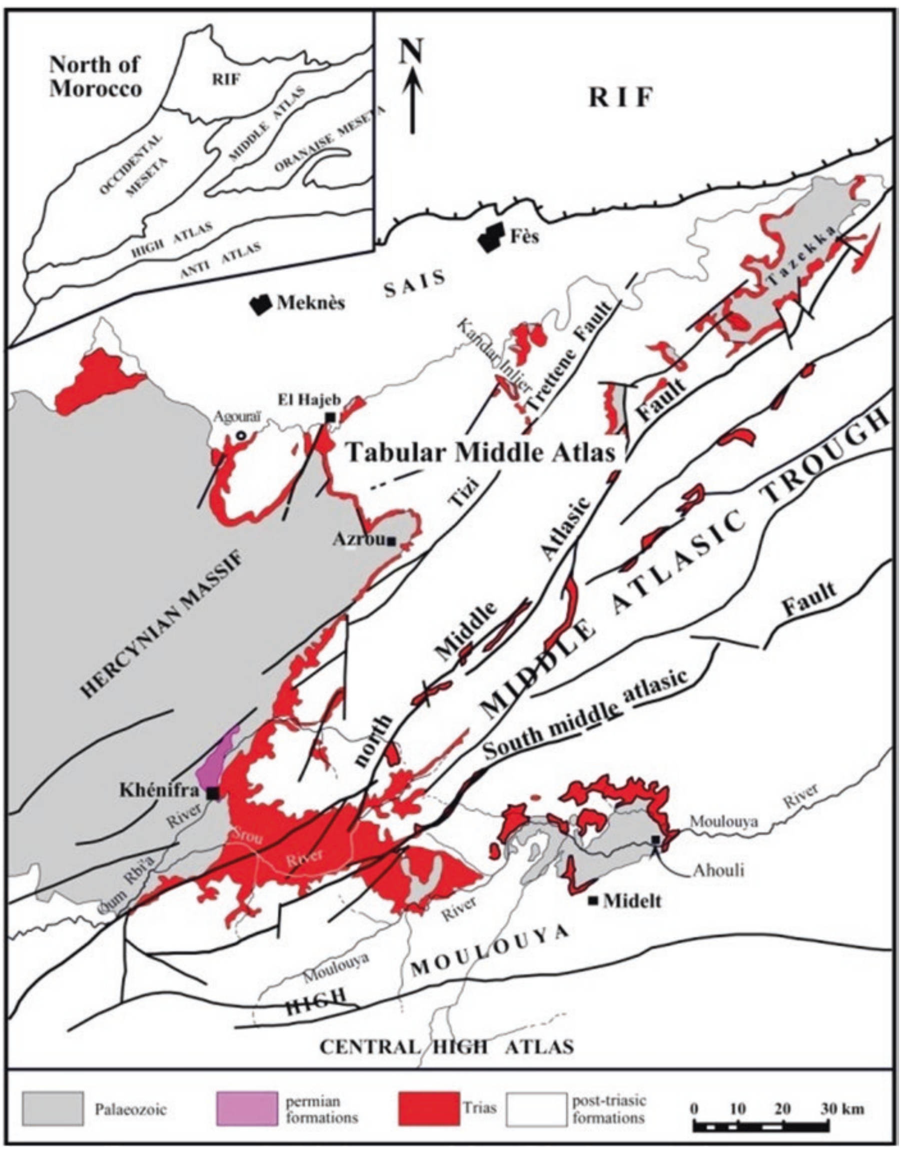

Fig. 2.1 The map above shows the main structural domain of the north of Morocco, and the Map below shows outcrops of Paleozoic, Trias and Lias in the Middle Atlas and its surrounding areas. (Inspired from Ouarhache 2002)

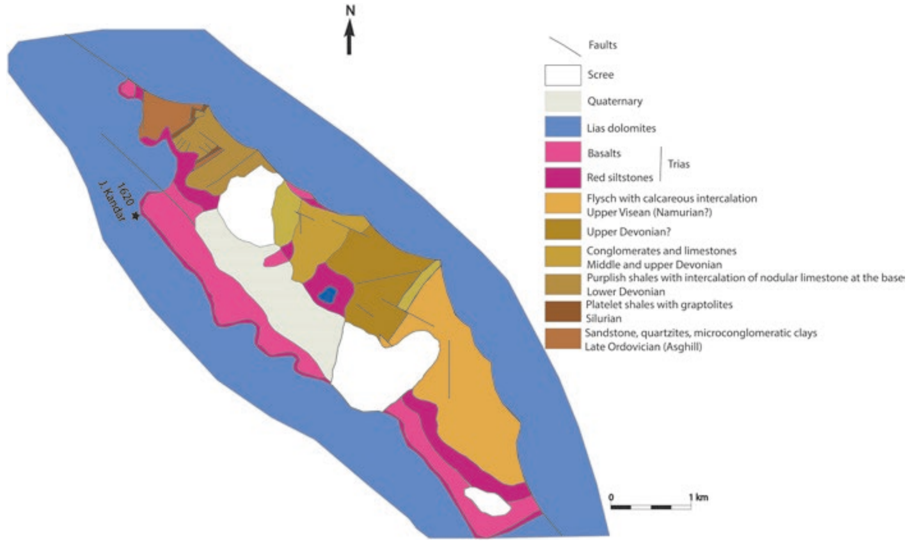

Fig. 2.2 Geological map of the Kandar buttonhole. (Ouarhache 1987)

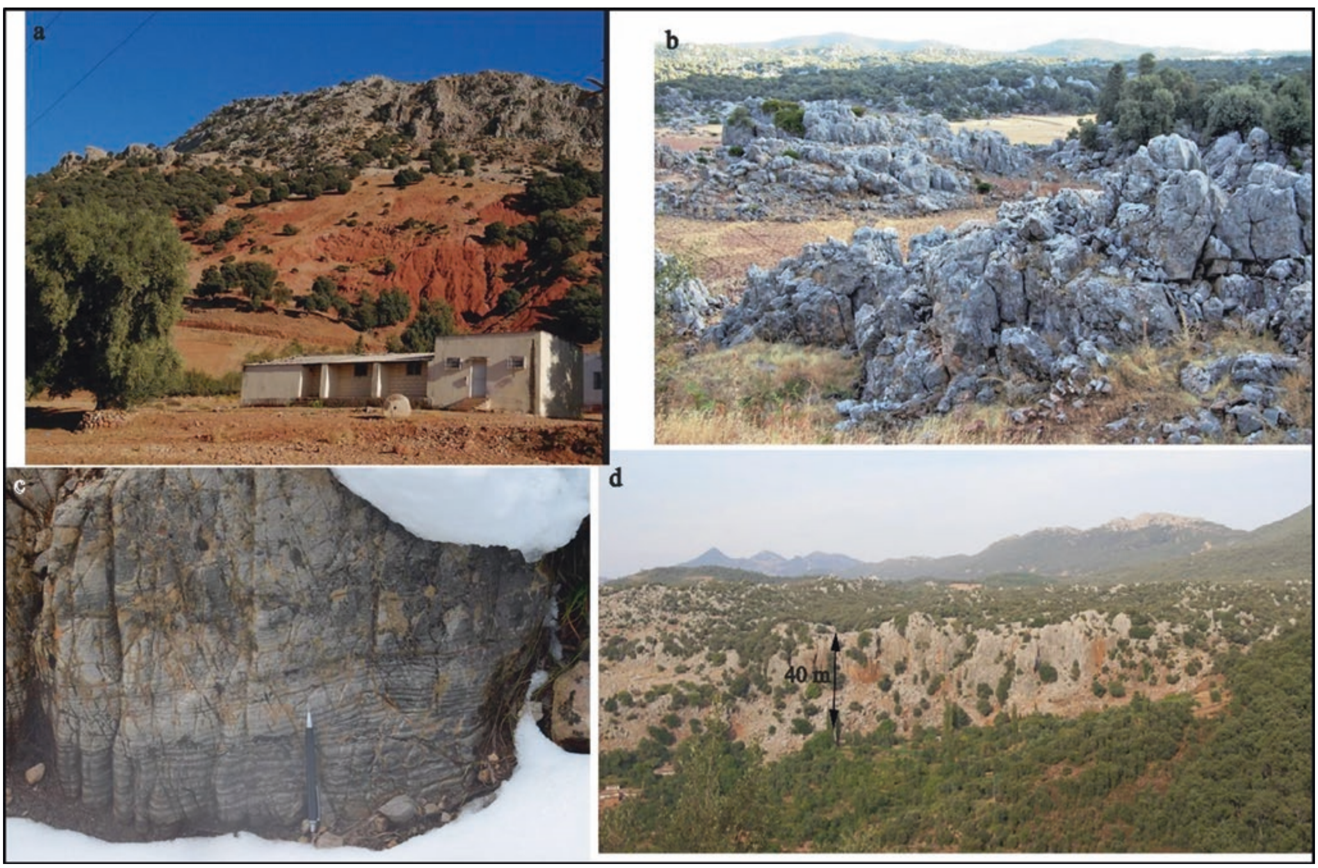

Fig. 2.3 Overview of the outcrops of the Middle Atlas: (**a**) Triassic clay deposits passing gradually to the Lower Lias dolomites; (**b**) Dolomites of the Kandar formation; (**c**) Stromatolites in Sinemurian dolomites; (**d**) massive Lower Lias dolomites

a spectacular way at the southern limit of the Middle Atlas at the Oued Srou valley.

Charrière (1990) subdivided the Triassic series into two members to emphasis and that the tectono-sedimentary evolution, and the Triassic transgression worked in two times:

– the first member, dating from the Middle to Upper Triassic?, is characterized by a dominance of silico-clastic deposits. These deposits, of a continental nature, which can reach a few tens of meters in thickness, outcrop in two localities of the Middle Atlas: at El Ghar (on the SE border of Tazzeka) and at Kerrouchène to the SW of the

Middle Atlas (Sabaoui 1987; Ouarhache 2002). These coarse deposits pass gradually in concordance with the deposits of lower or infra-basaltic argillites of the second member.

– the second member, dating the Upper Triassic, is characterized by a generalized by evaporitic-clays sedimentation on the Middle Atlas chain. These clays are marked by the presence of the first crystals of gypsum and halite. Above these clays is a basalt complex about 100 m thick and predominantly brown or greenish. These basalts are organized into several lava flows. When altered, this basalt mostly appears in decimeter balls. A petrographic study carried out by Robillard (1978) showed that these basalts have a doleritic and essentially subophitic structure. In some localities of the Middle Atlas, these basalts, resulting from a fissural volcanism of tholeiitic affinity, are intercalated with reduced sedimentary levels of hectometric to metric extension. The age of these levels is different from one sector to another and can range from the Carnian to the Hettangian or the Sinemurian (Baudelot et al. 1990). This difference is explained by Sabaoui (1998) as an emission of basalts in many episodes, separated by periods of volcanic calm. Above these basalts appear "the upper red clays" with evaporites followed by 10 m of gray to blackish clays.

2.2.3 Lower and Middle Lias

The history of the Middle Atlas during the Lower Jurassic begins with the installation of the carbonate platform of the Lower and Middle Lias, generalized on the scale of the entire western Tethys. The most widespread Jurassic outcrops in the Middle Atlas are from the Lower and Middle Lias. These deposits lie concordantly on the Late-Triassic deposits. The transition from Triassic gray clays to Sinemurian dolomites is gradual and shows a thinning of the clay levels and a development of the carbonate levels. It is done by alternating clayey limestone and marl (Colo 1961; Baudelot and Charrière 1983; El Arabi 1987; Charrière 1990; Sabaoui 1998).

The Lower and Middle Lias is characterized by carbonate sedimentation without detrital input. This sedimentation constitutes most of the outcrops of the Subtabular Causse, the anticlinal ridges and their periclinal terminations. In sedimentary continuity and by progressive change in facies, this sedimentation begins with deposits of a dolomitic and calcareo-dolomitic facies and ends with marl-limestone deposits.

Lower Liassic dolomitic and calcareo-dolomitic deposits (Fig. 2.3b) are rich in birdseyes (fenestrae structure), oncolites, algae, gastropods and stromatolites structures (Fig. 2.3c). In the Middle Lias, the deposit environment is deepening in the totality area of the Middle Atlas with the development of black nodular chert limestone rich in cephalopods and organic matter. From the Lower Carixian to the Middle Domerian, The Middle Atlas knows the spread and development of several reef constructions.

In the Lower and Middle Lias, five geological formations stand out from the Sinemurian to the Domerian (Table 2.1). The first one is the Ben Smime formation which presents an alternation of massive dolomites (Fig. 2.3d), dolomitic limestones and marls. The second and third are the Kandar and Lakraâ 1 formations which are respectively composed of dolomites and dolomitic limestones of the Sinemurian. The fourth concerns the formation of Lakraâ 2, dated from the Carixian. It is gray bedded limestone. This formation is often known by its reef structures. The fifth is that of Lakraâ 3 of Domerian age. It is composed of an alternation of marls and marly limestones. All these formations have their equivalents in the central Middle Atlas. These are the Tichaou, El Harira, Kandar, Tamakant 1, Tamakant 2 and Tamakant 3 formations (Charrière 1990; Sabaoui 1998).

The Lower and Middle Liassic sediments reflect the evolution from a supratidal environment to a distal platform environment. Compared to the Triassic and basal Liassic, the Lower and Middle Liassic is a period of relative stability. Nevertheless, from the Lotharingian, the platform undergoes a dislocation which intensifies during the Middle Lias. This early mobility would be linked to a phase of thermal and postrift detumescence which follows the "synrift" phase of the Upper Triassic in an NE-SW-oriented extension regime.

2.3 From Paleozoic to Lower and Middle Lias Lithostratigraphic and Sedimentological Sites

The Paleozoic, Triassic and Liassic (Lower and Middle) sites offer an example of two orogenies: Hercynian and Alpine. Paleozoic sites are presented by terrains of shales, sandstones and pelites reflecting a Hercynian orogenic cycle. The Triassic sites correspond to sandstone-conglomeratic levels and lower red clays, basalts and upper red clays from the Middle to Upper Triassic. This series of Tethyan affinity reflects a period of aborted continental rifting. The Lower and Middle Liassic sites are marked by limestone and dolomitic limestone representing a paleogeography of a stable carbonate platform and belong to the Triassic-Callovian sedimentary cycle, of Tethysian affinity.

During the inventory of lithostratigraphic and sedimentological geosites, 50 geosites were inventoried and have an information sheet (Table 2.2). Among these geosites, 5 are studied in this chapter (Fig. 2.4).

Table 2.1 Lithologic formations, stratigraphic attributions and geodynamic evolution from the Paleozoic to the Lower and Middle Lias (Sabaoui 1998)

Periods	Ages	Formations	Dominant lithology	Sedimentary cycles	Geodynamic stages
Lower and middle Lias	Domerian	Lakraâ 3	Alternation of marl-limestone and clayey and epirecifal limestone	First sedimentary cycle of Tethyan affinity	Installation of the stable carbonate platform
	Carixian	Lakraâ 2	External platform limestone		
	Upper sinemurian	Lakraâ 1	Limestone and dolomitic limestone		
	Lower sinemurian				
	Lower sinemurian	Kandar	Sebkha Dolomites		
	Sinémurien inf.	Ben Smime	Alternation of dolomitic limestone and marl		
	Hettangian (?)				
Trias	Upper Triassic	–	Red clays-basalts-red clays		Period of aborted continental rift
	Middle-Upper Triassic	–	Sandstone-conglomerates		
Paleozoic	Ordovician-Devonian	–	Schists, sandstones and pelites		Hercynian Orogenic Cycle

2.3.1 Kandar

The Kandar geosite (Sse36) (Fig. 2.4) is located about 30 km south of Fez. It is located on the southern edge of the Sais basin. It offers the most complete series from the Paleozoic of the Middle Atlas with terms ranging from the Lower Ordovician to the Upper Visean.

On 5 km of outcrops of Paleozoic terrain of this geosite in the Imouzzer Kandar inlier, there are facies of different ages and structures. These terrains, forming part of the Hercynian basement, outcrop within the Liassic limestones which constitute the whole of the Causse (Fig. 2.2). The appearance on the surface of these terrains is the result of the interplay of a large normal fault, oriented NW-SE, and erosion. These terrains are deformed, metamorphosed and inclined toward the SE by an average of 45°.

The deposits of the Kandar geosite are distributed and follow each other from the Ordovician to the Visean. The first deposits encountered are the Ordovician deposits, specifically Ashgillian "the Ashgill bar," represented by approximately 300 m thick deposits made up of pelites (Fig. 2.5a), sandstones, quartzites and microconglomerates (Fig. 2.5b). According to the series, the Silurian deposits (Fig. 2.5c), about 60 m thick, are represented by black shales (Fig. 2.5d) with fine laminations with clearly identifiable traces of graptolites. The very fine grain size and the abundance of organic matter suggest a deep and anoxic deposit environment. The very thick Devonian deposits (approximately 350 m) begin with shales with calcareous nodules (Fig. 2.5e) surmounted by purplish shales rich in fossils. On these shales lie conglomerates (Fig. 2.5f) followed by carbonate levels. The series is capped by pelitic deposits. At the end of the series are the Carboniferous terrains represented by Visean formations that begin with limestone lenses sheltering polypiers (*Caninia*). These limestones are surmounted by flysch with limestone levels rich in foraminifera.

On these Paleozoic terrains lie, in major angular unconformity, the Triassic deposits represented by a sandstone-conglomeratic level of centimeter to decimeter order from the Middle to Upper Triassic.

The Kandar geosite presents a lithostratigraphic and sedimentological particularity on the scale of all the Paleozoic outcrops of all the Middle Atlas inliers by its most complete Paleozoic serie of all the Middle Atlas as well as by several information that emerge from the outcrops making it possible to draw easily the chronological succession of the tectono-sedimentary evolution of the Hercynian terrains.

2.3.2 El Ghar

The El Ghar geosite (Sse15) is located southeast of the Tazzeka massif, 19.3 km northeast of Ribat al Khayr. It is at the front of the NMAF (North Middle Atlas Fault). This geosite shows one of the most important sandstone-conglomeratic series of the Middle-Upper Triassic in the Middle Atlas (Fig. 2.6). It is the best example of marginal-littoral to continental facies.

The sandstone-conglomeratic series of the El Ghar geosite (Fig. 2.7a) consists of three sandstone-conglomeratic levels over a thickness of 70 m (Sabaoui 1987):

– at the base of this series is the conglomeratic level, composed of subangular elements (Fig. 2.7b), with a thickness of 15 m. These elements are immature and coarse in size from 1 to 10 cm, resulting from the erosion of the Hercynian chain. These are essentially fragments of sandstone, flint, schist and micaschist welded together by a cement that is both clayey and calcareous.

Table 2.2 List of lithostratigraphic and sedimentological geosites inventoried at the level of the Paleozoic, Triassic and Lower to Middle Liassic terrains (Baadi 2021, modified)

Geosites	Identification code	Type of geosite	Ccoordinates			Administrative location	Property	Extended	Accessibility	Protected area
			X	Y	Z			–		–
Ait OfeIla	Sse01	Paleozoic	32°56′34.36″N	5°5′2.51″O	1898	Itzer	Public	–	Easy	–
Askour	Sse02	Lower and middle Lias	33°37′49.47″N	4°10′57.39″O	2500	Ribat al Khayr	Pubic	–	Difficult	–
Azzaba	Sse03	Paleozoic	33°48′50.07″N	4°40′32.42″O	792	Sefrou	Pubic	–	Medium	–
Bab Azhar	Sse04	Paleozoic	34°3′51.26″N	4°15′55.42″O	814	Tleta des Zerarda	Public	–	Difficult	–
Ben Smime	Sse05	Lower and middle Lias	33°29′42.14″N	5°11′23.00″O	1350	Azrou	Public	–	Medium	–
Beni Mkoud	Sse06	Trias-Lower Lias	33°53′49.23″N	4°20′39.31″O	1237	Ribat al Khayr	Public	–	Difficult	–
Bhalil	Sse07	Paleozoic	33°51′52.30″N	4°53′25.46″O	967	Sefrou	Public	–	Difficult	–
Bled Ech Chrif	Sse08	Lower and middle Lias	33°58′12.71″N	4°2′59.56″O	1375	Meghraoua	Public	–	Medium	–
Bon Massaoud	Sse09	Lower and middle Lias	34°6′6.82″N	4°5′1.08″O	1634	Taza	Public	–	Difficult	–
Bou Tazzert	5se10	Lower and middle Lias	33°25′48.27″N	4°56′46.34″O	1746	Almis Guigou	Public	–	Difficult	–
Bsabis	Sse11	Paleozoic	33°41′57.43″N	4°41′36.90″O	1565	Esabis	Public	–	Difficult	–
Col de Touaher	Sse12	Paleozoic	34°11′33.95″N	4°10′1.13″O	558	Bab Marzouqa	Public	–	Easy	–
Col du Zad	Sse13	Paleozoic	33°0′32.47″N	5°4′15.79″O	2252	Itzer	Public	–	Medium	–
Diapir de Mellaha	Sse14	Paleozoic	33°46′42.12″N	4°33′43.35 "0	880	El Menzel	Public	–	Difficult	–
El Ghar	Sse15	Trias-Lower Lias	33°53′19.88″N	4°15′46.40″O	1430	Tahala	Public	–	Medium	–
El Harira	Sse16	Trias-Lower Lias	33°55′13.95″N	4°21′48.77″O	1083	Tahala	Public	–	Medium	–
Ic h Amellal	Sse17	Lower and middle Lias	33°31′1.92″N	4°54′49.88″O	1902	Ifrane	Public	–	Difficult	–
Ic h Bab El Mansour	Sse18	Lower and middle Lias	33°39′55.20″N	4°11′47.62″O	1802	Taffert	Public	–	Difficult	–
Ic h Maalem	Sse19	Lower and middle Lias	33°42′17.66″N	4°9′57.89 ″O	2043	Bou-Iblane	Public	–	Difficult	–
Ic h n’Tili	Sse20	Lower and middle Lias	33°35′54.34″N	4°16′2.64″O	2341	Tafajight	Public	–	Difficult	–
Ic h Ouarich	Sse21	Lower and middle Lias	33°29′35.83″N	4°54′58.02″O	1935	Ifrane	Public	–	Difficult	–
Issouka	Sse22	Lower and middle Lias	33°26′30.04″N	4°20′5.48″O	1805	Imouzzer Marmoucha	Public	–	Medium	–
It Ougmar	Sse23	Paleozoic	33°24′38.41″N	4°52′24.74″O	1531	Azrou	Public	–	Difficult	–
Ito	Sse24	Paleozoic	33°35′42.02″N	5°21′31.48″O	1298	El Hajeb	Public	–	Easy	–

J. Ouaouserdoune	Sse25	Lower and middle Lias	33°28′23.82″N	4°54′37 69″O	1767	Ifrane	Public	–	Difficult	–
Jbel Bouslama	Sse26	Lower and middle Lias	33°55′42.65″N	4°15′42.15″O	1888	Bab Boudir	Public	–	Difficult	–
Jbel Hamda	Sse27	Lower and middle Lias	33°46′3.97″N	4°30′30.99″O	1330	Ribat al Khayr	Public	–	Difficult	–
Jbel Lakraâ	Sse28	Lower and middle Lias	33°51′52.33″N	4°20′51.37″O	1441	Ribat al Khayr	Public	–	Difficult	–
Jbel Messassa	Sse29	Paleozoic	33°53′54.16″N	4°23′18.89″O	1263	Ribat al Khayr	Public	–	Difficult	–
Jbel Nerkibat	Sse30	Lower and middle Lias	33°50′10.48″N	4°5′23.48″O	2086	Meghraoua	Public	–	Difficult	–
Jbel Sehrij	Sse31	Lower and middle Lias	33°55′45.99″N	3°59′31.24″O	1403	Meghraoua	Public	–	Difficult	–
Jbel Tazrakht	Sse32	Lower and middle Lias	33°44′36.73″N	4°36′48.27″O	1245	Ribat al Khayr	Public	–	Difficult	–
Jbel Tichaou	Sse33	Trias-Lower Lias	33°54′43.52″N	4°24′33.14″O	1132	Ribat al Khayr	Public	–	Difficult	–
Jbel Tnidilt	Sse34	Lower and middle Lias	33°55′22.54″N	4°17′54.81″O	1547	Ribat al Khayr	Public	–	Difficult	–
Jerf EI Gaz	Sse35	Lower and middle Lias	33°25′27.00″N	4°20′32.00″O	1400	Imouzzer Marmoucha	Public	–	Difficult	–
Kandar	Sse36	Paleozoic	33°46′47.21″N	5°3′55.63″O	956	Imouzzer Kandar	Public	–	Medium	–
Kerrouchène	Sse37	Trias-Lower Lias	32°48′44.14″N	5°19′9.02″O	1388	Kenouchène	Public	–	Medium	–
Koudiat Ech Chham	Sse38	Lower and middle Lias	33°27′5.37″N	4°55′45.58″O	1820	Ifrane	Public	–	Medium	–
Laârouch	Sse39	Lower and middle Lias	33°55′46.13″N	4°15′21.63″O	1358	Tabehirte	Public	–	Difficult	–
Mâafa Tamekrant	Sse40	Lower and middle Lias	33°28′48.57″N	4°55′41.86″O	1937	Ifrane	Public	–	Difficult	–
Maafa Tamezian	Sse41	Lower and middle Lias	33°29′29.01″N	4°55′58.59″O	1908	Ifrane	Public	–	Difficult	–
Merzidki	Sse42	Paleozoic	33°26′45.14″N	4°52′18.70″O	1601	Ifrane	Public	–	Difficult	–
Mou Aguerbez	Sse43	Lower and middle Lias	33°27′45.04″N	4°56′43.29″O	1811	Ifrane	Public	–	Difficult	–
Pontde Sebou	Sse44	Paleozoic	33°49′56.27″N	4°38′46.36″O	489	El Menzel	Public	–	Medium	–
Tamezziant	Sse45	Lower and middle Lias	33°26′47.54″N	4°53′28.50″O	1860	Ifrane	Public	–	Difficult	–
Tichoukt	Sse46	Lower and middle Lias	33°23′41.01″N	4°39′30.60″O	2744	Bo ulemane	Public	–	Difficult	–
Tizi Bou-Zaabel	Sse47	Lower and middle Lias	33°38′44.12″N	4° 9′18.36″O	2264	Bou-Iblane	Public	–	Medium	–
Tizi Oughmari	Sse48	Paleozoic	33°28′10.52″N	5°9′54.23″O	1617	Azrou	Public	–	Easy	–
Tleta Zerarda	Sse49	Paleozoic	33°59′36.85″N	4°22′58.81″O	763	Tahala	Public	–	Medium	–
Zitounat	Sse50	Paleozoic	33°24′9.13″N	5°1′12.94″O	1816	Azrou	Public	–	Medium	–

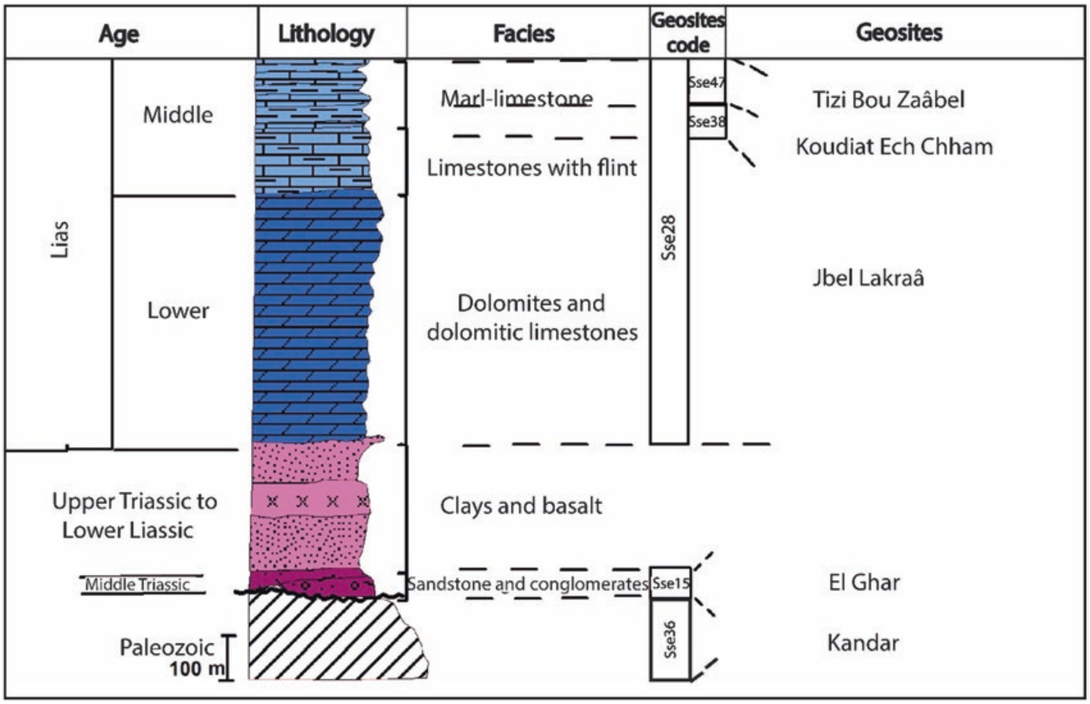

Fig. 2.4 Synthetic stratigraphic series from the Paleozoic to the lower and middle Lias showing indication of the stratigraphic position of each geosite

– above, there is another level (Fig. 2.7c) 30 m thick, composed of quartz sandstone beds (Fig. 2.7d) with cross bedding.
– the last level (Fig. 2.7e) is made up of a sandstone series 25 m thick. This level is organized in positive sequences evolving from conglomerates at the bottom to fine sandstones and siltstones at the top.

At the end of this series, gray saliferous clays from the Upper Triassic (3–4 m) outcrop with thin beds of marly limestone. The presence of sandstone-conglomeratic deposits under these red clays is a consequence of an episode of early tectonic extension compared to other regions of the Middle Atlas (Sabaoui 1998).

The El Ghar geosite is a key site in the Middle Atlas. Actually, the sandstone-conglomeratic deposits show perfectly the progressive transition with the infra-basaltic clays. This geosite has a unique thickness in the northern Middle Atlas reaching 70 m, furthermore for the exceptional quality of the three sandstone-conglomeratic levels outcrops composing the geosite.

2.3.3 Jbel Lakraâ

The geosite of Jbel Lakraâ (Sse28) is located 9 km northeast of Ribat al Khayr. This geosite shows the complete series of Lower and Middle Lias formations (Fig. 2.8) with the most important outcrops of the Middle Atlas due to their exceptional quality and thickness.

The deposits of the Jbel Lakraâ geosite are composed by four formations of the lower and middle Lias (Fig. 2.9a) constituting the main framework of the Jbel Lakraâ (Fig. 2.9b) which is part of the first ridge of the Middle Atlas. The geosite is limited to the NW by detachment contacts of these Liassic carbonate formations, at the level of the Triassic gypso-salt clays (Figs. 2.8 and 2.9c).

The carbonate formations of the Jbel Lakraâ geosite begin with the Kandar formation (Fig. 2.9d) which is 80 m thick. These are dolomites and calcareous dolomites with massive Sinemurian facies. Above, outcrops the formation of Lakraâ 1. This last one consists of dolomitic limestone 40 m thick surmounted by light Lotharingian limestone 20 m thick. These deposits show an intertidal to supratidal facies. Above lies the formation of Lakraâ 2 which is assigned to Lotharingian to Upper Carixian age. This formation is 130 m thick. It shows black limestone with flint. The chert is present in the shape of more or less thick kidney. The formation of Lakraâ 2 ends with bedded limestones without silex. Toward the upper half of this formation, the limestone begins to be separated by very thin interbedded marly joints, without apparent discontinuity, constituting the beginning of deposits of the Lakraâ 3 formation which is 50 m thick. These marl-limestone deposits, of Domerian age, reflect a very open platform environment.

Fig. 2.5 Some characteristic facies of the Paleozoic formations of the Kandar geosite: (**a**) Schistose pelites at the base of the quartzitic and sandstone deposits of Ashgill; (**b**) Ashgillian sandstone bar; (**c**) Silurian shales; (**d**) Silurian black shales; (**e**) Nodular limestone showing Lower Devonian synsedimentary slump structures; (**f**) Middle and Upper Devonian conglomerates

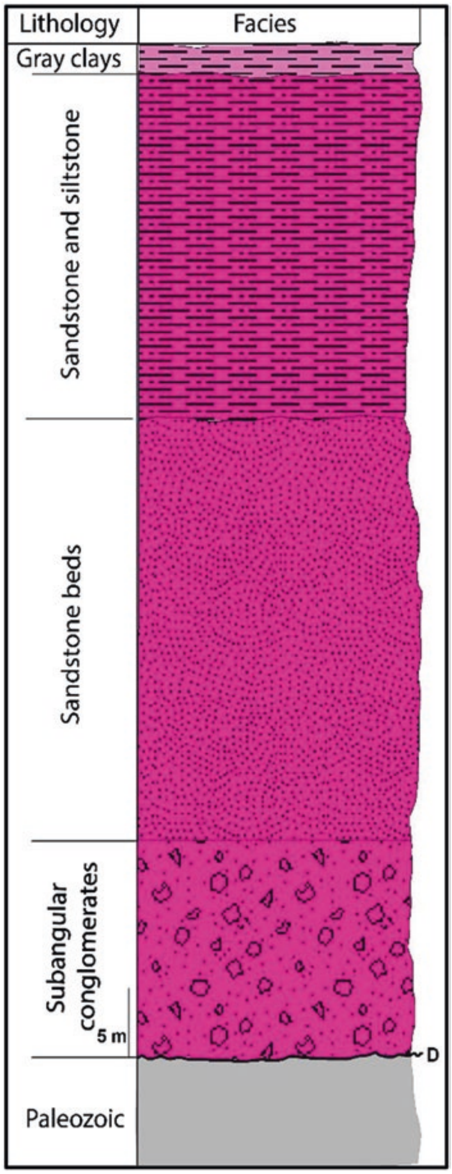

Fig. 2.6 Synthetic stratigraphic log of deposits, from the Middle to Upper Triassic, of the El Ghar geosite. (Sabaoui 1998; Baadi 2021)

The geosite of Jbel Lakraâ is a regional reference site allowing retracing the sedimentation history and the paleogeography of the region during the lower and middle Lias. Exceptionally, among the formations constituting the site, Lakraâ 1 formation does not exceed 20 m in thickness on the Causse, when, at Jbel Lakraâ, it can reach 60 m, which is typical in this geosite. The Jbel Lakraâ geosite shows the complete series of predominantly carbonate outcrops from the Lower and Middle Lias which illustrate the installation of a carbonate platform reflecting the transition from a littoral or supratidal sea to a distal platform environment.

2.3.4 Tizi Bou Zaâbel

The Tizi Bou Zaâbel geosite (Sse47) is located 62 km south-east of Ribat al Khayr (Fig. 2.10). This geosite highlights the innumerable reef mounds (mud-mounds) of the folded Middle Atlas.

The reef mounds of the Tizi Bou Zaâbel geosite (Figs. 2.10 and 2.11a) are calcareous in nature. They show a lateral passage to the Domerian marl-limestones of the Lakraâ 3 formation which are 40 m thick.

These mounds are well exposed in the topography because they resist to erosion and karstification. They correspond, in fact, to several reef sequences with three terms: a micritic term at the base, an intermediate biocalcarenite term and a “reef limestone” term at the top. These mounds (Fig. 2.11b) are decametric to hectometric in size, and their age is different from the reefs of the Subtabular Causse. These reef masses are designated by the term “mud-mounds” because their facies are dominated by micritical facies mud. These reef mud-mounds show more or less elongated masses along the crest and on the NW and SE edges of the third Bou-Iblane ridge. Their presence along and on the edges of the third ridge, during the Middle Lias, attests that this zone constituted a barely submerged ridge along which “mud-mounds” were installed. The formation of this ridge has was guided by the synsedimentary faults of oblique and other transverse accidents (CMAF: Central Middle Atlas Fault) (Sabaoui 1998).

The internal structure of the “mud-mounds” of the Tizi Bou Zaâbel geosite is different from that of the Subtabular Causse. In this geosite, the level of micrite has developed well while the other levels have been modestly expressed, which makes the originality of the geosite on the scale of the folded Middle Atlas.

2.3.5 Koudiat Ech Chham

The Koudiat Ech Chham geosite (Sse38), chosen on the Guigou plateau, is located 23 km south-east of Ifrane. This geosite corresponds to the most important reef construction of the Subtabular Causse. This is a reef series prograding from the NE to the SW (Fig. 2.12).

The deposits of the geosite of Koudiat Ech Chham show at their base marl limestone with ammonites from the Domerian. Above these marl-limestones, there are several reef sequences reaching a thickness of 100 m and constituting the Koudiat Ech Chham hill. These sequences are considered among the most recent Liassic deposit of the Guigou Plateau (El Arabi 2001) and of the central Subtabular Causse. They correspond to:

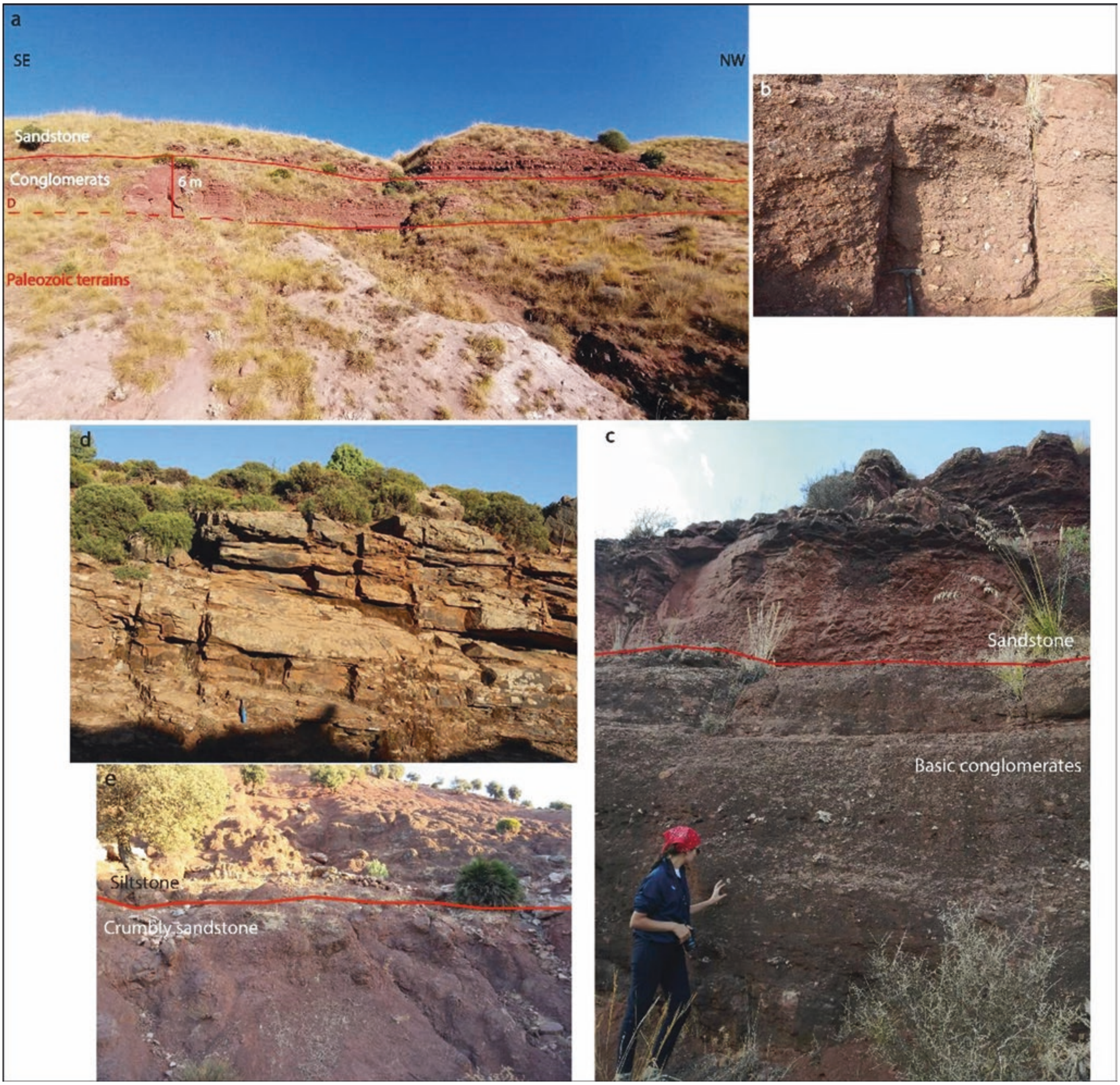

Fig. 2.7 Aspect of the outcrop of the El Ghar geosite (Baadi 2021): (**a**) Conglomeratic deposits resting in angular unconformity on Paleozoic terrains. To the SE, these conglomerates are masked by scree; (**b**) Subangular conglomerates with Palaeozoic elements; (**c**) Sandstone conformably resting on Middle Triassic basal conglomerates; (**d**) Sandstone benches; (**e**) Siltites resting conformably on friable sandstones

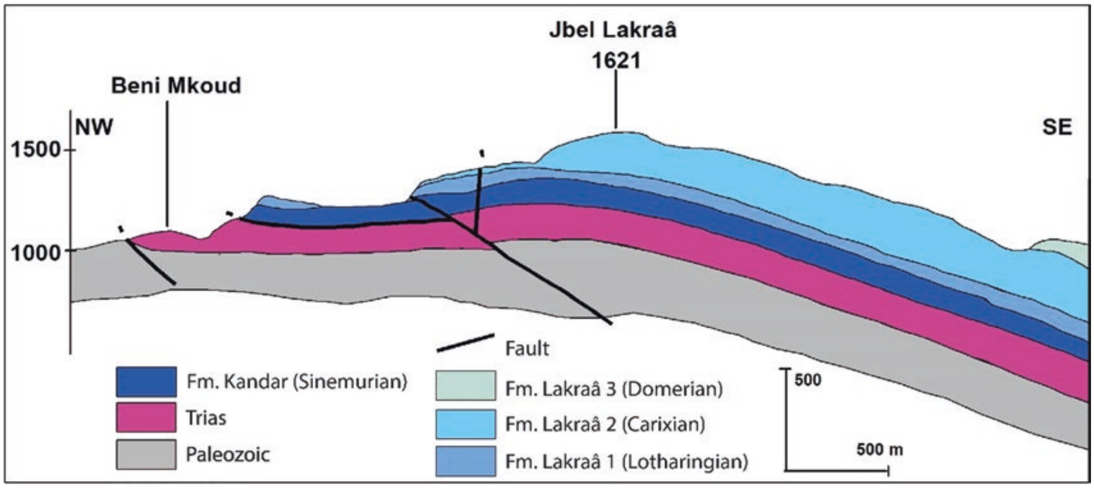

Fig. 2.8 Geological section of the main outcrops of the Jbel Lakraâ geosite. (Baadi 2021)

– a bed-level reef sequence of bioclastic limestones with oblique stratifications;
– a level sequence of bioclastic bars;
– a level sequence of reef limestones.

The Koudiat Ech Chham geosite provides a good example of the organization of Domerian reef constructions. It belongs to a shallow block, paleogeographically well individualized between two accidents with a noticeably SW-NE direction, which are the North Middle Atlas Fault (NMAF) to the SE and the Tizi n'Trettene Fault (TTF) to the NW. This block shows several hills with reef construction such as (Maafa Tamekrant and Maafa Tameziant) (Fig. 2.13) whose age is more and more recent going from NE to SW. Indeed, it goes from the Lower Carixian to the Lower to Middle Domerian. The diachronous and the migration in time of these reef settlements have been explained by a tilted block motion from the SW to the NE (El Arabi 2001).

2.4 Conclusion

The Middle Atlas Range contains the best exposures of lithostratigraphic, sedimentological, paleontological and paleogeographic assemblages of the Atlas chain. They include a diversity of facies allowing retracing the geological history of the chain. This diversity is marked by the quality of the outcrops allowing an excellent reading of the geological events from the Paleozoic to the Lower Jurassic. These are outcrops of shale in thin plates with graptolites, sandstone and nodular limestone running from the Ordovician to the Upper Visean; sandstone-conglomeratic levels of the Middle-Upper Triassic; and Liassic carbonates and reef-limestone marl from the Lower and Middle Lias.

The geological richness of the Middle Atlas has attracted the interest of geoscientists for more than a century. This great geological wealth of the region has made it possible to reveal 50 inventoried sites, 5 of which have been studied in this chapter. These geological wonders lead to place the Middle Atlas chain at a crossroads of geological events of regional and national importance. The inventory of these geosites revealed their geoheritage value and the remarkable sites of the chain. Their selection was based on the criteria of representativeness, rarity, geological diversity and state of preservation. These five geosites bear witness to the evolution of a large part of the sedimentary and paleogeographic evolution of the Hercynian and Alpine cycles. They gave their name to official nomenclatures of the geology of the Middle Atlas because their outcrops, which are of a unique quality, have remarkable layer thicknesses.

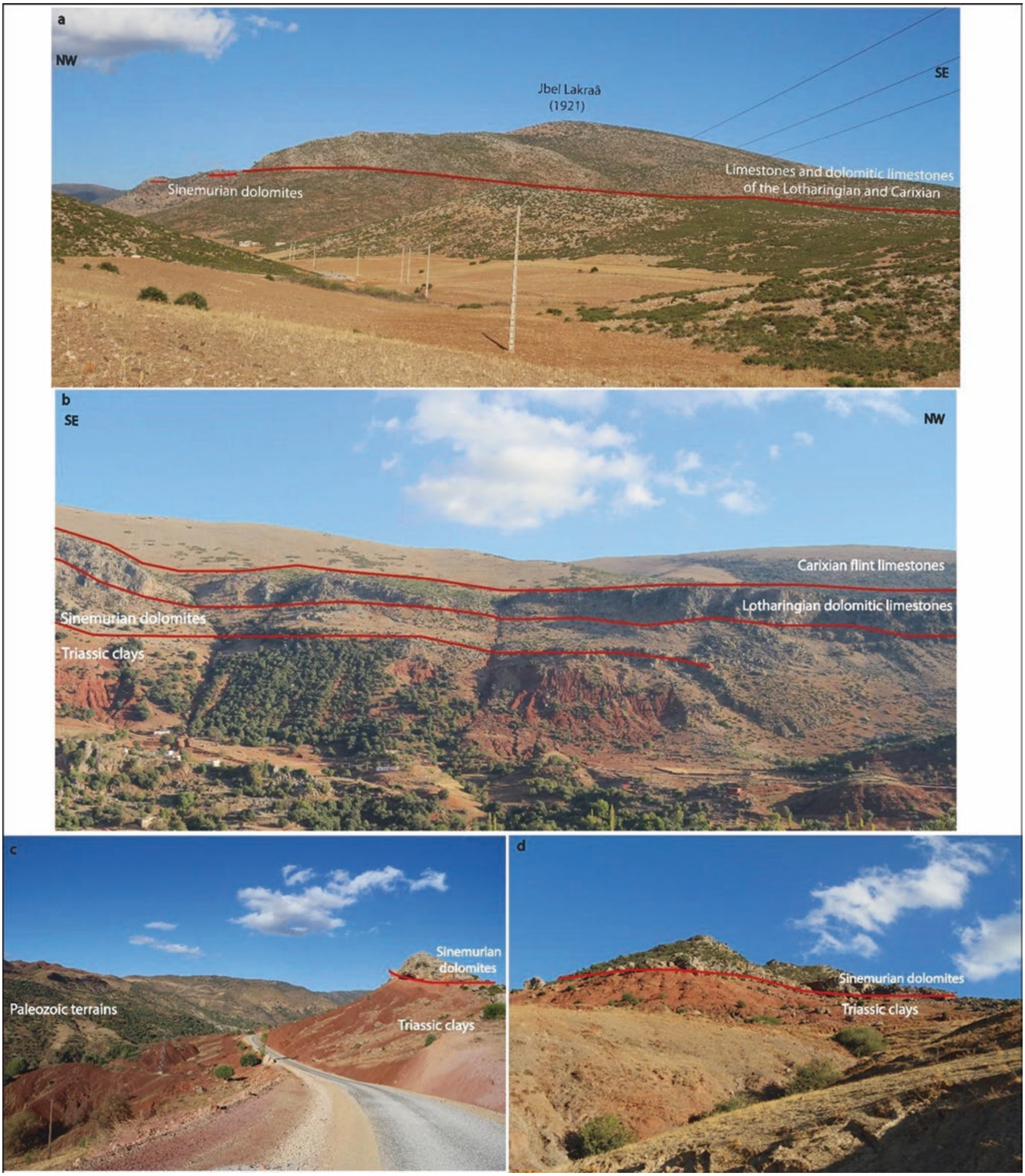

Fig. 2.9 (**a**) General view of the Jbel Lakraâ geosite (Baadi 2021); (**b**) Different formations constituting the Jbel Lakraâ geosite; (**c**) Detachment contact between Liassic and Triassic deposits; (**d**) Dolomitic deposits conformably resting on the Triassic deposits

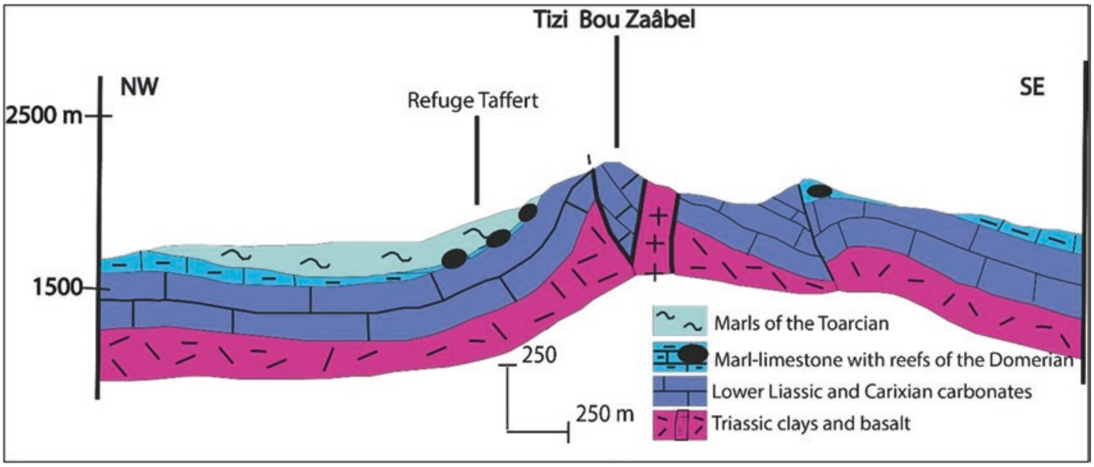

Fig. 2.10 Coupe géologique des marno-calcaires à monticules récifaux du géosite de Tizi Bou Zaâbel. (Baadi 2021)

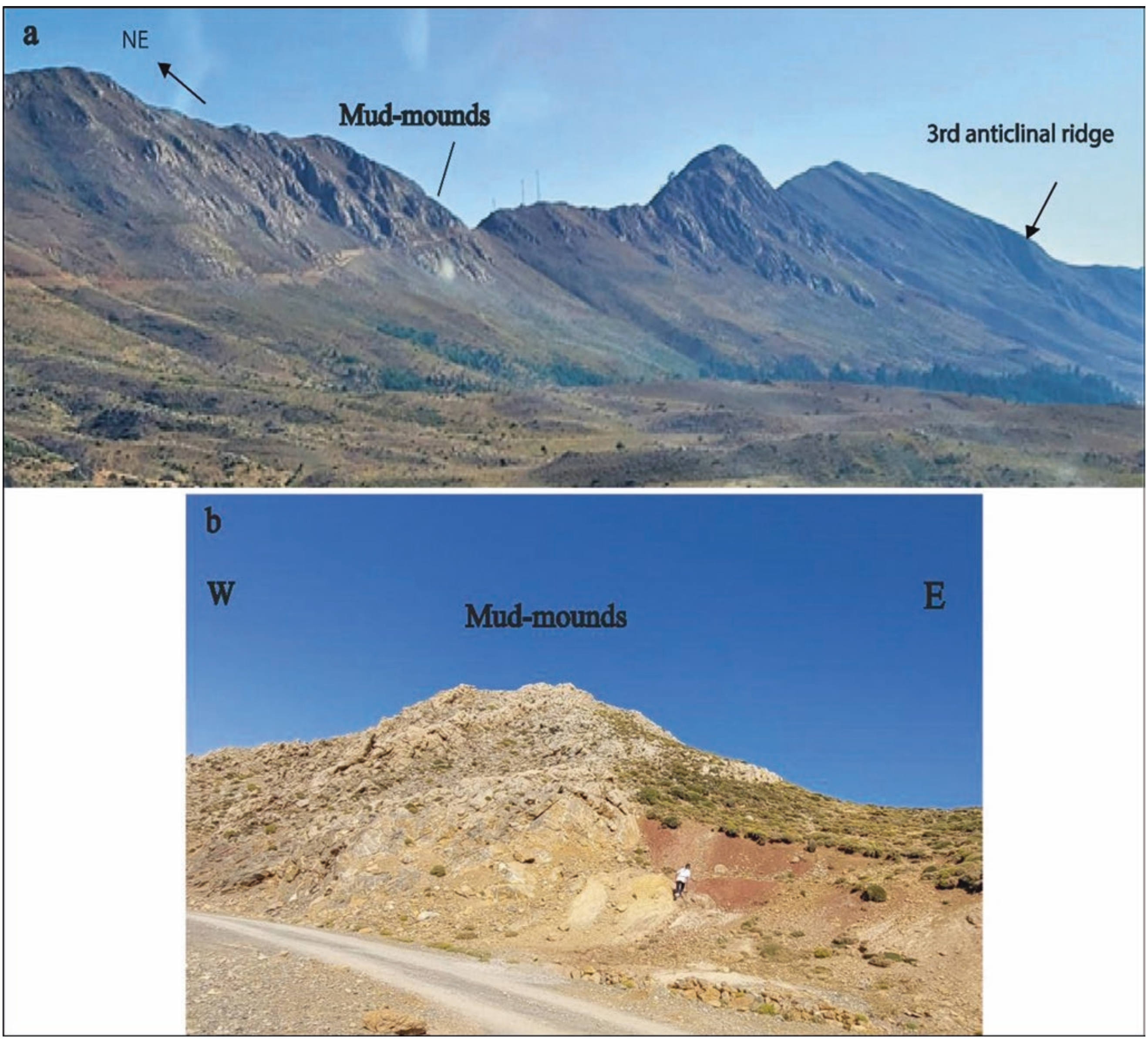

Fig. 2.11 (**a**) General view of the location of the mud-mounds of the Tizi Bou Zaâbel geosite, along the third Bou-Iblane ridge; (**b**) Contact of mud-mounds with surrounding deposits

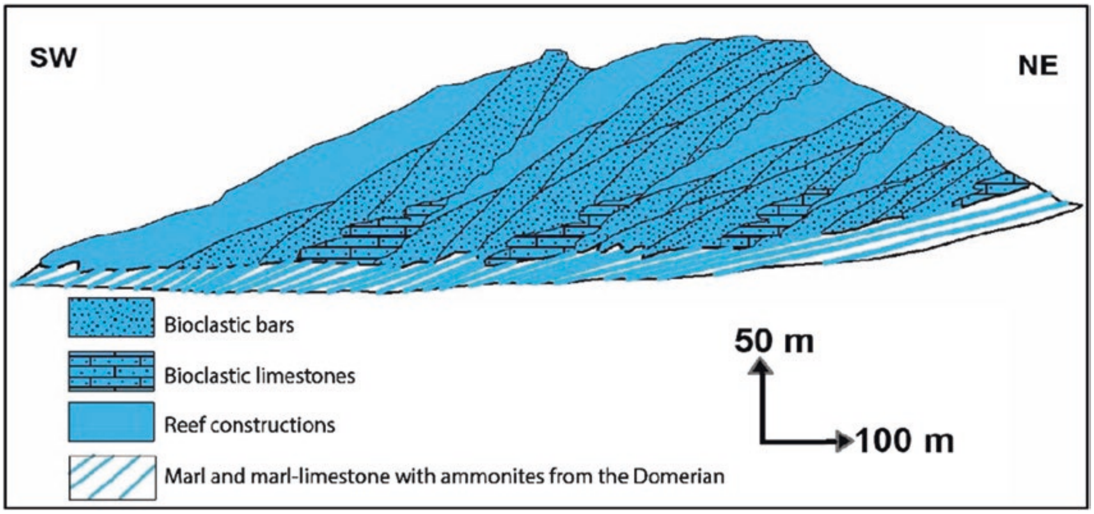

Fig. 2.12 Koudiat Ech Chham reef hill. (El Arabi 2001; completed)

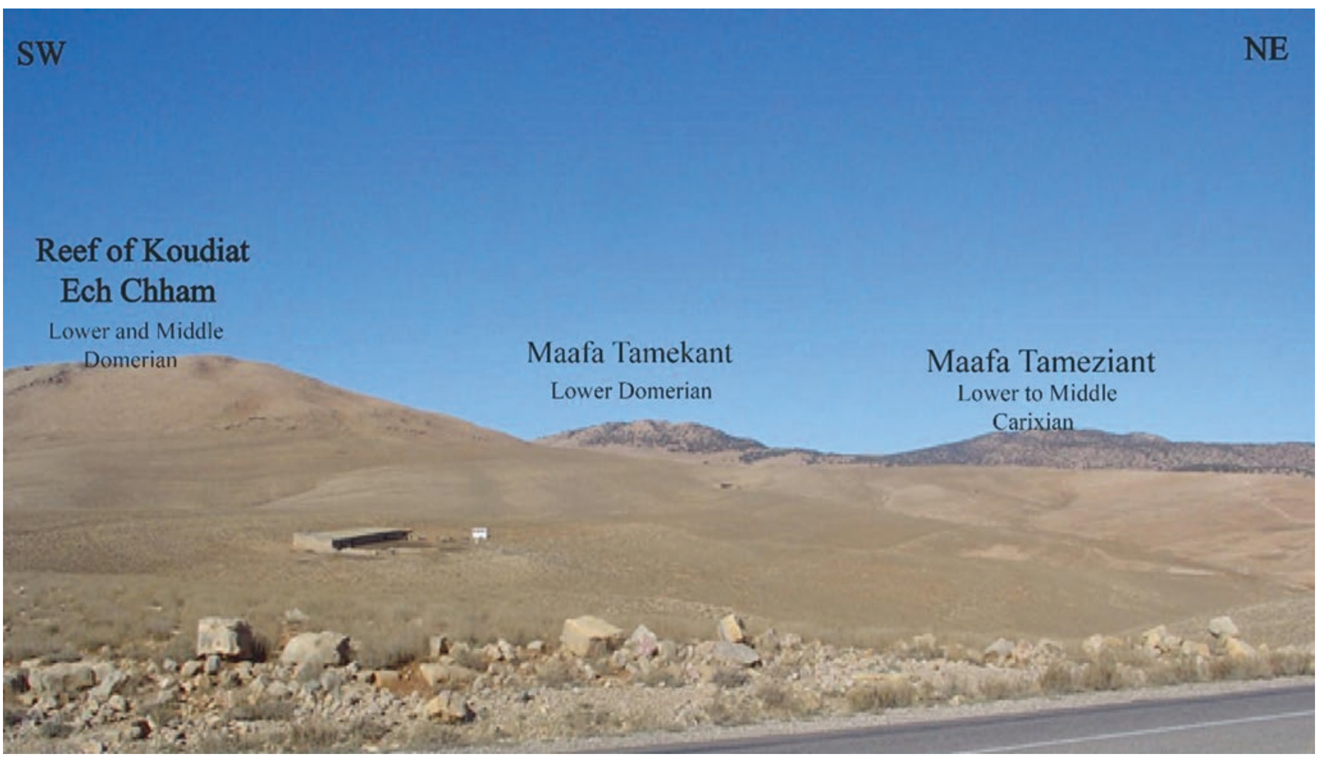

Fig. 2.13 General view of the Koudiat Ech Chham geosite, the photo shows in the background Maafa Tamekrant and Maafa Tameziant

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The Brown and Ammonitico-Rosso Levels: Geoheritage Reflecting the Toarcian Lithostratigraphy of the Middle Atlas (Morocco)

3

Ayad Akasbi, Hamid Amhoud, Abdellah Sabaoui, and Abdellah Oumou

Abstract

The Middle Atlas chain has a wealth of toarcian deposits with diverse characteristics. In the northern Middle Atlas, these deposits are more dilated, with marly dominance and represented by the formation of Bechyne Marls of the terminal Domerian-Toarcian. In the central Middle Atlas, they are more calcareous, more reduced and are called "Faciès de Mibladène." These facies intercalate at the level of the subsident zones a turbidite level of the Lower Toarcian with a particular facies commonly called Brown level, and in the bordering zones and certain unstable zones, they contain a nodular facies of Ammonitico-Rosso type of the Middle Toarcian. These two levels represent a geoheritage with unique characteristics in the Middle Atlas. The study of the Toarcian geosites has made it possible to reveal the spatio-temporal distribution of the Toarcian deposits and to retrace the periods of individualization and filling of the Middle Atlas basin by testifying to a paleogeographic configuration organized into emergent zones, protected mudflats, basin edge and deep basin.

Keywords

Brown level · Ammonitico-Rosso · Toarcian · Geoheritage · Geosites · Middle Atlas

3.1 Introduction

At the scale of the Middle Atlas (Fig. 3.1), the distribution of deposits covering the Domerian-Toarcian interval is governed by the activation of longitudinal and transverse faults that have induced a compartmentalization of the basin into subsident sectors, separated by resistant zones. During its Jurassic history, the Middle Atlas has subsident zones in the NE which are constituted by synclinal depressions, limited on the SW side by the platform of the central Middle Atlas. Within these synclinal depressions, with a value of Jurassic depocenters and according to an NE–SW profile, the Toarcian deposits are represented by the formation of the Bechyne Marls (Benzaquen et al. 1965) or Taffert Marls (Du Dresnay 1962, 1988) of the terminal Domerian-Toarcian, which are underlain by the Ouarirt Limestones (Benzaquen et al. 1965) of the Domerian by means of a regionally valued bioturbated surface. The deposits of the Bechyne Marls formation, very dilated to the NE, progressively narrow toward the SW (Middle Atlas) where they are qualified as "Mibladene facies" (Dubar 1942; Igmoulan 1993; Saadi 1996).

The Toarcian deposits differ, therefore, depending on whether they are in the subsident synclinal zones of the NE or on the SW platform. These deposits present a geopatrimonial richness that allows to trace the lithostratigraphic history of the Middle-Atlasic chain through its Brown and Ammonitic-Rosso levels as emblematic and representative geosites of the Toarcian of the region.

3.2 Synclinal Zones and Associated Brown Level

3.2.1 Northern Middle Atlas

Deposits of the Bechyne Marls formation are continuously exposed in the Meghraoua syncline in the NE of the northern Middle Atlas (Fig. 3.1). This area corresponds to a vast syncline, framed on the west by the first anticlinal wrinkle and on the east by the second anticlinal wrinkle. In this depocenter, toarcian deposits with deep basin facies are intercalated by a turbiditic level, known in the geology of the Middle Atlas by the "Brown level" (Colo 1961). This level, turbiditic

A. Akasbi (✉) · H. Amhoud · A. Oumou
Faculty of Sciences, Moulay Ismail University, Meknes, Morocco

A. Sabaoui
Faculty of Sciences Dhar El Mahraz, Sidi Mohammed Ben Abdellah University, Fez, Morocco

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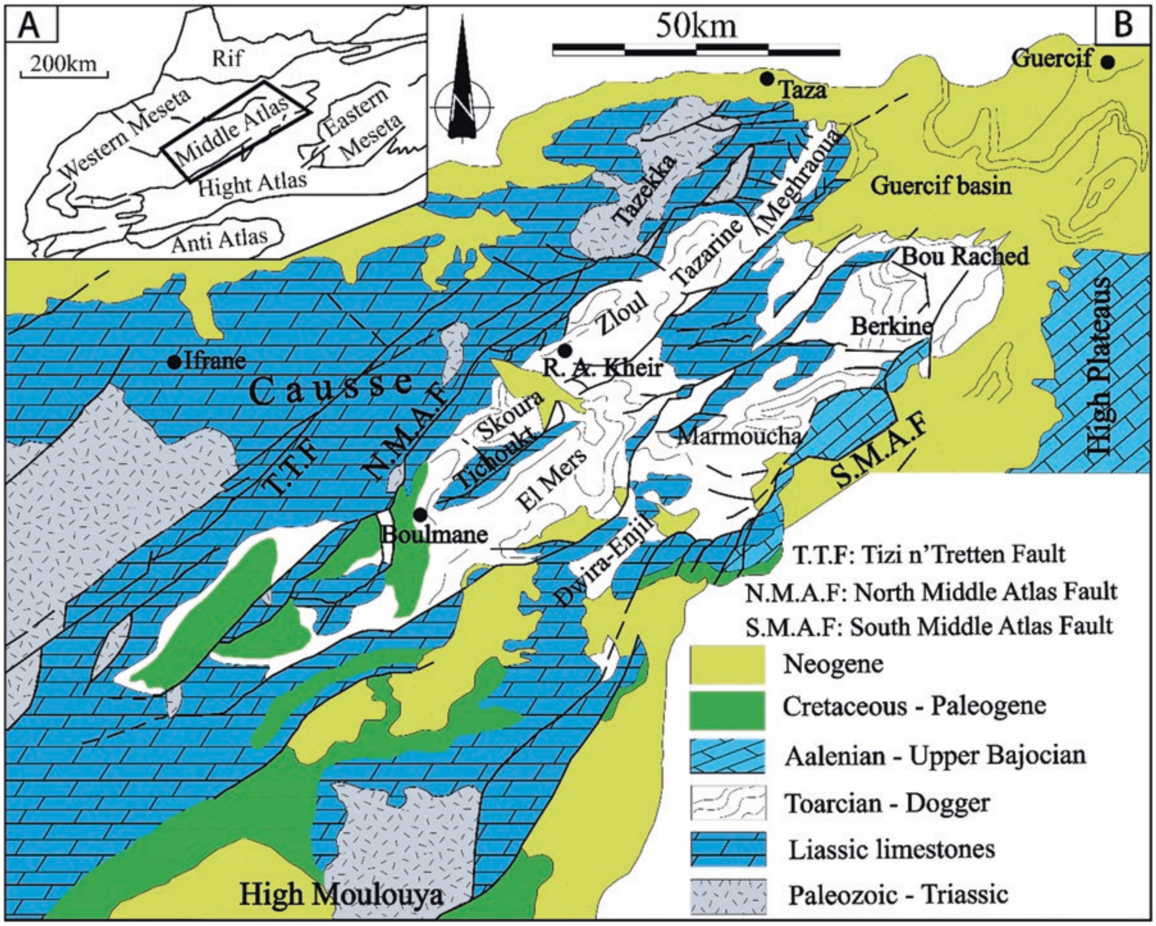

Fig. 3.1 (**a**) Location of the Middle Atlas. (**b**) Simplified geological map of the Middle Atlas. (From Fedan 1988); modified for the north-eastern part by Akasbi (1993) and Akhssas (1993)

in nature (Akhssas 1993; Akasbi et al. 2001), is equivalent to the top of the turbiditic Tagoudite Formation in the High Atlas (Evans and Kendall 1977; Studer 1980; Bernasconi 1983; Brechbühler 1984). Its geographical location in the province of Taza and its easy access on the Meghraoua-Bou Iblane road as well as its outcrop qualities give it the character of a geosite (Fig. 3.2).

The outcrops of the Bechyne Marls are located immediately east of the village of Meghraoua along the left bank of Oued Tmourhout (topographic sheet of Meghraoua at 1:50,000). The Bechyne Marls formation, about 200 m high, is subdivided into three sets of unequal dimensions (Figs. 3.3a and 3.4):

(a) *Anterior brown level* (about 15 m): It corresponds to an alternation of metric levels of grey and compacted marls and decimetric banks of strongly bioturbated grey limestones, increasingly rare toward the top. The first packstone limestone banks are black and turbiditic in character with oblique and intersecting stratifications and horizontal laminations. The fauna is represented by belemnite rostrums and ammonites including *Dactylioceras* sp. of the Lower Toarcian (Polymorphum Zone) and numerous *Dactylioceras mirabile* Fucini. and *Dactylioceras simplex* Fucini. (Colo 1961). The marls at the top of this assemblage provided a rich and diversified microfauna of foraminifera, consisting of Nodosariidae (*Dentalina gumbeli* Schwager, *Lenticulina subalata* (Reuss), *Lenticulina münsteri* (Roemer) and *Lenticulina* sp.) and Ceratobuliminidae represented exclusively by the species *Garantella stellata* Kaptarenko.

(b) *Brown level* (maximum 10 m): It stands out in the topography by its brown color and its resistance to erosion. It rests on the underlying marl by a clear surface which announces a radical change of facies. It is formed by a succession of sandstone limestone beds interspersed with brown marl layers (Figs. 3.3b and 3.4). The internal structures of the limestone beds vary between horizontal laminations (term **Td** of the Bouma sequence 1962), criss-crossing and convoluted laminations (term **Tc** of the Bouma sequence 1962) and oblique laminations (term **Tb** of the Bouma sequence, 1962). The vertical arrangement of these facies as well as their association with pelagites reflects distal

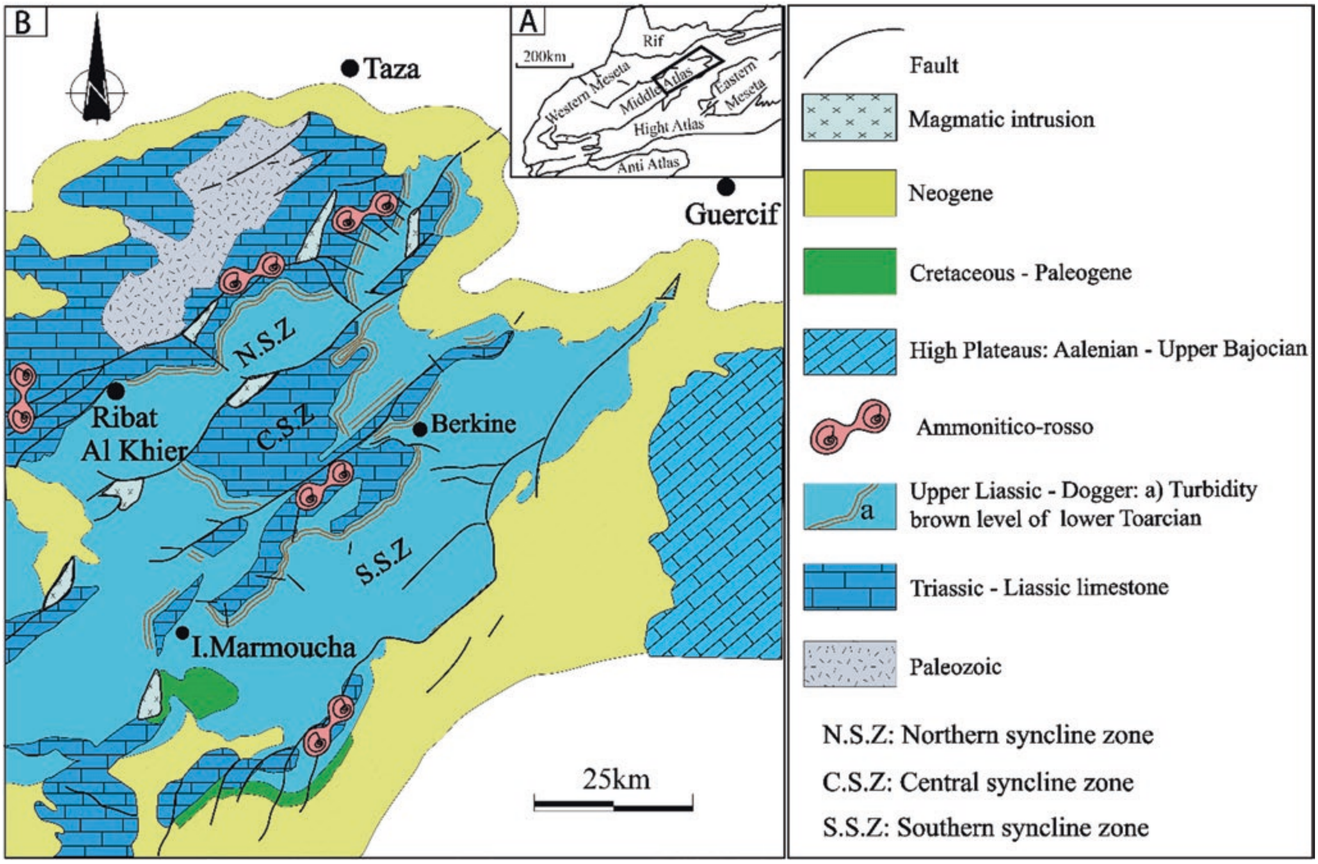

Fig. 3.2 Simplified geological map of the Middle Atlas (Akasbi et al. 2001) with location of Brown and Ammonitico-Rosso levels

turbidite-type depositional conditions, marked by the predominance of Mutti and Ricci-Lucchi's (1975) subfacies **D**. The summit limit of this assemblage is difficult to define because of its progressive passage toward the overlying marls. This passage can be materialized by the progressive disappearance of the brown color correlative to the disappearance of the sedimentary structures.

(c) *Posterior brown level* (approximately 165 m): These are grey indurated marls (Figs. 3.3c and 3.4), admitting at their base a nodular marl-limestone level or term marl-limestone of Colo (1961), famous in the geology of the Middle Atlas. This level (15 m), easily identifiable in the topography admits dark gray limestones, strongly bioturbated. The traces of bioturbation (burrows) are filled by a darker clayey micrite. An ammonite (*Hildoceras sublevisoni* (Fucini)) collected in this level allowed us to assign it an age of Middle Toarcian (Bifrons zone, sublevisoni subzone). The marl levels of the middle part of this assemblage are attributed to the Middle Toarcian (Bifrons zone) thanks to the collection of *Hildoceras sublevisoni* (Fucini), *Hildoceras tethysi* (Geczy), *Hildoceras semipolitum* Buckman, *Lytoceras* sp. and *Osperlioceras bicarinatum* (Zieten). The diverse foraminiferal microfauna is composed of *Lenticulina münsteri* (Roemer), *Lenticulina* sp., *L. cordiformis* (Terquem) mg. P., *L. tenuistriata* (Franke) mg. *F., Dentalina nodigera* Terquem et Berthelin and *D. pseudocommunis* Franke. The summit gray marls (last 55 m) are particularly rich in foraminifera including *Nodosariidae* inherited from the underlying levels to which is added the new species *Lenticulina chicheryi* Payard mg. *L.* These summit levels are classified in the Upper Toarcian thanks to a fauna of ammonites with notably *Catulloceras* cf. *insignisinile* Branco, *Polyplectus discoïdes* Zieten and *Pleydellia aalensis* Zieten (Colo 1961). The collecting of *Pleydellia* sp., associated with Hammatoceratidae at the very top of this assemblage allowed us to characterize the top of the Aalensis zone.

3.2.2 Central Middle Atlas

In the central Middle Atlas (Termier 1936; Fedan 1988) and according to an NW-SE profile, the Toarcian deposits are organized in two formations: the Bechyne Marls of the Terminal Domerian-Lower Toarcian and the Amane Illila Formation of the Middle-Upper Toarcian or even Aalenian. These deposits are widely exposed around the Tichoukt wrinkle from its SW end to its north-eastern fall. They

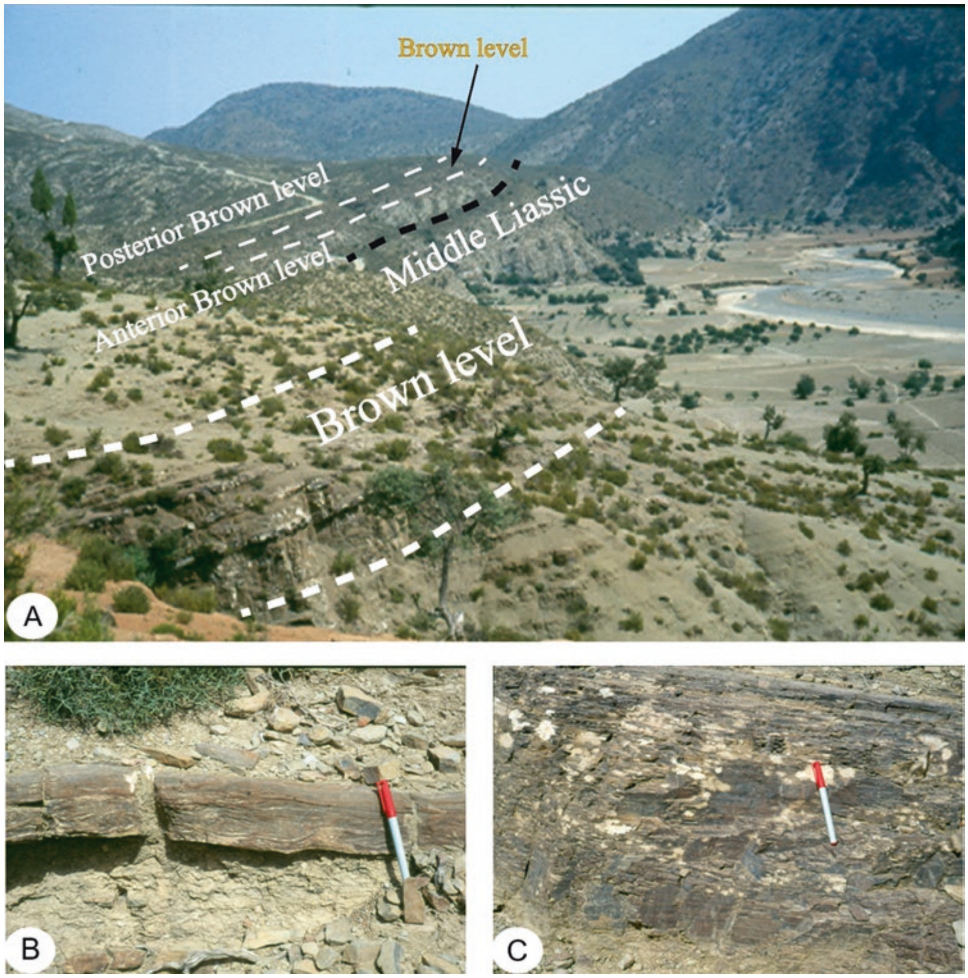

Fig. 3.3 Photographs of the Toarcian deposits of the Meghraoua syncline and the associated Brown level: (**a**) General view with the Brown level; (**b**) Detail of the Brown level with turbidite banks of obliquely stratified and convoluted sandstone; (**c**) Hemipelagic brown marl of the Brown level

decrease toward the SE of the Middle Atlas where they are qualified as "Mibladène facies" (Dubar 1942; Igmoulan 1993; Saadi 1996). These deposits, which occupy the El Mers syncline and the SE edge of the Middle Atlas, are smaller (about 60 m) and predominantly limestone.

3.2.2.1 Skoura Syncline and Tichoukt Ridge Border

The Toarcian deposits in this region become more calcareous and are formed by the superposition of two sedimentary formations of Toarcian age: the Bechyne Marls Formation and the Amane Illila Formation.

The Bechyne Marls formation (30–35 m) is attributed to the Lower Toarcian (Polymorphum zone; Akasbi 2003). It is limited at the top by an erosive surface that underlines the base of the Amane Illila Formation.

The Amane Illila Formation (17 m) constitutes a bar that forms a well individualized lithostratigraphic marker within the Toarcian-Bajocian marls. It is constituted by pseudonodular limestones, with lenticular stratification which are organized in massive banks with erosive bases and oblique and/or undulated stratifications. They are surmounted by an encrinite in decimetric bands which forms the massive body of the bar. This formation is classified in the Middle Toarcian (Bifrons zone) by *Hildoceras bifrons* Bruguiere (Charrière 1990). The overlying pinkish-gray limestones are organized in large benches limited by undulating surfaces with concentrations of bioclasts and lithoclasts. The internal structures of the beds correspond to horizontal, oblique and intersecting laminations testifying to channel filling and indicating a NE direction of progradation. A fragment of poorly preserved ammonite, collected in scree, whose doubtful determination is to be compared with Hammatoceratidae from the top of the Middle Toarcian and Upper Toarcian.

This bar ends in an undulating and erosive ferruginous surface, affected by nodular bioturbation and presents a concentration of diverse bioclasts. It is attributed to the Middle-Upper Toarcian and reflects successive arrivals of prograding bio-detrital outwash in a shallow outer platform type marine environment.

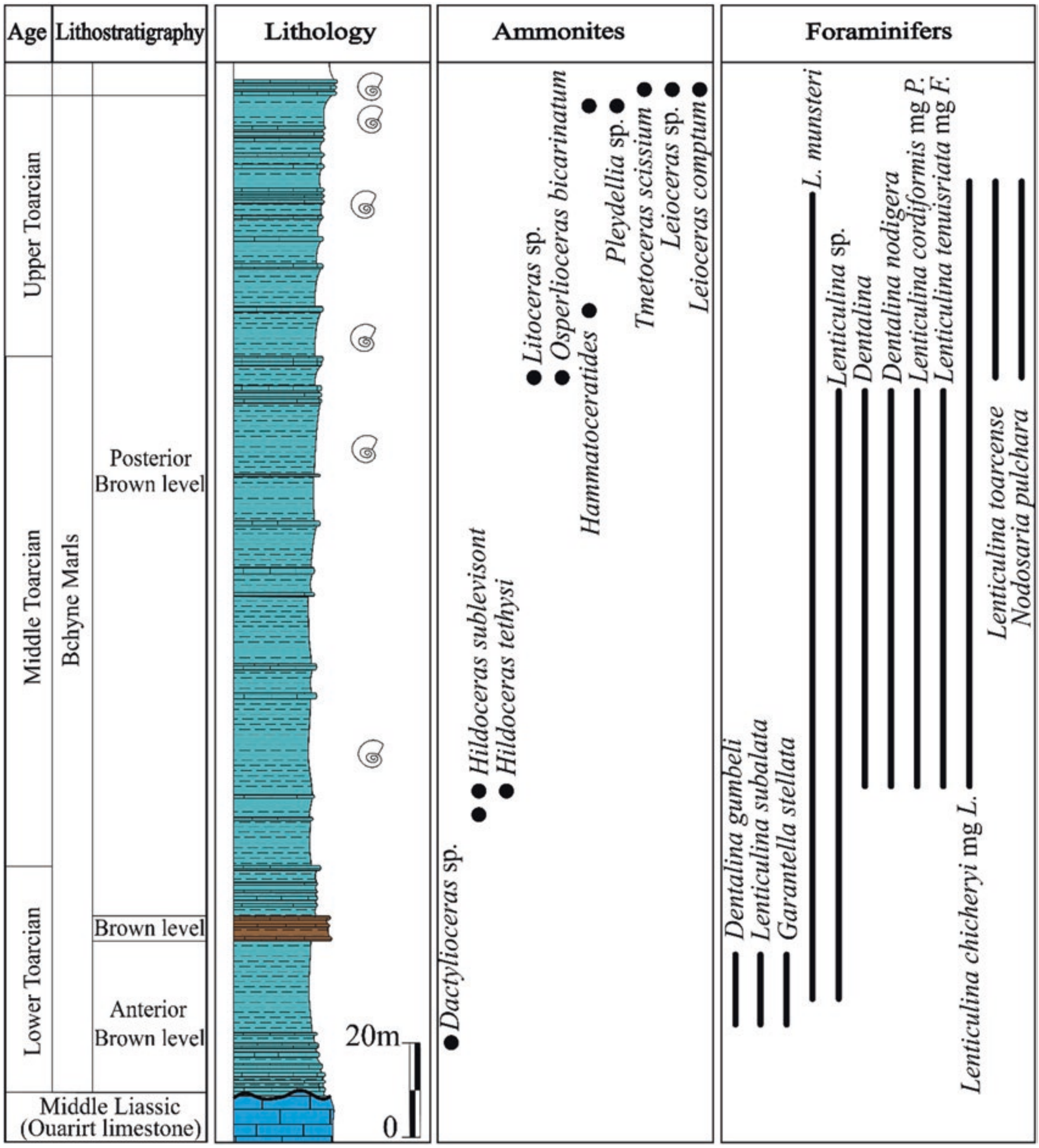

Fig. 3.4 Lithostratigraphy of the Bechyne marl formation of the Meghraoua syncline and distribution of ammonites and foraminifera

3.2.2.2 Remainder of the Central Middle Atlas

In general, the Toarcian deposits are characterized by the "Mibladen facies" (Fig. 3.5) composed of two sets: the green marls of the Lower Toarcian or "Mibladen Beds" (5 m) and the overlying limestone bar (25–30 m) of the Middle Toarcian-Aalenian?

The green marls (5 m) or Mibladen Layers (Dubar 1942) are compact and admit thin layers of bioturbated limestone (tracks and *chondrites*). These marls yielded a foraminiferal microfauna dominated by Ceratobuliminids: *Garantella praestellata* nov. sp. and Nodosariids: *Lingulina dentaliniformis* Terquem *Lingulina lanceolata* Hausler, *Lingulina cernua*, Berthelin, *Citharina longuemari* (Terquem) var. *angusta*, *Ichtyolaria lignaria* (Terquem) and *Lenticulina* sp.

The limestone bar begins with gravelly limestones ordered in continuous or lenticular 10–20 cm beds with undulating surfaces that show horizontal and rarely oblique or intersecting laminations. This term is attributed by comparison with neighboring areas to the Lower Toarcian (Benshili 1989). The remainder consists of grayish-yellow limestones rich in lithoclasts and granoclastic bioclasts. The remainder of this bar is composed of banks of reddish bioclastic limestones, channelized and with a microbrecciated appearance.

This term is capped by a landmark level, which forms a cornice in the topography that gullies the previous member. With thickness of approximately 5 m, it is constituted of stratocroissant decimetric benches, with reddish patina and showing figures of oblique stratifications indicating a direc-

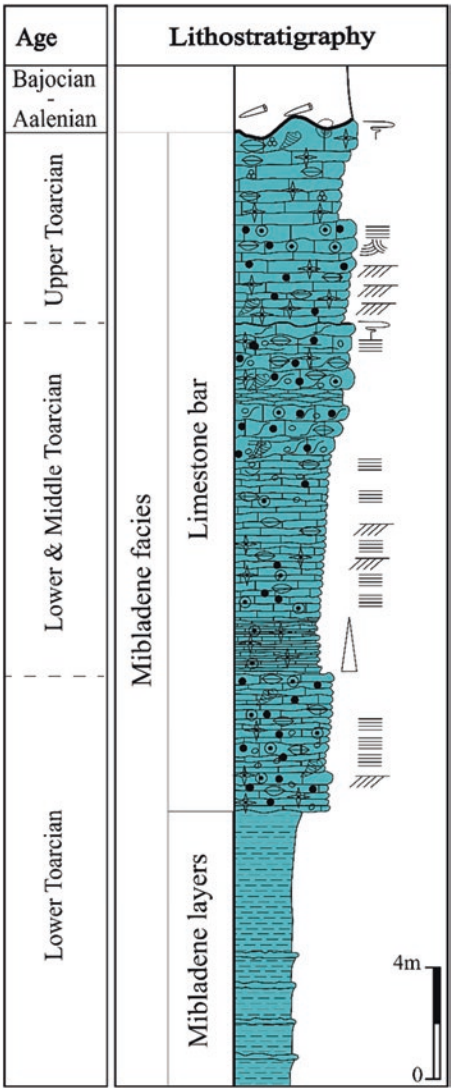

Fig. 3.5 Lithostratigraphic evolution of the Upper Lias of El Mers syncline (Tagnamas locality)

tion of progradation toward the NE. The last bank of this succession, 70 cm thick, is relatively rich in fauna: regular sea urchins of the *Pentacrinus* type, bivalves, brachiopods, nautilus and ammonites: *Catulloceras* sp. of the Meneghinii zone. It is strongly gullied and affected by a ferruginous and bioclastic crust that follows the shape of the gully with numerous belemnites, brachiopods, sea urchins, bivalves and vertebrate bones and by a phosphate coating, lined with stromatolithic structures of algal origin. In the deep irregularities of the gully lie shreds of light grey or beige limestone very rich in gastropods, bivalves, nautiloids and ammonites, some of which are phosphatized: *Graphoceras decorum* Buckman, *Graphoceras* gr. *concavum* (Sowerby), *Graphoceras* sp., *Pseudammatoceras* sp. cf. P. *guliense* (Reinz), *Docidoceras* sp., *Ludwigella* sp., *Bradfordia* cf. *costata* Buckman, and other Graphoceratids and Hammatoceratids. This fauna, very condensed in these limestone flakes, corresponds only to the Upper Aalenian (Concavum zone).

These carbonate deposits, attributed to the Lower-Middle Toarcian and Upper Toarcian (Speciosum and Meneghinii zones), evolve in an external platform with high energy and active progradation following filling followed by a clear slowing of sedimentation with a tendency to harden the bottom. This bar is capped by a deep gully, impregnated with a ferruginous and phosphate crust, rich in fauna and whose hollows are clogged by limestone shreds that attest to the condensation of the Terminal Toarcian and the whole Aalenian.

3.2.3 Correlations

At the scale of the northern Middle Atlas, the Toarcian deposits show significant variations in thickness and changes in lithology (Fig. 3.6). They materialize the differentiation and individualization of synclinal basins separated by high zones or wrinkles. The subsident zones are filled by essentially marly and thick deposits, of calm environments, whereas the high zones or wrinkles are with more calcareous and more reduced deposits, attesting to relatively dynamic environments. In general, the deposits of the Bechyne Marls formation show the maximum thickness in the center of the basin and the minimum on the northern and southern margins. At the level of the wrinkles and their flanks, they are more reduced and richer in limestones and show less deep and high energy characters that are expressed and accentuated in the Upper Toarcian-Alenian.

In detail, the "anterior Brown level marls," of the Lower Toarcian, occur in the NE (Meghraoua) under the same facies (gray or blue marls with clayey limestone layers) which are increasingly reduced toward the SW of the Middle Atlas. The "Brown turbidic level," Lower Toarcian, whose outcrops are limited to the northern Middle Atlas is marked at the base by a sedimentary discontinuity at the contact of the marls brown level and its upper limit coincides with the disappearance of the last turbidic layer and the dominance of marly pelagic deposits.

The "Brown level," more and more developed toward the NE, is totally absent to the SW in the central Middle Atlas and on the Middle Atlasian Causse. It is also absent at the level of the anticlinal wrinkles that constitute high grounds and limit on both sides the lobes occupied by the three synclinal zones (Fig. 3.6). This level, lacunar on the Middle Atlas Causse (Robillard 1981; Sabaoui 1987, 1998) and in the Central Middle Atlas, is very developed in the depocenters of the folded Middle Atlas. This turbidic bedding reflects the fracturing of the Liassic carbonate platform at the Domerian-Toarcian transition, which reached its peak at the end of the Lower Toarcian (Levisoni zone). The gap at the

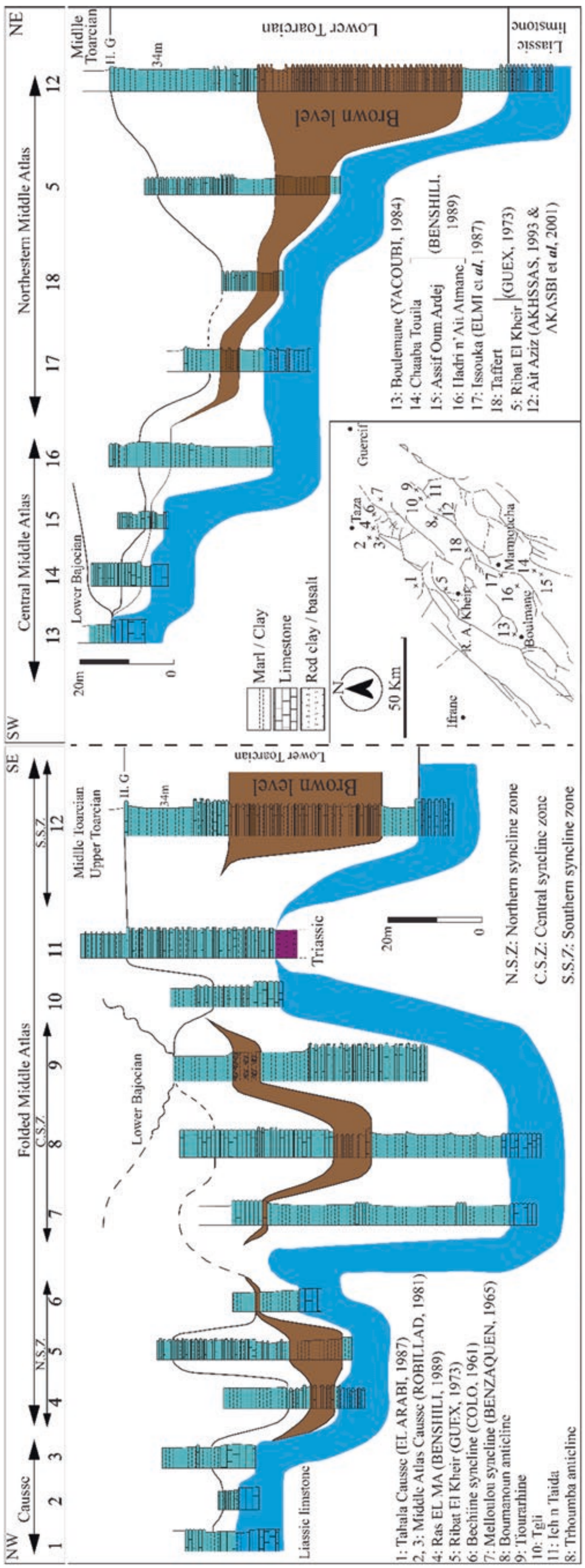

Fig. 3.6 Correlation of the Lower Toarcian and "Brown level" sections at the Middle Atlas. (Akasbi et al. 2001)

top of the Lower Toarcian (Levisoni Zone: Elmi and Benshili 1987) corresponds to the accentuation of the SW–NE paleogeographic differentiation following the dislocation of the Lower and Middle Liassic carbonate platform. Thus, two areas of sedimentation with different evolutions can be distinguished: on the one hand, the exondation of the SW parts and the installation of an unstable NE-facing slope, inducing landslides and resedimentations, and on the other hand, the sinking of the northern parts and the establishment of a basin regime that receives the products of dismantling of the emerged or submerged areas (Fig. 3.7).

The "post Brown level marls," of the Middle-Upper Toarcian (Aalensis zone), show at their base a level of nodular limestones or marl-limestones of low thickness and rich in ammonites of the Bifrons zone, Sublevisoni subzone. They continue into the Middle and Upper Toarcian with marly and sometimes marl-limestone facies, reflecting a relative homogenization of the deposits. In the furrowed areas, there is a predominantly marly series with very spaced intercalations of clayey limestone, whereas in the vicinity of the wrinkles, there is a reduction in the thickness of the marls and development of limestone. On the Middle Atlasian Causse, the reduction of the deposits of the Middle and Upper Toarcian under the Amane Illila bar suggests gaps in sedimentation during this period.

At the scale of the central Middle Atlas (El Mers syncline and the southern edge), the Toarcian series is represented by the "Faciès de Mibladène" (Mibladène layers and limestone bar) which rests on the Pliensbachian Megalodontid Limestone. Within this part of the Middle Atlas, these deposits undergo notable variations from one region to another:

- The Mibladene Beds (Terminal Domerian-Lower Toarcian) are constituted in the axis of the synclinal troughs by greenish-gray marls with belemnites and ammonites that intercalate, locally, layers of *Cancellophycus* limestone. On the northern flank of the El Mers syncline, these deposits are thin and contain a bar of prograding oolitic and bioclastic limestones (Benjelloun 1994). On its southern edge, in the Iwansitene area and near the Amrar wrinkle, the Mibladene Layers are represented by a metric footprint of reddish clays that testify to the individualization of a shoal that will later evolve to the Amrar wrinkle.
- The limestone bar presents lateral variations in facies and thickness, induced by the synsedimentary mobility of longitudinal and transverse faults that delimit the synclinal basins (Benjelloun 1994). Indeed, this bar, more developed in the center of the basins, is reduced on the edges (Tichoukt SE and Amrar NW). Toward the SW, this gap,

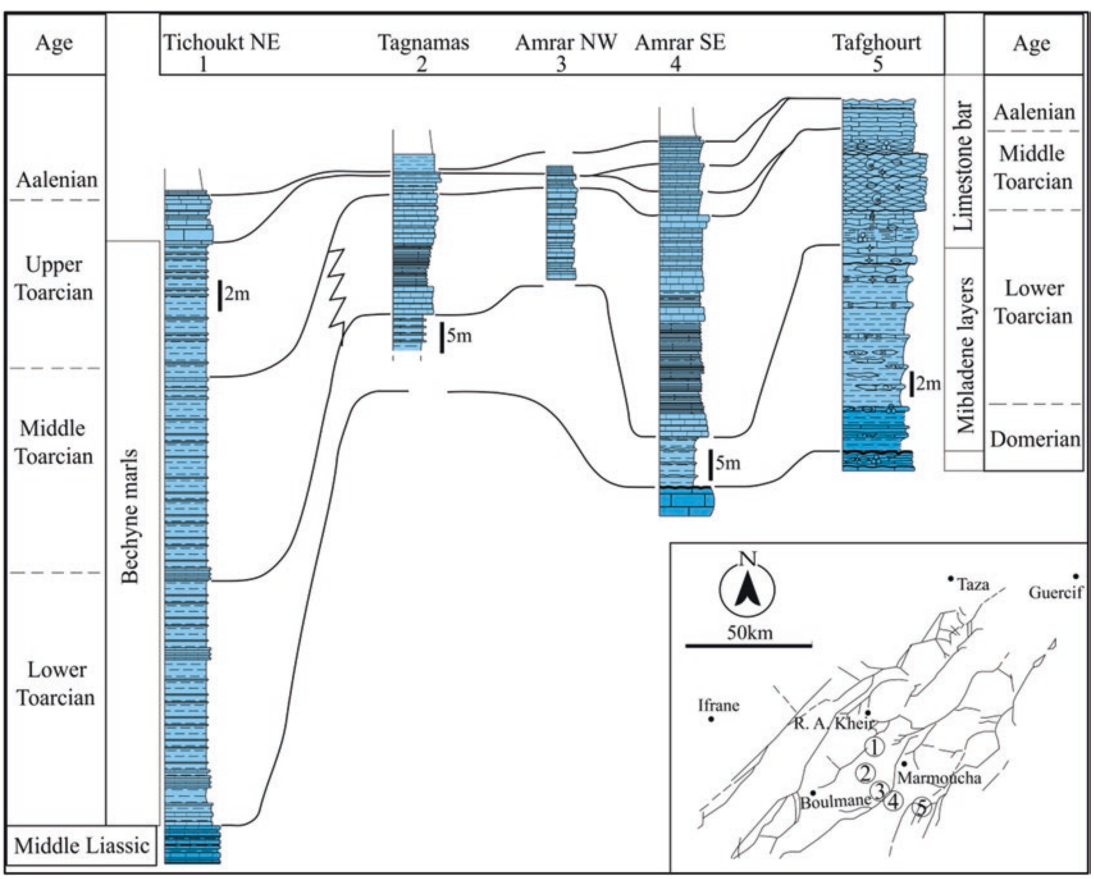

Fig. 3.7 Lithostratigraphic correlation of the Toarcian deposits of the central Middle Atlas

older, covers all the Toarcian, Aalenian and Lower Bajocian (Discites, Laeviuscula and the base of the Sauzei zone). This bar is more developed toward the NE (Oued Bessem); Benshili 1989) where it is formed by oolitic-gravelly deposits of the Middle and Upper Toarcian (Bonarellii and Speciosum zones) and oolitic deposits of the Upper Toarcian.

In the Skoura depocenter and around the Tichoukt wrinkle, the Toarcian deposits are represented by the Bechyne Marls formation of Lower Toarcian age in the SW and Lower-Middle to Upper Toarcian in the NE (Fig. 3.7). This formation is overlain by the limestone bar or Amane Illila Formation (Charrière 1990) which is progressively younger to the NE: Middle Toarcian to the SW and Upper Toarcian to the NE. These deposits pass laterally to the SE to the Mibladene Facies (Fig. 3.7). The stratigraphic position of the Mibladen Layers and their age allow them to be correlated with the "Brown level marl and limestone" of the northern Middle Atlas where they reflect more open and deeper conditions. The limestone bar is part of a prograding external platform installed after a generalized regression at the scale of the central Middle Atlas inducing the gap of the Levisoni zone (Elmi and Benshili 1987). The Brown level defined in the Bechyne Marls formation is absent in the whole central Middle Atlas.

These deposits reflect an SW–NE paleogeographic differentiation following the dislocation of the Lower and Middle Liassic carbonate platform and the individualization of two sedimentation areas with different evolutions: a deep basin to the NE and a protected mudflat to the SW. The gap at the top of the Lower Toarcian (Elmi and Benshili 1987) corresponds to the accentuation of the SW–NE paleogeographic differentiation leading to a regression of the marine areas toward the NE and the emersion of the regions located to the SW and the establishment of turbidites in the northeastern domain (Fig. 3.8). The Middle Toarcian deposits reflect neritic outer

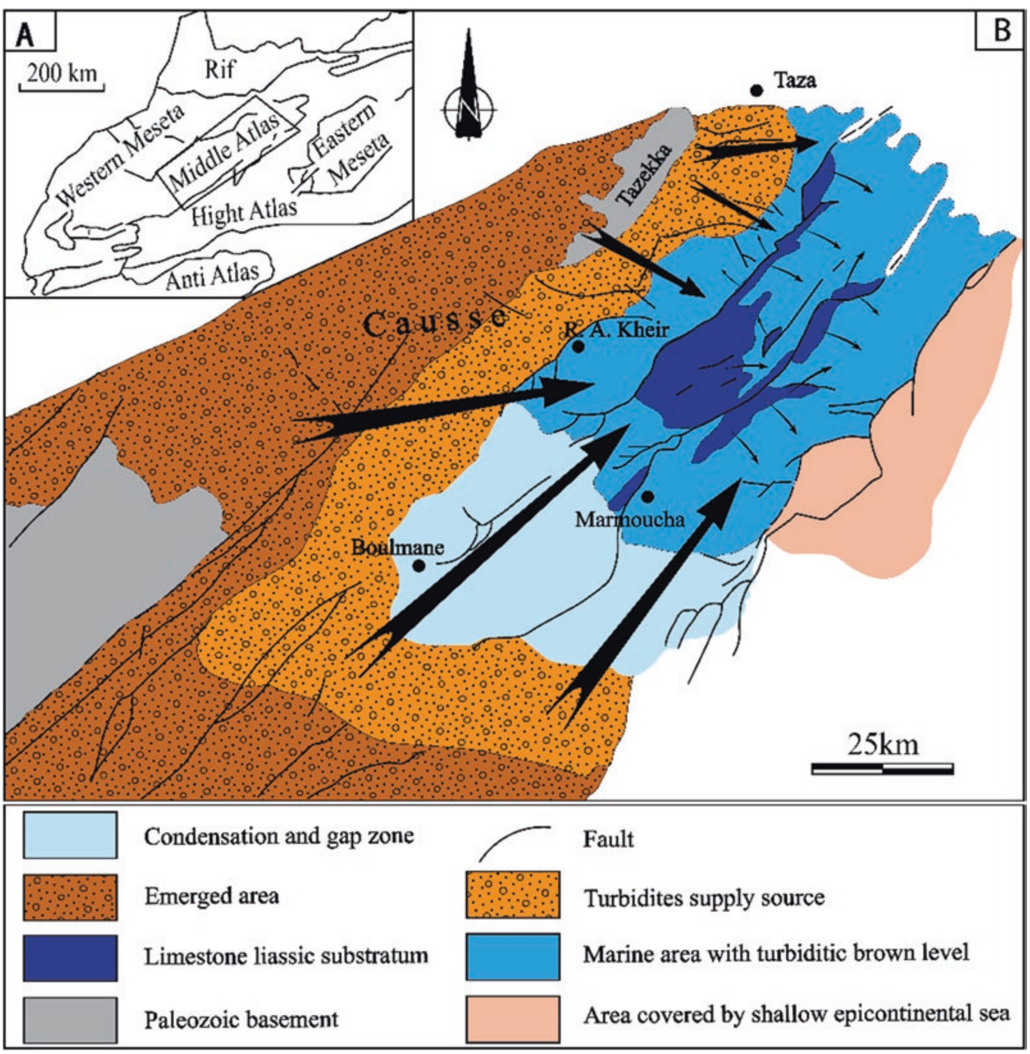

Fig. 3.8 (**a**) Place of the Middle Atlas in the Moroccan-Atlasic domain; (**b**) Paleogeographic context of the setting of the turbidite "Brown level" in the Lower Toarcian and location of the different sources of contributions. (Akasbi et al. 2001)

shelf conditions in an agitated environment (Elmi 1981; Elmi et al. 1989; Forest et al. 1999; Durlet and Thierry 2000). The Upper Toarcian corresponds to the last two clusters of the limestone bar in the Amrar region, which reflect the arrival of a biodetritic spreading in a highly agitated and open neritic environment and which materializes the continuation of progradation toward the northeastern subsident zones.

3.2.4 Synthesis

The Toarcian evolution of the Middle Atlas is guided by the structural and paleogeographic framework established in the Middle Lias. Indeed, after the dislocation of the carbonate platform and the birth of a structural framework organized in tilted blocks, we witness during the terminal Domerian-Lower Toarcian the installation of subsident mudflats or umbilics, more or less confined, filled by hemipelagic marls (Mibladen Layers). Some raised blocks, emerged or submerged, are the site of deposits of marls or reddish clays. On the other hand, to the NE the conditions become more open and announce the passage toward the deep northern zones (Marls with Brown level). The Brown level reflects the fracturing of the Liassic carbonate platform at the Domerian-Toarcian transition, which reached its climax at the end of the Lower Toarcian (Levisoni zone). It corresponds to the accentuation of the SW–NE paleogeographic differentiation following the dislocation of the Lower and Middle Liassic carbonate platform. From the end of the Lower Toarcian to the Upper Toarcian and after a generalized regression on the scale of the central Middle Atlas, we witness the return of marine zones over the entire region and the installation of a neritic carbonate platform. This reconquest is expressed by prograding encrinitique deposits, brachiopod and bivalve lumachelles, and by prograding oolitic and bioclastic nodular limestones. The regions located to the NE, in a subsident position, ensure the transition from the platform to the northern basin (Tichoukt NE). In the Terminal Toarcian and the Aalenian, paleogeographic differentiations become more pronounced and lead to a regression of the sea toward the NE.

3.3 Mobile Zones and Associated Ammonitico-Rosso Level

The outcrop of the Toarcian in general and of the "Ammonitic-Rosso" (Fig. 3.2) in particular is present at the level of the fourth anticlinal wrinkle (Colo 1961) which constitutes a line of reliefs extending from the Tafghourt and Tsiouant Jbels in the SW to Jbel Arhezdis in the NE. This wrinkle shows a varied field framework: carbonate deposits of the Lower and Middle Lias which are juxtaposed to the Aaleno-Bajocian deposits with facies of the Highlands (Jbels Tafghourt and Tsiouant), marls of the Toarcian and limestones and dolomites of the Highlands (Adrar Bou Naceur) and deposits of the Middle Jurassic, particularly the Boulemane marls and the Cornice limestone(s). At the level of this wrinkle, the Toarcian deposits surround the SE flank of Tafghourt. They are constituted by the Mibladen facies containing greenish marls or Mibladen Layers of the Lower Toarcian and limestone bar that covers the Middle Toarcian-Upper Toarcian interval (Meneghinii zone). These Toarcian outcrops contain particularly a level of Ammonitic-Rosso of the Middle Toarcian. Its geographical and geological position at the southern edge of the Middle Atlas as well as its easy access on the road Almis Marmoucha and Missour allow it to acquire the character of a geosite.

3.3.1 Ammonitico-Rosso and Associated Facies: Case of the Tafghourt Geosite

The Mibladen Layers are represented by bioturbated, yellowish or greenish marls that acquire a purplish hue at the top. At the base, they contain nodules of yellowish bioclastic limestones which evolve toward the top to continuous banks with undulating surfaces and rich in fauna: pectinids, solitary and colonial polypiers, brachiopods and reworked fragments of bryozoans and encrinas. The marls also contain decimetric clusters of reef bioconstructions that grow in number and size toward the top.

The limestone bar, which shows, above the yellowish oolitic and bioclastic limestones, limestones that show an "Ammonitico-Rosso" character (Figs. 3.9 and 3.10e, f). These are pinkish or pinkish-gray nodular limestones of the "Ammonitico-Rosso" type, arranged in 10–20 cm banks and limited by ferruginous surfaces or separated by joints or greenish marly interbeds. The macrofauna, abundant, is represented by belemnites, terebratulae and ammonites of the Middle Toarcian (Bifrons zone; Lusitanicum subzone): *Hildoceras* sp. and *Nodicoeloceras* sp., *Hildoceras lusitanicum* Meister, *Hildoceras crassum* Mitzopoulos and *Hildoceras* sp. and *Hildoceras* sp. In detail, these facies are organized in two doublets: the first is encrinite and rich in fine bioclasts and the second is formed by a decimetric border of yellowish marls, surmounted by ferruginized stratocroissant banks and showing traces of intense reworking. This procession contains ammonites of the Middle Toarcian (Bifrons zone; Lusitanicum subzone): *Hildoceras* sp. and *Nodicoeloceras* sp., *Hildoceras* lusitanicum Meister, *Hildoceras crassum* Mitzopoulos and *Hildoceras* sp. and *Hildoceras* sp. Benshili (1989) cited a fauna belonging to the Gradata zone with notably: *Collina* sp., *Collina gemma* Bonnarelli,

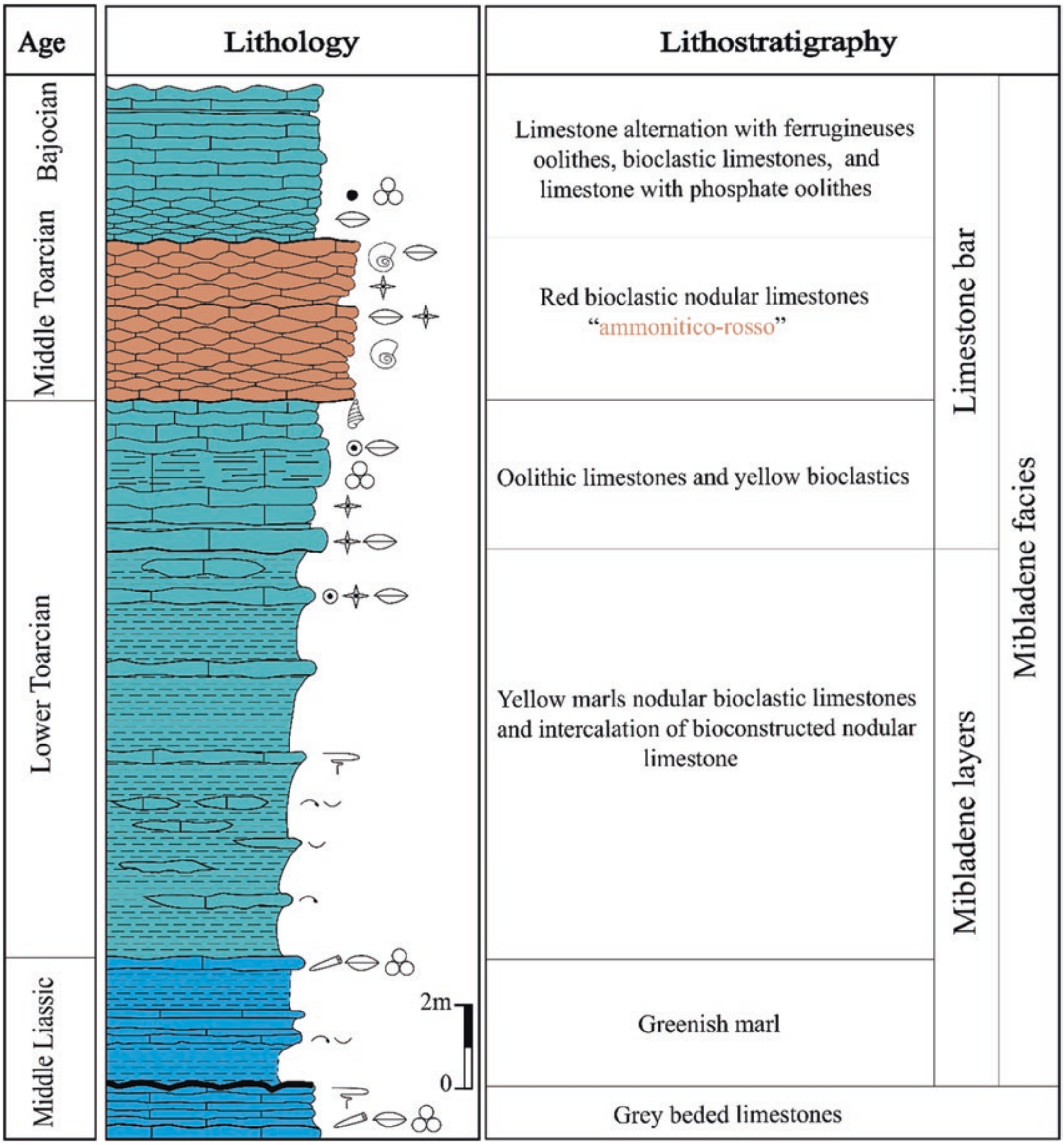

Fig. 3.9 Lithostratigraphy of the Toarcian-Bajocian deposits of the fourth anticlinal wrinkle (locality of Tafghourt)

Porpoceras sp., *Porpoceras encosmum* Dezi et Ridolfi, *Pseudogrammoceras* sp., *Pseudogrammoceras subregale* Pinna and *Polyplectus discoides* (Zitten.). The rest of the bar is an alternation of levels with reddish-tinged ferruginous oolites and thicker (4 m) lighter bioclastic levels. The macrofauna is represented by bivalves, brachiopods, belemnites and ammonites, represented essentially by the genus Hildoceras reworked from the deposits of the Middle Toarcian (Bifrons zone). In this alternation, a 20–30 cm long bench is formed by an accumulation of ovoid cobbles, constituted by the superposition of sheets of algal origin (Fig. 3.10e, f). Their size (millimetric to decimetric) increases from the base to the top of the bed. Numerous whole bivalve shells (pectinidae), belemnite rostrums, a few ferruginous tubercles, isolated polypiers and ammonites, some of which are very worn and arranged obliquely in the sediment, line the surface of this bed.

These deposits, which extend over the Lower Toarcian-Bajocian interval, materialize the progradation of oolitic and bioclastic strands from an adjacent shoal (yellowish oolitic and bioclastic limestones) and by nodular limestones that reflect an "Ammonitico-Rosso" type environment. This environment, which undergoes a progressive deepening and the penetration and development of nektonic fauna under a low water level (Benshili 1989), is a sloping, high-energy microvessel that constitutes the passage to the basin. This type of environment settles in particular on the steep slopes of tilted blocks where umbilicals can develop (Elmi 1981; Ameur and Elmi 1981; Delgado et al. 1981; Mekkahli 1998; Ameur 1999).

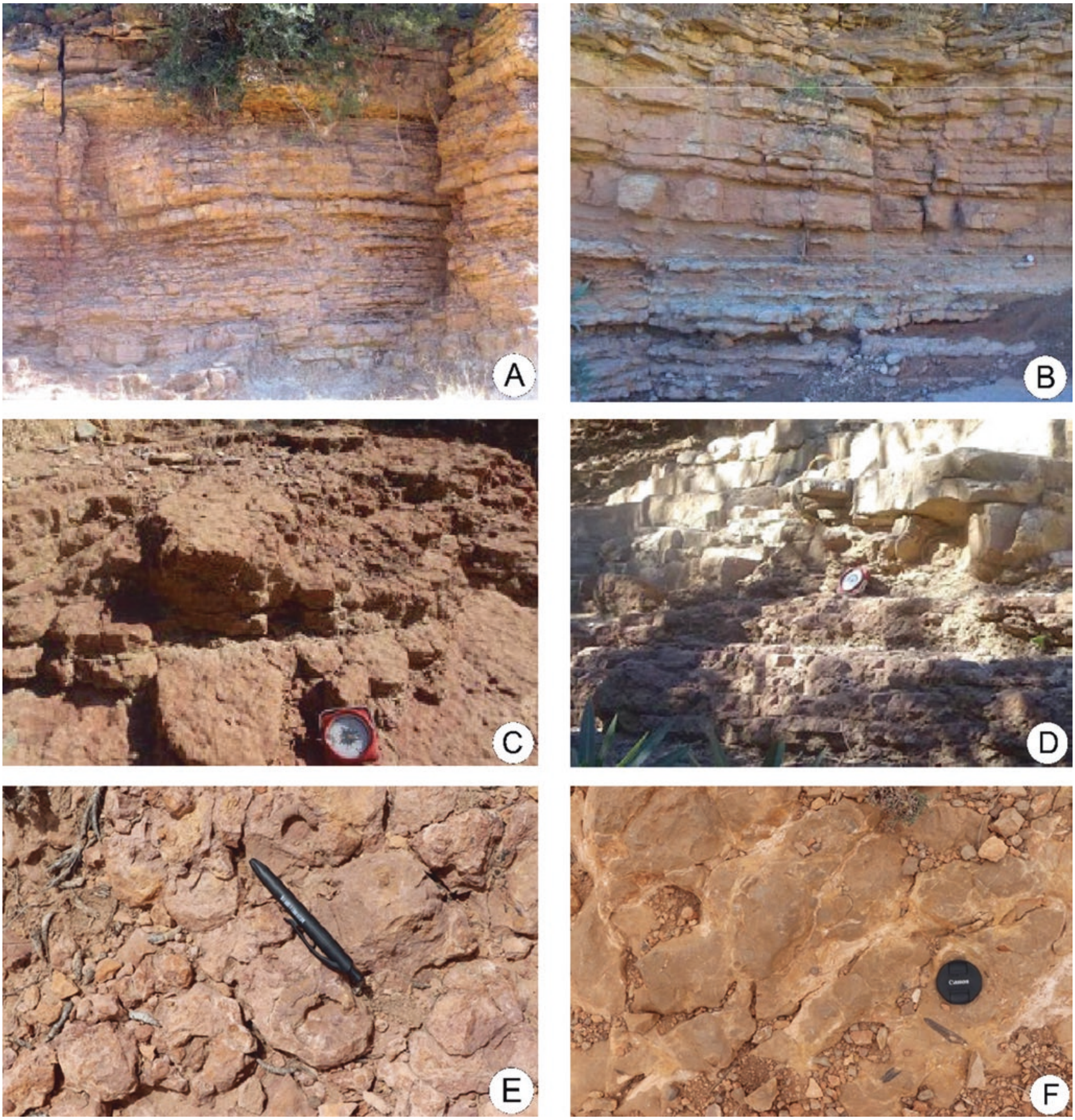

Fig. 3.10 Photographs of the Toarcian deposits and associated Ammonitic-Rosso level facies (Photos A, B, C, D: in El Hammichi et al. 2016). (**a**) Overview of the Oued Zraa Ammonitico-Rosso; (**b**) Detail of fig. A; Appearance of filamentous limestones with nipple structures (Hummocky Cross Stratification) at Oued Zraa; (**c**) Detail of the Ammonitico-Rosso level showing an intraformational unconformity; (**d**) Transition between red nodular limestones and gray limestones with marly layer at the base of the ammonitico-rosso (**e**) Ammonite-rich nodular level of the Ammonitico-Rosso in the Tafghourt area; (**f**) Nodular surface of an Ammonitico-Rosso bench

3.3.2 Comparisons and Correlations

On the southern edge of the Middle Atlas, the Toarcian series (Fig. 3.10) is composed of Lower Toarcian marls, which characterize a fairly protected carbonate ramp environment, and are capped by deposits rich in small reworked and transported fragments indicating the progradation of a high-energy barrier. The Middle Toarcian (Bifrons Zone) is a period of opening and homogenization of the depositional environments favoring the installation of a highly agitated and well-oxygenated external platform. At the end of the

Middle Toarcian and the beginning of the Upper Toarcian, the slowing of sedimentation, accompanied by a decrease in depth, allowed for the condensation and reduction of deposits, which are subject to strong reworking in an environment that oscillates between an external platform traversed by currents and the sometimes emerged shoal rim. These phenomena are accentuated and lead to the partial lacuna of the Upper Toarcian and total lacuna of the Aalenian.

At the level of the third anticlinal wrinkle and on its SE edge, the Bechyne Marls are thin and are affected by the lacunae of the Brown level marls, the base of the post Brown level marls and the marlstone term (Akhssas 1993). To the NE of this wrinkle, the Toarcian, transgressed by the Boulemane Marls, is affected by progressive unconformities. It is formed by alternating marl and limestone deposits, overlain by blue-green pelagic marls that pack disorganized decimetric to metric blocks of friable, laminated and contorted sandstone. This chaotic, local-order level represents the equivalent of the “Brown level” and results from a slide movement of partially consolidated sediments down a slope. In the Taffert area, the marl-limestone term of the Bechyne Marls formation, begins with a nodular level of the “Ammonitico-Rosso” type which is dated to the top of the Lower Toarcian (Sabaoui 1998).

At the level of the Azrou Ourhioul wrinkle, the Toarcian is represented by limestones and marlstones which differ from the formation defined in the basin by its reduction in thickness, by the lacuna of some of its members such as the brown level and by its richness in limestones.

In the second anticlinal rift (Fig. 3.11), the Toarcian is more reduced and limestone-rich than in the center of the basin and shows shallower, high-energy characteristics that are expressed and accentuated in the Upper Toarcian and Lower Aalenian-Bajocian (Sabaoui 1998). These bottom facies are constituted by oolitic and bioclastic limestones, locally brecciated or lumachellic, rich in high energy organisms toward the top of the Amane Illila formation.

On the northern margin of the basin (Middle Atlasic Causse and first anticlinal wrinkle Fig. 3.11), the best exposed and most complete outcrops are located near the Ain n’Tislit forest house where the Bechyne Marls formation, about 30 m thick, rests on the Domerian marl limestone with a ferruginous and slightly gullying surface. This formation begins with marls (9 m) interspersed with very thin limestones. These marls are surmounted by two levels of Ammonitico-Rosso type of yellow limestones (2 m) in small pseudonodular banks (5 cm), separated either by marly joints (1–2 cm) or by a simple diastema which can be presented in the form of a ferruginous border and by lumpy levels (80 cm), very rich in very small calcareous ammonites and sea urchin plates. It is a red clayey limestone (30 cm) with an erosive base, then a yellow to pink limestone (30 cm). These two levels of “Ammonitico-Rosso” type are surmounted by a bank (20 cm) of ferruginous and microbrecciated calcarenite whose elements are rolled and oolites and oncoliths are abundant there. Ammonites collected, *Peronoceras* sp. and *Dactylioceras* sp. (or *Rakusites* sp.), *Phylloceras* sp., *Mercaticeras* sp., *Nodiweloceras* sp., *Hildaites* sp. and *Harpoceras mediterraneum* Pinna, indicate the Lower-Middle Toarcian. This age is the same as that attributed to equivalent levels located south of Taza (Robillard 1978). This attribution excludes the possibility of paralleling them with the brown benchmark level that is absent in the entire Middle-Atlasic Causse. The “Ammonitico-Rosso” levels change upward to blue marls, with small undated limestone beds. The existence of Upper Aalenian ammonites 10 m above the Ammonitic-Rosso level shows an important reduction of the Middle and Upper Toarcian or

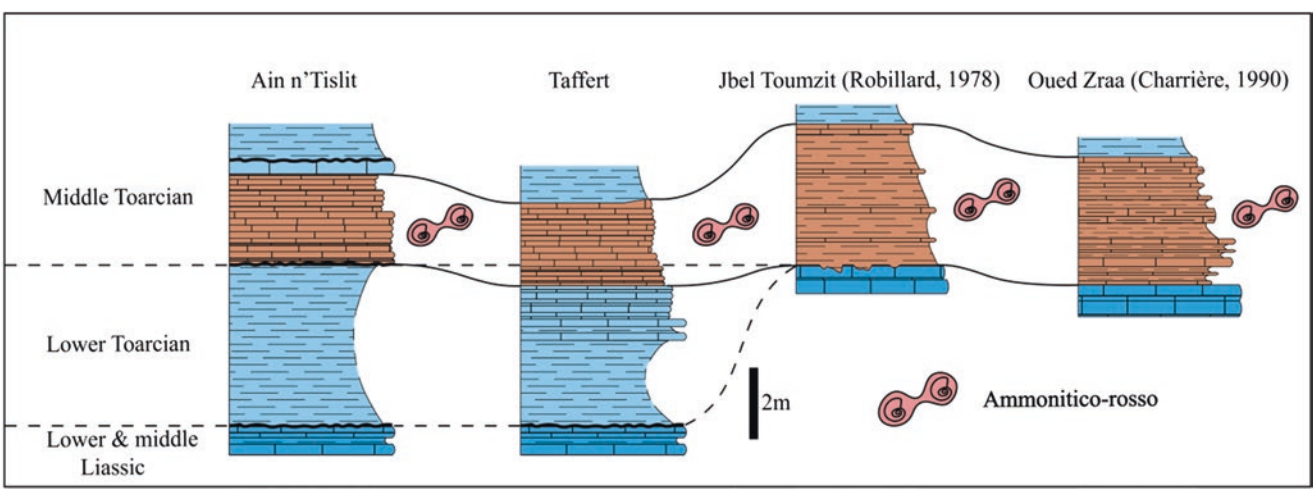

Fig. 3.11 Correlation of the Ammonitico-Rosso of the Middle Atlas

even its absence. At Oued Zraa (Fig. 3.10a–d) (Charrière 1990; El Arabi et al. 1999; El Hammichi et al. 2016), two "Ammonitic-Rosso" have been reported within the Bechyne Marls, the most representative of which, located south of Ahoufi, consists of red nodular limestones separated by a marly interlayer or by a micritic limestone bed and containing ammonites of the Sublevisoni and Lusitanicum zones. The associated facies are made up of massive limestones, marls and marl-limestones and finally of limestones with filaments affected by "hummocky cross stratifications." North of Ribat El Kheir (Colo 1961; Charrière 1990; Sabaoui 1998), the Toarcian, marly very reduced, shows in its median part a calcareous-marl Level dated to the Middle Toarcian by *Hildoceras* gr. bifrons of the Bifrons zone (Charrière 1990) which constitutes the lateral equivalent of the "Ammonitico-Rosso" of the Oued Zrâa. This level, very rich in quartz grains, passes laterally to a chaotic level whose reworked elements can reach 5 cm. The rest of the Toarcian, marly, is progressively enriched in limestone layers. Toward the NE, at Jbel Hamda (Colo 1961; Charrière 1990; Sabaoui 1998), at Aïn Tislit (Sabaoui 1987, 1998) and south of Taza (Robillard 1981), "Ammonitic-Rosso" and assimilated rubefied levels underline the northern-mid-Atlasic accident. They determine, as mentioned by El Arabi et al. (1999), a mobile zone that separates a subsident basin environment at the location of the folded Middle Atlas to the SE from a sloping and unstable gutter that ensures the passage to the more stable platform located on the present Middle Atlas Causse to the NW. The mobility of this articulation zone is the result of the combined effects of the North-Middle Atlas Fault and normal faults of NW-SE and E-W direction (Auajjar 2000).

These deposits, which represent an "Ammonitico-Rosso" type environment (Elmi 1981; Ameur and Elmi 1981; Delgado et al. 1981) are affected by synsedimentary deformation (progressive unconformities open to the west and slumps). They record the combined effects of positive eustatism, related to the early Middle Toarcian transgressive interval, and paleoecological isolation, related to the mobility of the North-Middle Atlasic Accident (El Arabi et al. 1999) on the outer shelf break, while being influenced by the surrounding marine basin. This arrangement (Fig. 3.12) explains that the "Ammonitico-Rosso" assemblages are ecologically and geographically isolated on the edge of the outer platform, while being influenced by the surrounding marine basin. In this context, the Ammonitico-Rosso appears in a localized area, inserted in a relatively elevated block corner, at the intersection of two active tectonic lineaments (NMAF and transverse paleofault). An alignment of Ammonitico-Rosso deposits punctually distributed across the northernmost segment of the NMAF zone stakes a major paleogeographic and structural boundary at the articulation of a stable platform and the subsident trench (El Hammichi et al. 2016).

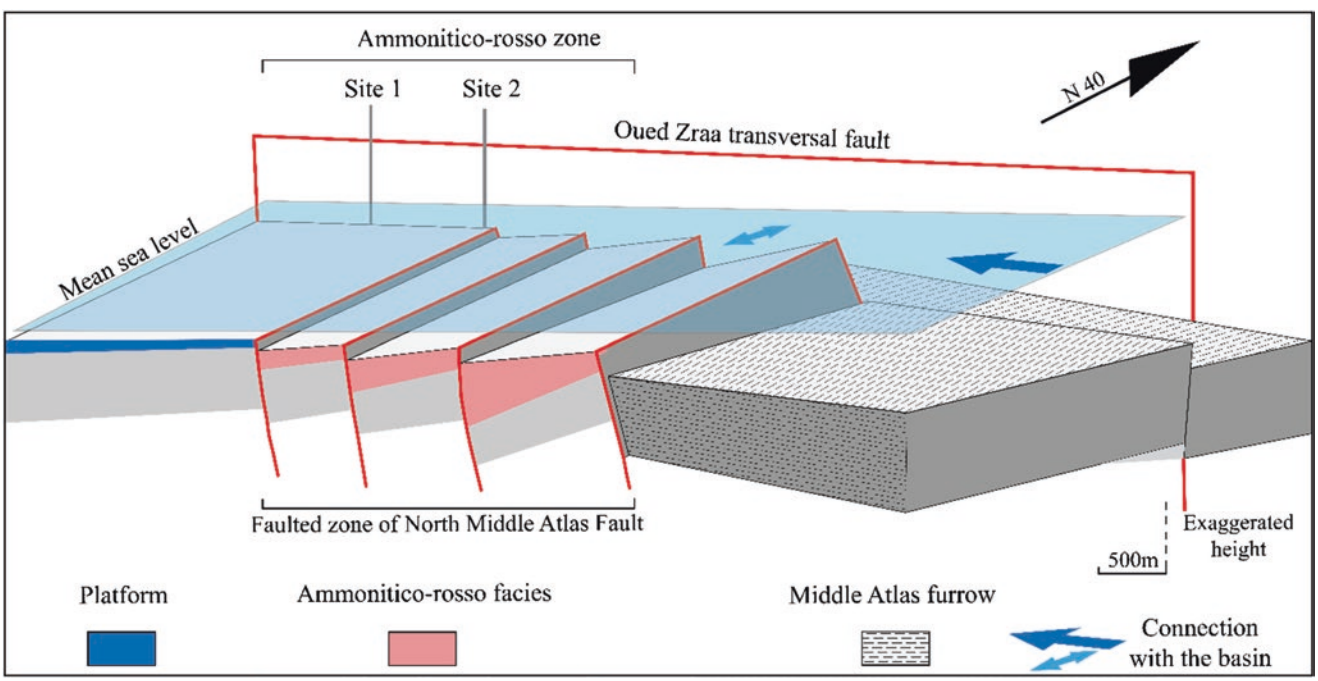

Fig. 3.12 Tectono-sedimentary compartmentation model associated with the building of the Toarcian Ammonitico-Rosso from Oued Zraa area. (El Hammichi et al. 2016; simplified)

3.4 Conclusion

The Toarcian series of the Middle Atlas is constituted by varied deposits which are marked by lateral passages of notable facies from SW to NE. In the northern Middle Atlas, they are very dilated and predominantly marly and decrease toward the SW where they are considerably loaded with limestone.

In the northern Middle Atlas, the Toarcian is represented by the Bechyne Marls formation which rests on the Ouarirt Limestone formation of the Middle Lias. It corresponds to gray or blue marls with pyritic ammonites and posidonomia and admitting rare limestone layers. Its thickness is of 200–450 m in the axis of the synclinal basins and is very reduced or even absent on the flanks and at the level of the anticlinal wrinkles (0–5 m). This formation is composed of blue marls with ammonites, belemnites and posidonomids, which admit limestone, clayey limestone and calcareous claystone layers more abundant toward the top. The abundance of ammonites specimens, allowed the dating of the different terms of this formation, which are spread from the lower Toarcian (Polymorphum zone) to the upper Toarcian (Meneghinii zone). The main stratigraphic results to be retained are: the Bechyne Marls formation begins at the extreme top of the Upper Domerian; in fact, the base of this formation is classified in the Upper Domerian (Emaciatum zone) and in the Lower Toarcian (lower part of the Polymorphum zone, Mirabile subzone).

The Brown level, which is present only in the folded Middle Atlas, is of Lower Toarcian age, posterior to the Polymorphum zone.

The nodular level in the folded Middle Atlas, whose equivalent in the Middle Atlasian Causse when it exists, is the "Ammonitico-Rosso" level, is essentially of Middle Toarcian age (Bifrons zone).

On the other hand, in the central Middle Atlas and at the SE edge of the basin, the Toarcian deposits are very small compared to those of the northern Middle Atlas. They are represented by the "Mibladène facies" which rests on the Pliensbachian Megalodontid limestones (Fm. Tizi Nehassa). This facies comprises two terms: green, yellow or red marls intercalated with thin banks of bioclastic limestones, known as the "Mibladene Layers" and attributed to the Lower Toarcian, and a bar of nodular, bioclastic and oolitic limestones dated to the Middle-Upper Toarcian, or even the Aalenian. At the level of the fourth anticlinal wrinkle, this bar, which partly shows an "Ammonitico-Rosso" character, is affected by condensations and very important gaps reflecting the instability of this zone at the time of the sedimentation.

At the end of the Lower Toarcian (Levisoni Zone), the establishment of the Brown Level in the northern Middle Atlas reflects the culmination of the individualization of the Jurassic basin of the Middle Atlas. It results, on the one hand, the maximum opening of the basin, organized in active wrinkles and synclinal subsident basins and framed by residual platforms (Causse and Highlands), and on the other hand, the emersion of the Middle Atlas Causse and the SW edge of the Middle Atlas which served as a source of these turbidites. The products of erosion of the emerged or submerged areas are conveyed by turbidity currents toward the northern parts and deposited in elongated lobes following Middle Atlas directions.

The Middle Toarcian knows the return of the marine environment in all regions located NE of the Boulemane meridian. The activity of the boundary accidents led to the birth, in these mobile areas, of sloping micro-basins or elongated umbilicals following the Middle Atlas directions. In the northern Middle Atlas, a deep basin is established, which is filled by marly terrigenous very thick in the center of the basin and reduced and rich in limestone near and on the right of active wrinkles. In the central Middle Atlas, it is a shallow external carbonate platform, bordered to the SW by the Boulemane Shoal, which emerged during the Domerian, and which separates it from the restricted domain located further SW. The paleogeographic framework of the Upper Toarcian is based on that of the Middle Toarcian. Nevertheless, we note on the one hand a tendency toward a progressive decrease in depth and on the other hand a notable synsedimentary activity of the transverse faults that cut this synclinal zone into panels that will constitute the future subbasins or depocenters.

During the Terminal Toarcian-Aalenian, the paleogeographic differentiation into very subsident zones (depocenters) and high zones (ripples and sills) is accentuated. In this system, the Middle Atlasian Causse and the Highlands are emerged or submerged and the Boulemane Highlands as well as its northern edges are exundated. Further to the NE, a platform becomes generalized and is the seat of a reduced and essentially calcareous sedimentation. The platform, which undergoes episodic emersions of local order at the level of the SW panels in high position, is shallow and agitated more to the NE reflecting the progradation of deposits toward the Tethyan zones. Products emanating from the breakup of these emerged or submerged areas are transported to the northern depocenters in a Platform-Talus-Basin regime.

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4 Jbel Serhla: A Particular Geosite of Lithostratigraphic, Paleogeographic and Paleontological Importance

Khaoula Baadi, Abdellah Sabaoui, and Bernard Lebreton

Abstract

The Middle Atlas, which is an intracontinental chain of lozenge shape, shelters a diversity of outcrops going from the Ordovician to the present. It is subdivided into two parts corresponding to the subtabular Causse and the folded Middle Atlas. The latter shows a succession of anticlinal wrinkles and synclinal depressions (depocenters) oriented NE-SW. This work focuses on the geosite of Jbel Serhla which is located in the half-depocenter of Tilmirat. It is part of the central synclinal depression. This geosite shows a perfect example of the filling of the Middle-Atlasic chain by its Bajocian formations of Boulemane and Recifa. These formations present exceptional characteristics at the scale of the whole chain, namely their thickness which reaches 670 m, their extent and the quality of the outcrops. This geosite has provided us with very rich lithostratigraphic and paleogeographic data. In addition, the discovery of the Tamezguida n'Rbi cave within the lower cornice of the Recifa formation. At the entrance of the cave, we recognized an accumulation of fossilized bones in a sedimentary gangue. These are bones of Bovidae with metacarpals and phalanges which may be the work of Bearded Vultures (*Gypaetus barbatus*).

Keywords

Geosite · Bajocian formations · Bones · Bearded Vultures · Jbel Serhla

K. Baadi (✉) · A. Sabaoui
Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, Fez, Morocco

B. Lebreton
French Speleology Federation, Lyon, France

4.1 Introduction

The Middle Atlas corresponds to an intraplate sedimentary basin, lozenge-shaped and NE-SW direction. The geological terrains of this basin are essentially of Triassic and Jurassic age and of Tethyan obedience. Outcrops of the Lower and Middle Lias form the backbone of the four anticlinal rifts, while those of the Upper Lias and Dogger outcrop in the synclinal depressions.

The Jbel Serhla geosite is located in the second synclinal gutter which is bounded to the NW by the second anticlinal wrinkle and to the SE by the third anticlinal wrinkle. It is part of the Tilmirat half-depocenter which shows Bajocian and Bathonian terrains. Within this half-depocenter, Jbel Serhla is located in the lower limb of the Recifa formation which shows here an exceptional thickness at the scale of the Middle Atlas (670 m).

In this work, we want to expose the structural, sedimentary and paleogeographic framework of the formations of the half-depocenter of Tilmirat, where the geosite of Jbel Serhla is located. The study of the formations constituting this geosite reveals a discovery of quaternary sediments in the cave of Tamezguida n'Rbi, and on the other hand, an assemblage of bones associated with these sediments.

4.2 Lithostratigraphic and Paleogeographic Study

The Jbel Serhla geosite deposits are located in the Tilmirat half-depocenter, which is part of the central synclinal trough of the Middle Atlas (Fig. 4.1). They start with Boulemane marls with *Posidonomyes* of the Lower Bajocian. To the NE of this half-depocenter, this formation is very dilated and shows a thickness of 600 m. It shows two members:

– The lower member is made up of compacted and laminated marl with a dominant pelagic fauna.

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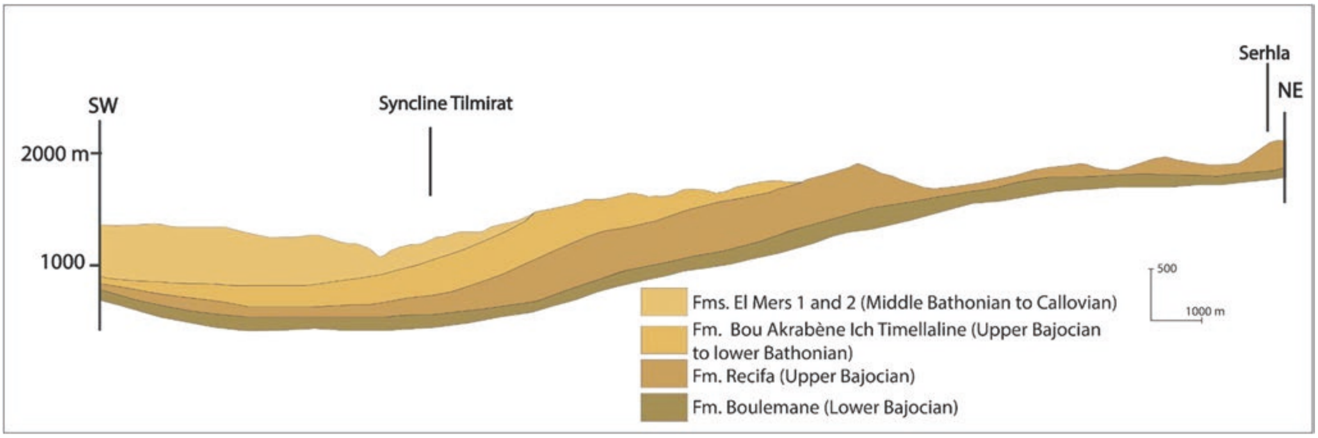

Fig. 4.1 Geological section of the half-depocenter of Tilmirat

– The upper member, of marl and limestone nature, records a progressive decrease of the bathymetry of the depositional environment which is a distal platform with slight regressions.

Above the Boulemane formation is the Recifa formation of upper Bajocian age. It is also called formation of the cornice limestones (Termier 1936). It consists of peri-reef bars and oolitic levels separated by marly deposits. In the area of the geosite of Jbel Serhla, this formation of Boulemane which is very dilated (670 m). It shows three sedimentary members whose total thickness is (Fig. 4.2):

– the lower member or lower cornice corresponds to a succession of limestone bars with a peri-reef facies. It draws many ridges well visible on the field.
– the intermediate member is marly with marl-limestone intercalations.
– the upper member or upper cornice is constituted of limestones with oolitic dominance.

The Recifa Formation shows lateral variations in thickness (Fig. 4.3a) going NW toward Aderj and especially SE toward Taffajjight. For example, its thickness reduces to 60 m (Fig. 4.3b) at Taffajjight. This variation is related to the syn-sedimentary play of the South Middle Atlasic Fault SMAF that affects the Bou-Iblane wrinkle and its SW termination at Ich n'Tilli. Thus, at the perianticlinal termination of the Bou-Iblane wrinkle, the deposits of the Recifa Formation (Fig. 4.3c) are synchronous with a tectonic episode of platform dislocation by individualizing wrinkles with reduced series of very subsident zones constituting depocenters. The Boulemane marl and cornice limestone series corresponds to a filling mesosequence of Klupfelian type (Sabaoui 1987).

The geodynamic evolution of the Middle Atlas during the Upper Lias-Callovian is marked by several phases: mobility, filling and senescence of the Middle Atlas Basin. The latter was filled in during the Upper Lias and the Aaleno-Bajocian by essentially marly deposits where carbonate episodes developed (Fig. 4.4).

The presence of the Boulemane Formation, with *Posidonomia* and Ammonites, shows relatively deep facies deposits filling a very subsident euxinic basin environment. The marly-limestone deposits of the upper member of this formation announce a slight bathymetric decrease, linked to the sedimentary filling of the depositional environment. They indicate a distal platform facies. To the SW of Taffajjight, these deposits are aggrading at the edges of the half-depocenter.

The importance of the thickness of these formations is explained by the subsidence of the basin within the half-depocenter where the geosite of Jbel Serhla is located, which allowed the deposition of powerful series, although it is reduced on its edge.

Concerning the deposits of the Recifa Formation, the limestone bars of the lower member hold a maximum thickness in the whole Middle Atlas, of 433 m, characterizing a proximal external platform environment. The intermediate marl member characterizes a distal platform environment with subsidence favoring the deposition of marls that intercalate the limestones. The last member is reminiscent of the first member which is sometimes the only one represented of this formation on the edges of the depocenter.

The deposit of the Recifa Formation within the half-depocenter is synchronous with a tectonic episode that dislocated the platform by individualizing zones of subsident sedimentary accumulation and reduced series wrinkles.

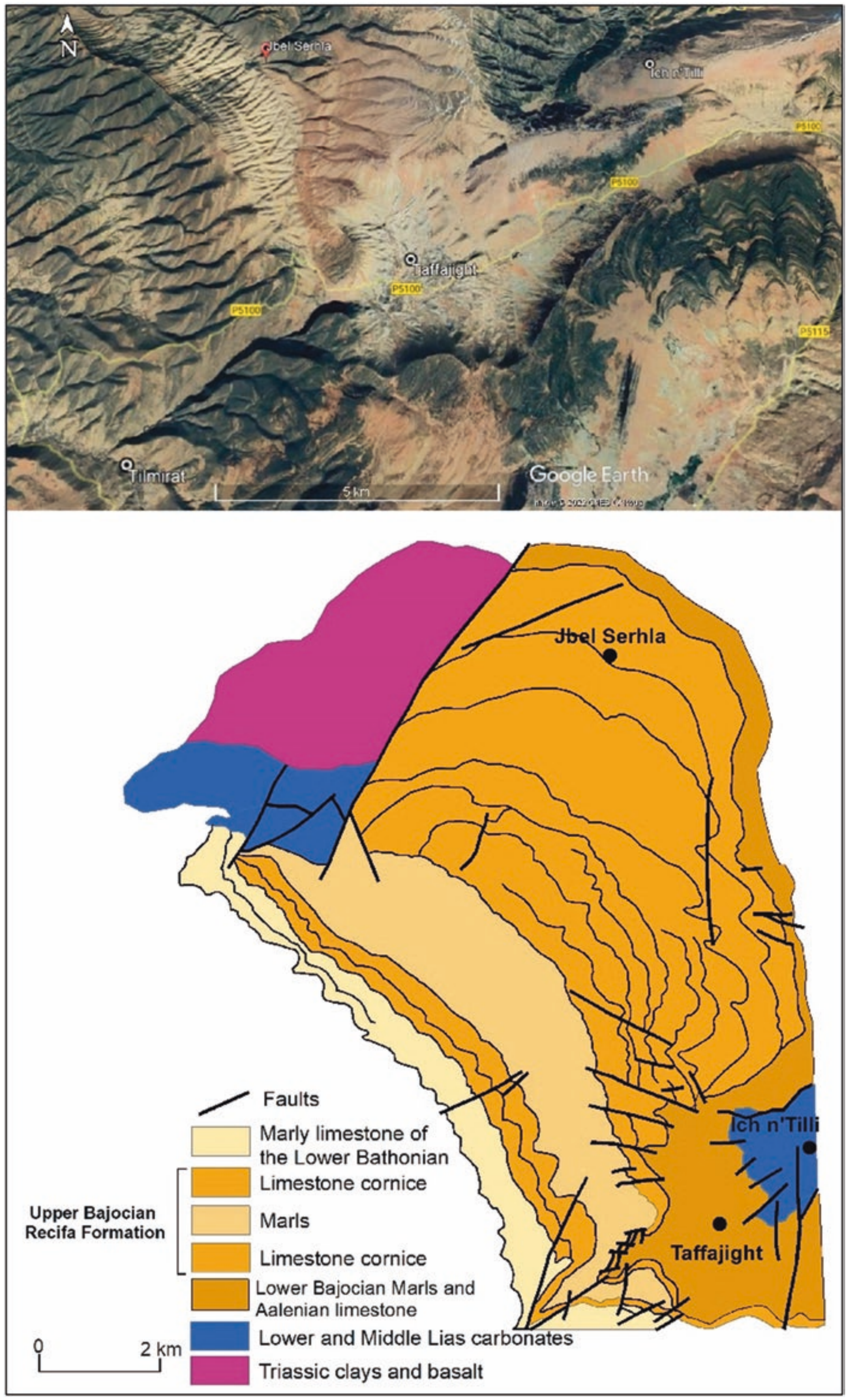

Fig. 4.2 Geological map of the Jbel Serhla geosite with a satellite image locating the geosite (Baadi 2021)

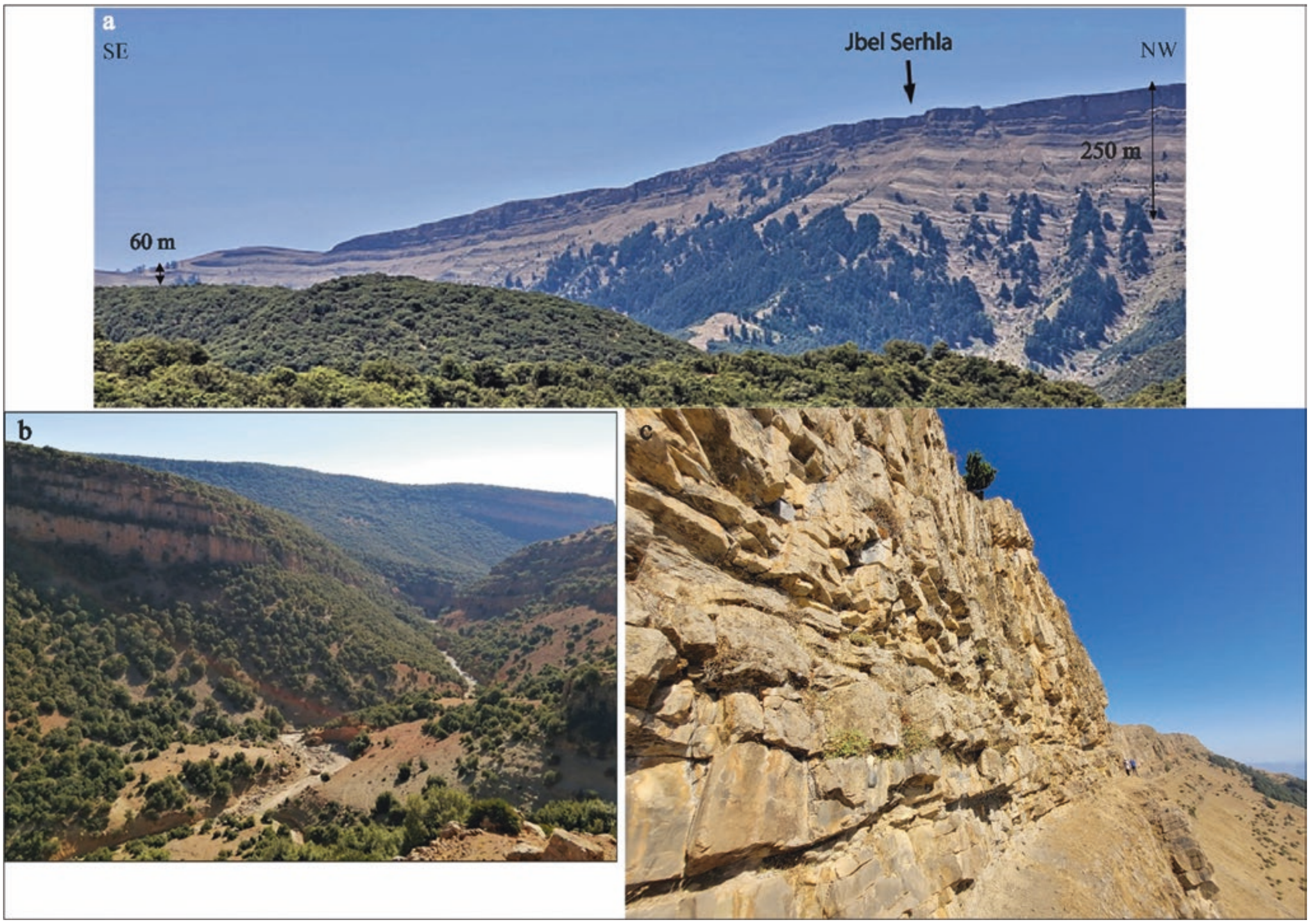

Fig. 4.3 (**a**) General view of the cornice limestones of the Jbel Serhla geosite; (**b**) Cornice limestones showing a decrease in thickness (60 m at Taffajjight); (**c**) Upper peri-reef bar of Jbel Serhla

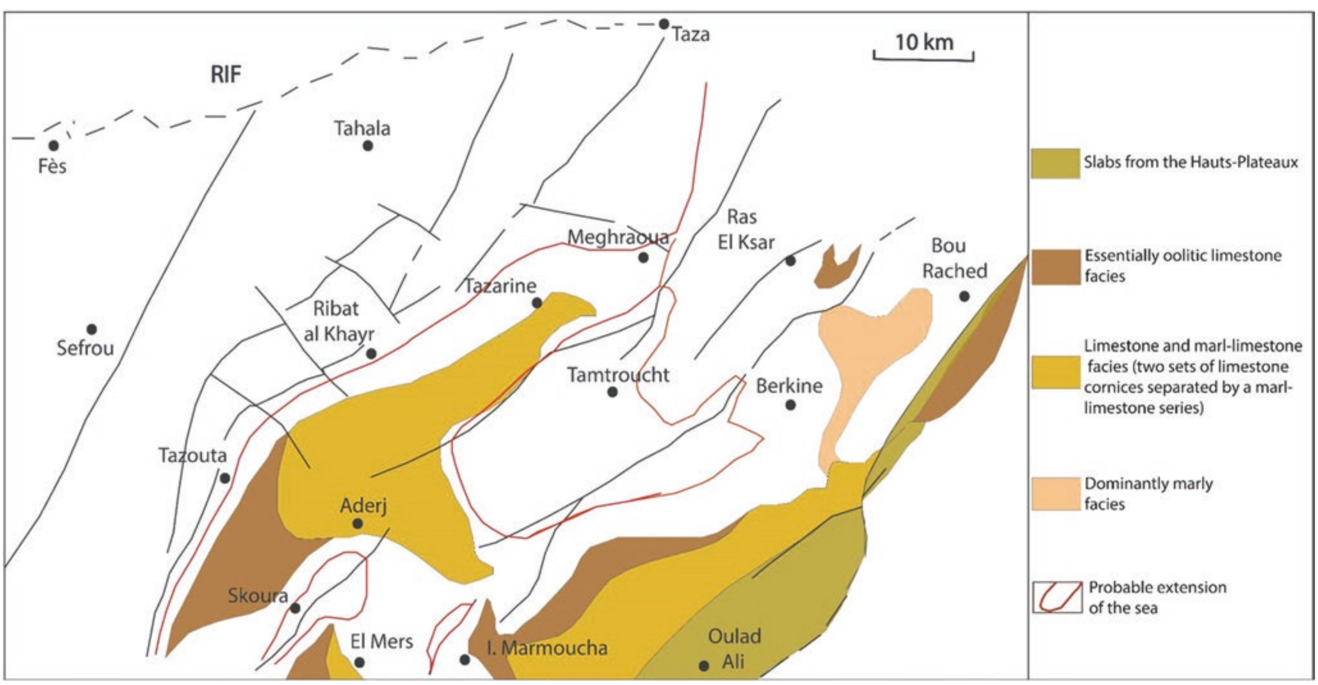

Fig. 4.4 Paleogeographic map of the Northern Middle Atlas in the Upper Bajocian (Sabaoui 1998)

4.3 Geodynamic Evolution

From the base of the Lower Bajocian Boulemane Formation to the summit of the Upper Bajocian Recifa Formation, the region experienced a Klupfelian megasequence (Sabaoui 1998). The region corresponded to a basin that experienced at that time a very important subsidence allowing the thick deposition of Lower Bajocian marls, rich in pelagic fauna. A regressive tendency started at the upper part of the Boulemane formation characterized by marly-limestone deposits. This Klupfelian sequence ends in the Upper Bajocian high hydrodynamic deposits (reefs and oolites).

During the Bajocian, the half-depocenter was filled in by relatively thick marl and marl-limestone sedimentation. During this period, the area was the site of syn-tectonic sedimentation that was predominantly marl, organized in accretionary sequences (Fedan 1989). Increased subsidence of the depocenters leads to confinement of the sedimentation. From the Upper Bajocian to the Middle Callovian, sedimentation is essentially calcareous, silico-clastic and evaporitic. These deposits, which constitute the ultimate terms of the Middle-Atlasic basin series in the Jurassic, characterize the senescence of the basin, which ends with the total and definitive retreat of the Tethysian Sea.

4.4 Bone Assembly: Cave of Tamezguid n'Rbi

On a steep cliff of the Jbel Serhla geosite (Fig. 4.5a), at an altitude of 1980 m, within the lower cornice complex (Fig. 4.5b), is the Tamezguid n'Rbi cave (Fig. 4.5a), which is very difficult to access. On the northern slope and at the entrance to the cave, consolidated detrital sediments partially fill the cave. They contain a bone breccia very rich in bone remains (Fig. 4.5d). These deposits, 3 m thick, are caught in a sedimentary gangue (Fig. 4.5c). Given the extent of the consolidation, the age of these bones would be at least several thousand years.

Scrapings are regularly made and reveal sectioned diaphyses. We can see, still in place, metacarpals and phalanges of small Bovids (Fig. 4.5e).

This accumulation of bones, at such a high altitude, in a steep area and in the entrance of a cave, leads us to believe that it is the work of several generations of Bearded Vultures (*Gypaetus barbatus*) that have taken up residence. The Bearded Vulture is a vulture known locally as Merz Ikhsan (bone breaker). This large raptor, with exclusively necrophagous behavior, does not hunt or kill animals but feeds mainly on the bones of carcasses of animals that have died naturally or have been abandoned by predators. It does not feed on meat but only on fresh, highly nutritious bones, which it swallows whole. Thanks to its elastic gullet and very powerful digestive juices, the swallowed bones can reach up to 25 cm. If the bones are too big, it has the habit of taking them to altitude and letting them fall to the ground in order to reduce them to better swallow them. It is this particular and unique behavior that earned him the nickname of "bone breaker."

Although all studies show its presence, still today, but only in the Toubkal National Park, inhabitants of the Middle Atlas confirm having seen it. These Moroccan individuals probably represent the last population of the Bearded Vulture in the Maghreb (Toubkal National Park 2016).

4.5 Conclusion and Recommendations

The Jbel Serhla geosite offers a complete set of information on the Bajocian deposits and contributes to an excellent understanding of the paleogeography of this period, from the Boulemane marl that testifies to the filling of the very subsident euxinic basin environment to the cornice limestones that characterize a distal subsident platform environment. The deposits of this geosite present a unique thickness in the whole Middle-Atlasic chain. The presence of the Boulemane and Recifa formations deposits on the Jbel Serhla geosite correspond to a filling mesosequence of Klupfelian type. This one knows an evolution from marly deposits of basins to limestones of platform with high hydrodynamism.

The discovery of a bone assemblage in the cave of Tamezguida n'Rbi is interesting because of the rarity of this type of deposit, but also because of the geographical location of the site. Also, the cave of this geosite may be a site and prehistoric par excellence. The discovery of these bones, whose age would be at least several thousand years, is probably due to the action of Bearded Vulture.

We recommend that a paleontological and prehistoric study be carried out on the bones of the cave of Tamezguida n'Rbi to precisely date the bones and determine the nature of the fossils found.

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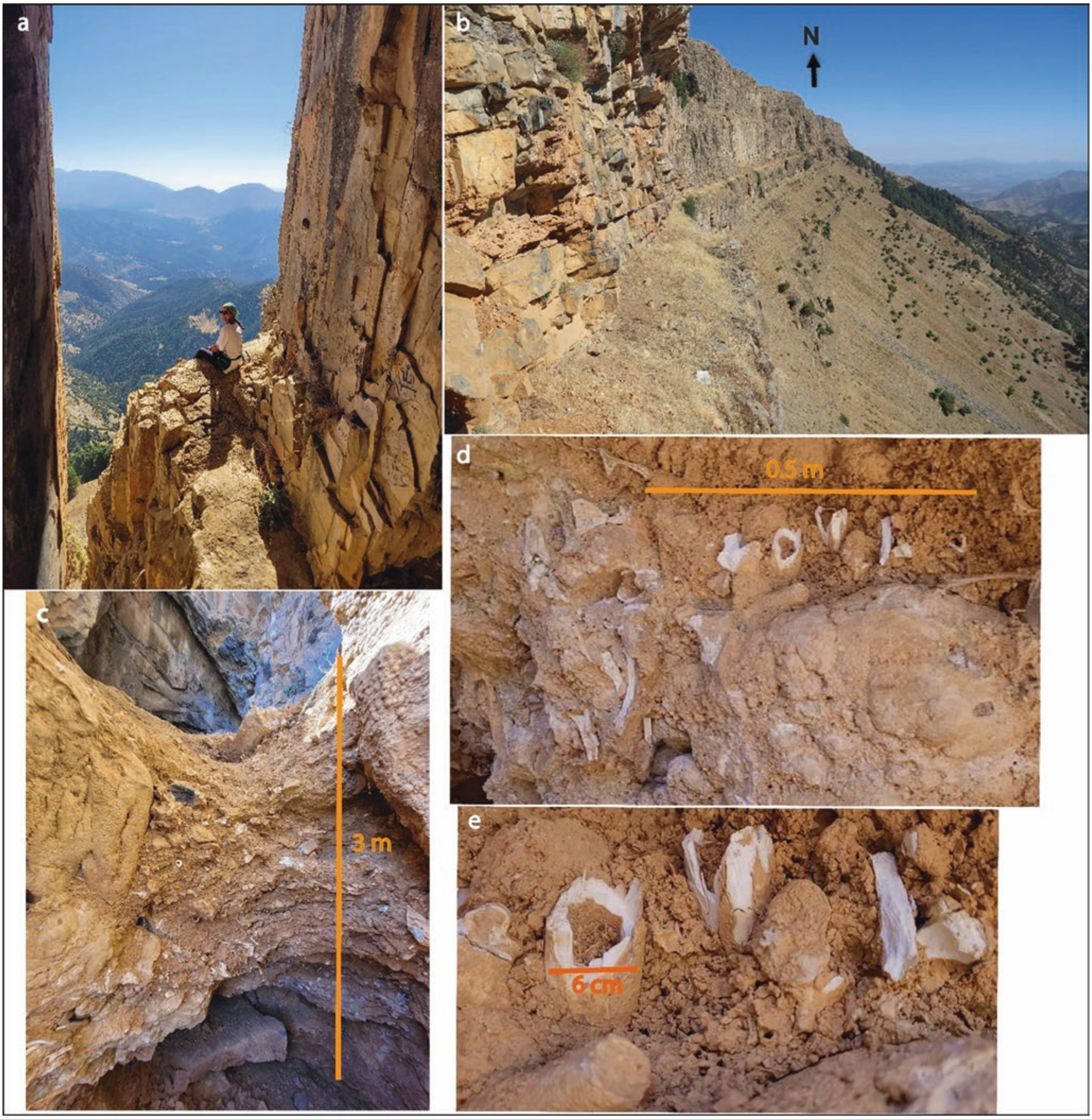

Fig. 4.5 (**a**) Entrance to the Tamezguid n'Rbi cave; (**b**) Location of the Tamezguid n'Rbi cave on a cliff located in the lower member of the Recifa formation; (**c**) A sedimentary gangue of bones 3 m thick; (**d**) Accumulation of bones; (**e**) Severed diaphyses and phalanges of Bovidae

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5 Cenozoic Sites of the Middle Atlas (Morocco): An Alpine Heritage to Be Preserved

Khaoula Baadi and Abdellah Sabaoui

Abstract

For more than a century, the lithostratigraphic and sedimentological study has occupied a priority of geological studies in the Middle Atlas revealing the regional geological history. The Cenozoic lithostratigraphic and sedimentological geosites of the region disclose this geological history by exposing multiple geological phenomena. This present work exposes an initiative which aims to (i) draw up an inventory of the Cenozoic lithostratigraphic and sedimentological heritage of the Middle Atlas chain, (ii) present the sites with representative and rare characteristics and (iii) present the state of preservation of these geosites. The result obtained during the inventory led to 21 inventoried geosites of which 71.42% passed to the stage of the quantitative assessment. Although no geosite had a high score of Sd ≥ 2.5 and all 15 had an Sd < 2.5, some geosites present a high threat of deterioration. Among these geosites, eight were selected for their representativeness, rarity and geological diversity for a possible detailed study by presenting their state of preservation.

Keywords

Cenozoic lithostratigraphic and sedimentological heritage · Inventory · Assessment · Preservation · Middle Atlas

5.1 Introduction

The Middle Atlas is known for its remarkable geological characteristics, and also for the abundance of its natural resources. It has attracted the attention of several geoscientists since the beginning of the twentieth century. It has given rise to important scientific investigations relating to the Cenozoic heritage through several stratigraphic, sedimentological and paleontological studies. There have been so many studies on the Paleogene (Choubert and Marcais 1952; Choubert and Faure-Muret 1962; Andreu and Charrière 1986; Andreu et al. 1988; Fedan 1988; Ait Slimane 1989; Charrière 1990; Charrière 1992; Juidette 2000; Mouflih et al. 2006; Charrière and Haddoumi 2016; El Attmani et al. 2020), on the Miocene, testifying to the juxtaposition of the different deposits of Atlantic and Mediterranean obedience (Colo 1961; Lorenchet de Montjamont 1963; Sabaoui 1987; Saint Martin 1987; Andreu et al. 1988; Charrière 1990; El Hamzaoui 1994; Sabaoui 1998; El Fartati et al. 2019; El Fartati et al. 2021) and on the Plio-Quaternary, which focused more on travertine, fluvial, lacustrine and volcanic deposits (Martin 1981; Harmand and Cantagrel 1984; Charrière 1990; Sabaoui 1998; Gourari 2001; Hinaje 2004; El Azzouzi et al. 2010; Amine et al. 2019; Hinaje et al. 2019).

While geological research work in the Middle Atlas is very extensive, the region lacks in-depth studies to promote the richness and diversity of its geoheritage.

Geosites with significant features, rare and perfectly preserved, are of paramount importance in illustrating regional and national geological history. Frequently, they integrate complex phenomena. The heritage value of many globally significant geosites is determined by the information they present. The Cenozoic geoheritage has been highlighted in this work through the inventory and assessment of the Cenozoic lithostratigraphic and sedimentological sites of the Middle Atlas by exposing their state of preservation. These sites make it possible to retrace the evolution of the various Paleogene, Miocene and Plio-Quaternary deposits and to show their state of preservation. The proposal for an inventory and an assessment of these geosites reveal their scientific value as well as their state of preservation.

K. Baadi (✉) · A. Sabaoui
Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, Fez, Morocco

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5.2 Cenozoic Heritage on Geological Outcrops

The Cenozoic heritage has marked the geological history of the Middle Atlas by all the outcrops and geological events which are distinguished by transgressive and regressive series intersected by significant volcanism. The diversity of the Cenozoic outcrops makes it easy to understand the geological history of the chain, although they do not cover the entire Middle Atlas.

Paleogene outcrops are only known west of the Boulemane meridian. They are characterized by a series of varied deposits (Fedan 1988; Ait Slimane 1989). It is known by Paleocene pink marls, gray gypsum marls, Eocene limestones and Oligocene conglomerates.

The Lower and Middle Miocene is incomplete. Upper Miocene outcrops are mainly found in the Oued Zra and Skoura basins. Other outcrops, of limited extension, are present at Ribat al Khayr, Tazarine, Jbel Sarij, Jbel El Ahmar and Bizi (Sabaoui 1998). The distribution of these outcrops shows that the extension of the transgression, of Upper Miocene age, concerned the NW part of the Middle Atlas which showed an island at the level of the Tazzeka massif (Charrière 1990; Sabaoui 1998). The Miocene deposits rest in angular unconformity on the Jurassic fields. The series shows from bottom to top several which are:

- the formations of Oued Zra of Vallesian age. It is made up at the base of red silts with volcanic intercalations (Fig. 5.1a) followed by gray clays with micromammals then by marl-limestones and lacustrine limestones (Fig. 5.1b). The equivalent of the Oued Zra formation in the Skoura basin are variegated marls with thin beds of limestone with lumpy microfacies.
- the Upper Tortonian Oued Mdez formation (Charrière 1990). It begins with predominantly conglomeratic (Fig. 5.1c) and sandy detrital deposits, followed by green marls with gypsum and then by sandstone with interbeds of blue marls with oysters.
- the Aghram Amellal formation (Sabaoui 1998) from the Upper Tortonian to the Messinian. This formation outcrops in several localities which are Aghram Amellal, Ribat al Khayr, Tazarine and Taanint Ou Moudou. It corresponds to yellow marls (Fig. 5.1d), reef limestones and sandstones or sandstone limestones.
- the Miocene series ends with the formation of the Col de Tazouta (Charrière 1990). It consists of sandy marls with ostracods and foraminifera.

The Pliocene and Quaternary terrains are poorly represented in the Middle Atlas. During the Pliocene, the Middle Atlas is characterized by a few fluvio-lacustrine continental deposits located in intra-mountainous basins. These deposits are known by the formation of the puddingstones of Skoura (Termier 1936). The facies is a well-consolidated conglomerate with a sandy or marly matrix. Sabaoui (1998) clarified their extension into the Skoura depression by discovering new outcrops north of Tizi Issoulitène. These puddingstones are unconformable on the Jurassic and Miocene terrains. The formation of the Skoura puddingstones is followed by lacustrine limestone slabs, carbonated paleosols and travertines from the Upper Pliocene to Early Quaternary. These travertines correspond to dam, resurgence or alluvial plain facies. Above these outcrops are alluvial deposits constituting veritable stepped and sometimes interlocking terraces.

Quaternary outcrops show coarse detrital deposits that form cones, glacis, lacustrine limestones and sometimes travertines. This Quaternary period saw significant volcanic activity in the subtabular Causse.

5.3 Cenozoic Geodynamic Evolution

The geodynamic evolution of the Middle Atlas during the Cenozoic took place in several stages marking the evolution of the chain.

After the first Triassico-Jurassic sedimentary cycle, the Middle Atlas experienced a tectonic inversion, linked to the rapprochement of Africa and Europe. Thus, it experienced the period of major tectogenesis from the Cretaceous to the Middle Miocene.

In the Upper Miocene, the N and NW part of the Middle Atlas experienced extensive bedrock tectonics along transverse structural lines (Charrière 1990) and presents an opening megasequence constituting the third sedimentary cycle of the Middle Atlas. The geological formations of the Upper Miocene are marked by the succession of two marine intrusions of Atlantic-Mediterranean obedience. Without a sedimentation gap, different environments succeeded one another from the Middle Tortonian to the Upper Tortonian (continental, laguno-lacustrine, laguno-marine and marine). During the same period, the Middle Atlas experienced a volcanic upwelling due to fracturing, under an extensive regime. This tectonic is important in the northern part of the Middle Atlas in the Skoura and Ribat al Khayr sector. Indeed, the Upper Miocene experienced an extension which led to the installation of two gulfs of the southern Rifian furrow (Fig. 5.2) penetrating to the center of the folded Middle Atlas (Charrière 1990; Sabaoui 1998).

During the Lower Pliocene, the second tectorogenic phase took place. This is a tectonic phase, with a compressive regime, which was manifested by a tectorogenic remobilization of the main structural lines and tangential deformations whose activity was more intense before the Upper Miocene. This results in the accentuation of both the structures and the

Fig. 5.1 (**a**) Volcano-sedimentary intercalation deposits of the Oued Zra formation; (**b**) Marl-limestone and lacustrine limestone of the Oued Zra formation; (**c**) Basic conglomerates of the Oued Mdez formation; (**d**) Deposits of the Aghram Amellal formation

lifting of wrinkles and reliefs which continues until the present, but with less importance. From the Middle-Upper Pliocene to the Quaternary, the Middle Atlas is the seat of a shortening regime which is manifested by tectonic, magmatic and seismic activity. This contributed to increased heat flow and the establishment of alkaline volcanism (Harmand and Cantagrel 1984) and thermal springs (Rimi 1999). The effusive magmatic activity was manifested during the Quaternary by several emissive centers planted on the trajectory of major NE-SW to NW-SE accidents (Charrière 1990; Hinaje 2004).

5.4 Cenozoic Geoheritage

In the Cenozoic, the geodynamic evolution of the Middle Atlas, which shows a great diversity of geological outcrops, determined the geodiversity of the region. This geodiversity is summarized through a Cenozoic geoheritage endowed with countless witnesses, at different spatial and temporal scales, of the stratigraphic, sedimentological and paleogeographic history of the Middle Atlas chain. The heritage value of the region is linked to the uniqueness of the sites, which may reflect geological characteristics representative of the geological history of the region.

To perform an inventory of Cenozoic geosites and make a quantitative assessment and determination of their degree of deterioration, we applied the methodology of Baadi et al. (2020).

5.4.1 Inventory

The disclosure of this geoheritage has led to an inventory of 21 sites that proclaim the geological riches of this geological period (Table 5.1).

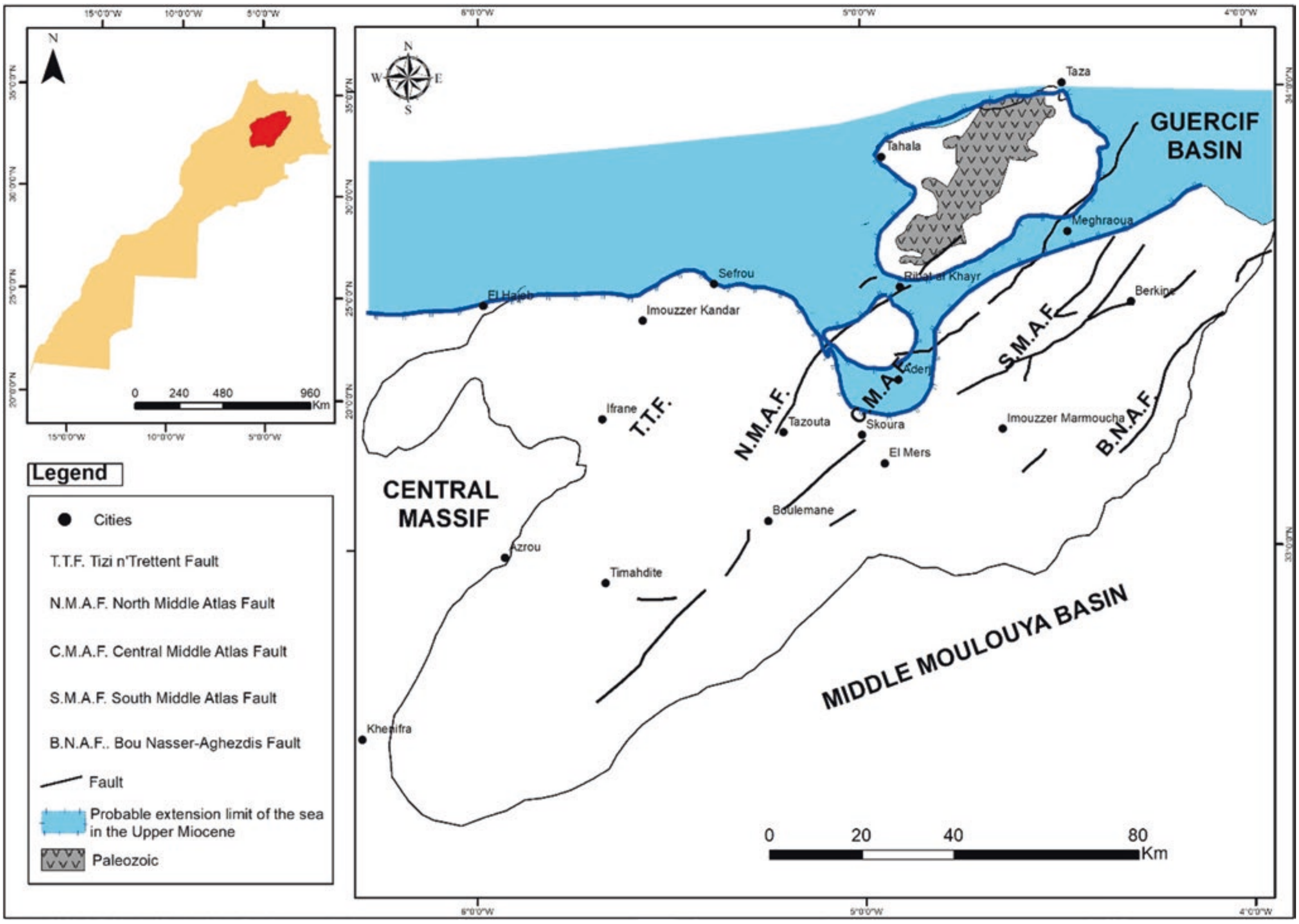

Fig. 5.2 Map of the extension of the transgression of the Middle Atlas during the Upper Miocene. (After Sabaoui 1998)

5.4.2 Quantitative Assessment (Ss) and Degree of Deterioration (Sd)

After having selected the first list of geosites from the inventory, the quantitative assessment step is an essential step to guarantee the objectivity of the selection of sites according to their scientific importance. The purpose of this step is to make a sorting leading to objectively select a list of indexed sites based on clear and well-defined criteria (Table 5.2). It is a central link in objectively determining the scientific value of a geosite.

The evaluator must choose a degree of criterion to reach the final score by multiplying it by the weighting coefficient determined for each one (Table 5.2).

Four geosites out of 21 inventoried Cenozoic geosites presented an Ss ≥ 2.5, 11 sites a 1.5 ≤ Ss < 2.5, and the remaining 6 had an Ss < 1.5. The latter were withdrawn from the selection given their low scientific value (Table 5.3).

The proposal to calculate the “degree of deterioration“of a geosite is a decisive step in determining the overall value of the site and completes the assessment of scientific value. This calculation aims at a third selection of geosites on the basis of their degree of deterioration, with the aim of determining the geosites which must be reported to the authorities if they require an urgent conservation procedure. It is based on five criteria (Table 5.4).

Thus, 15 geosites were selected for the degree of deterioration stage (Table 5.5). Among these 15 geosites: no site has an Sd ≥ 2.5, 12 geosites have a 1.5 ≤ Sd < 2.5 and 3 geosites have an Sd < 1.5.

The score having been calculated, we can then arrive at the assessment of the final score of the total value of the geosite “Sv” which will be equivalent to the following formula:

$$Sv = Ss - Sd$$

This equation means that the total value of a geosite is conditioned by two opposing variables, the nature of the scientific score “Ss” is by definition positive, since it contributes to the increase in the value of “Sv,” unlike the nature the score of the degree of deterioration “Sd” which is by definition “negative” because it contributes to the reduction in the value of “Sv.”

Table 5.1 List of Cenozoic lithostratigraphic and sedimentological geosites of the Middle Atlas

Geosites	Identification code	Type of geosite	Ccoordinates			Administrative location	Property	Extended	Accessibility	Protected area
			X	Y	Z					
Aderj Plateau	Sse01	Plio-Quaternary	33°37′26.06″N	4°26′50.14″W	1057	Aderj	Public	–	Easy	–
Aghram Amellal	Sse02	Miocene	33°40′56.61″N	4°27′25.41″W	989	Aderj	Public	–	Easy	–
Aghram Iroumine	Sse03	Miocene	33°38′45.15″N	4°28′20.43″W	913	Aderj	Public	–	Easy	–
Bel Jeraf	Sse04	Plio-Quaternary	33°49′33.85″N	4°50′46.28″W	928	Sefrou	Public		Difficult	–
Beni Mghora	Sse05	Plio-Quaternary	33°41′47.08″N	4°21′13.42″W	1229	Ribat al Khayr	Public	–	Medium	–
Col Touaher	Sse06	Miocene	34°11′33.95″N	4°10′1.13″W	558	Bab Marzouqa	Public	–	Easy	–
El Karia	Sse07	Plio-Quaternary	33°46′15.02″N	4°19′8.88″W	806	Ribat al Khayr	Public	–	Easy	–
Foum Khneg	Sse08	Miocene	33° 9′3.06″N	5° 3′13.22″W	1928	Timahdite	Public	–	Easy	–
Gara Tazouta	Sse09	Miocene	33°38′45.09″N	4°39′2.78″W	1374	Tazouta	Public	–	Medium	–
Ich n'Bouk	Sse10	Plio-Quaternary	33°38′56.20″N	4°25′1.79″W	1125	Aderj	Public	–	Difficult	–
Laazib	Sse11	Plio-Quaternary	33°43′58.52″N	4°22′56.49″W	1064	Ribat al Khayr	Public	–	Medium	–
Lebbouaddis	Sse12	Miocene	33°49′44.56″N	4°38′58.29″W	657	Sefrou	Public	–	Difficult	–
Miocene of Bizi	Sse13	Miocene	33°55′56.35″N	3°59′13.69″W	1482	Meghraoua	Public	–	Difficult	–
Oued Mdez	Sse14	Miocene	33°39′9.53″N	4°33′56.28″W	916	Tazouta	Public	–	Easy	–
Oued Zra	Sse15	Miocene	33°42′29.36″N	4°38′29.87″W	1049	Tazouta	Public	–	Easy	–
Ribat al Khayr	Sse16	Miocene	33°49′3.70″N	4°25′16.91″W	1102	Ribat al Khayr	Public	–	Easy	–
Sidi Yahya	Sse17	Plio-Quaternary	33°44′29.00″N	4°19′34.39″W	1073	Ribat al Khayr	Public	–	Medium	–
Silt of Sefrou	Sse18	Miocene	33°51′28.61″N	4°51′3.45″W	805	Sefrou	Public		Easy	–
Skoura Travertines	Sse19	Plio-Quaternary	33°35′7.52″N	4°31′54.07″W	882	Skoura	Public	–	Easy	–
Tannint ou Moudou	Sse20	Miocene	33°40′1.92″N	4°29′10.04″W	839	Aderj	Public	–	Easy	–
Timahdite limestones	Sse21	Eocene	33°14′21.58″N	5° 3′18.18″W	1839	Timahdite	Public	–	Medium	–

Table 5.2 Scoring of the criteria for the quantitative assessment "Ss"

Representativeness	1. The site presents several known and previously known geological phenomena;
	2. The site has less known geological phenomena in the area. It testifies to the existence of singular geological processes;
	3. The site presents unusual geological phenomena in the area. It bears witness to unprecedented geological processes.
Rarity	1. The site holds more than 5 similar cases in the area;
	2. The site holds less than 5 similar cases in the area;
	3. The site represents a unique reference in the area.
Geological diversity	1. The site has only one geological particularity (mineralogical, paleontological…);
	2. The site holds 2 types of geological particularity;
	3. The site holds more than 2 types of geological particularity.
State of preservation	1. The site is neither preserved nor protected by any law; it is not found in a geopark, a reserve or a natural park, etc.;
	2. The site is neither well preserved nor protected by any law but is located in a geopark, a reserve or a natural park, etc.;
	3. The site is well preserved by a legislative law; it is in a geopark, a reserve or a natural park, etc.
Documentation	1. The site is not listed in any published work;
	2. The site holds at least one article published in national and international journals, thesis or dissertations, etc.;
	3. The site holds more than two articles published in national and international journals, dissertation work or dissertations, etc.

As for the results of the calculation of their total value (Fig. 5.3), this was positive for 13 geosites, which explains why the scientific value of these geosites exceeds the value of the degree of deterioration and the 2 remaining therefore have an $Sv < 0$ which means that the scientific value does not exceed the value of the degree of deterioration of the geosite.

5.5 Cenozoic Geosites

We kept 8 sites presented for a possible detailed study among the 12 geosites arrived at the global value of the sites. They record, through lithostratigraphic and sedimentological data, a large part of the Middle Atlas which has experienced the succession of several post-Hercynian sedimentary cycles of different affinities: first of Atlantic affinity (geosite "Timahdite limestones"), then of Atlantic-Mediterranean affinity (geosites "Oued Zra," "Oued Mdez," "Taanint Ou Moudou,", "Ribat al Khayr" and "Col Touaher") and finally the last Plio-Quaternary sedimentary "cycle," with superficial deposits (geosites "Aderj Plateau" and "El Karia").

5.5.1 Paleogene Geosite: Timahdite Limestones

The site of "Timahdite limestones" (Sse21) is located on the southern edge of the city of Timahdite. It is located at the north-eastern end of the El Koubbat syncline. This geosite has the particularity of offering data that allow us to reconstruct the paleoenvironment.

The Middle Eocene "Timahdite limestones" site deposits outcrop on a massive slab of pink-colored limestone constituting the Timahdite formation (Fig. 5.4a). These pink limestones (Fig. 5.4b) have a high fossiliferous concentration. These are gastropods, echinids, crustaceans, foraminifera and algae (Dasycladales). The pink limestone slab (Fig. 5.4c) shows a cuesta-shaped structure. Outcrops of these Eocene deposits appear on the uplifted compartment of the NE-SW trending Timahdite fault. The collapsed compartment on the NW side of this fault shows basaltic flows which mask the previous terrains. Basalt outcrops cover much of the Azrou-Timahdite Plateau.

During the Lower and Middle Eocene, the Timahdite region, where this site is located, was invaded by a shallow sea where a large biomass proliferates. The dasycladales are considered to be good indicators of a paleoenvironment where the water depth does not exceed 20 m. The geosite fauna also shows a shallow carbonate platform environment with low sedimentation energy under a relatively warm paleoclimate.

Unfortunately, the scientific value of this site suffers from an overexploitation of its limestones as ornamental rocks, which is at the origin of a strong degradation.

5.5.2 Miocene Geosites

5.5.2.1 Oued Zra

The Oued Zra site (Sse15) is located 10 km north of Tazouta. It is located in a continental basin installed on the SE edge of the subtabular Causse. The deposits of the site

Table 5.3 Quantitative assessment of Cenozoic geosites

Cenozoic geosites	Quantitative assessment criteria (Ss)					Pointing	Final scoring matrix (Ss)					Total (Ss)	Result (Ss)
	Representativeness	Rarity	Geological diversity	State of preservation	Documentation		Representativeness *24%	Rarity *18%	Geological diversity *20%	State of preservation *24%	Documentation *14%		
Aderj plateau	3	3	3	1	3	13	0.72	0.54	0.6	0.24	0.42	2.52	High
Aghram Amellal	2	2	2	1	2	9	0.48	0.36	0.4	0.24	0.28	1.76	Medium
Aghram Iroumine	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Bel Jeraf	2	2	2	1	2	9	0.48	0.36	0.4	0.24	0.28	1,76	Medium
Beni Mghora	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Col Touaher	3	3	3	1	3	13	0.72	0.54	0.6	0.24	0.42	2.52	High
El Karia	3	3	3	1	3	13	0.72	0.54	0.6	0.24	0.42	2.52	High
Foum Khneg	3	3	3	1	3	13	0.72	0.54	0.6	0.24	0.42	2.52	High
Gara Tazouta	1	2	1	1	3	8	0.24	0.36	0.2	0.24	0.42	1.46	Low
Ich n'Bouk	2	1	2	1	3	9	0.48	0.18	0.4	0.24	0.42	1.72	Medium
Laazib	1	1	2	1	3	8	0.24	0.18	0.4	0.24	0.42	1.48	Low
Lebbouaddis	1	1	1	1	3	7	0.24	0.18	0.2	0.24	0.42	1.28	Low
Miocène of Bizi	3	2	2	1	2	10	0.72	0.36	0.4	0.24	0.28	2	Medium
Oued Mdez	3	2	2	1	3	11	0.72	0.36	0.4	0.24	0.42	2.14	Medium
Oued Zra	3	2	3	1	3	12	0.72	0.36	0.6	0.24	0.42	2.34	Medium
Ribat al Khayr	3	2	3	1	3	12	0.72	0.36	0.6	0.24	0.42	2.34	Medium
Sidi Yahya	1	1	2	1	2	7	0.24	0.18	0.4	0.24	0.28	1.34	Low
Silt of Sefrou	2	2	2	1	2	9	0.48	0.36	0.4	0.24	0.28	1.76	Medium
Skoura Travertines	3	2	2	1	3	11	0.72	0.36	0.4	0.24	0.42	2.14	Medium
Tannint Ou Moudou	3	2	3	1	2	11	0.72	0.36	0.6	0.24	0.28	2.2	Medium
Timahdite limestones	3	2	2	1	3	11	0.72	0.36	0.4	0.24	0.42	2.14	Medium

Table 5.4 Scoring of the criteria for the degree of deterioration "Sd"

Vulnerability	1. The site is not threatened by human activity;
	2. The site is threatened by a single type of anthropogenic action (construction, tourist activities, agriculture, harvesting samples, etc.);
	3. The site is threatened by more than two types of human actions.
Fragility	1. The site is not exposed to any form of natural degradation (floods, tides, erosion, landslide, etc.);
	2. The site is exposed to only one type of natural degradation;
	3. The site is exposed to more than two types of natural degradation.
Accessibility	1. The site is more than 1 km from an asphalt road;
	2. The site is 500 m to 1 km from an asphalt road;;
	3. The site is less than 500 m from an asphalt road.
Demography	1. The site is located in a low demography area where residents do not exceed 4000 people;
	2. The site is located in a medium-demographics area between 4000 and 400,000 people;
	3. The site is located in an area with a high population exceeding 400,000 inhabitants.
Number of visitors	1. The site is visited annually by less than 1000 visitors;
	2. The site is visited annually by 1000 to 10,000 visitors;
	3. The site is visited annually by more than 10,000 visitors.

(Fig. 5.5) constitute the first Upper Miocene deposits in the Middle Atlas.

The deposits of the Oued Zra site (Figs. 5.6a, b) are in angular unconformity on the Jurassic terrains. They begin with a continental red series with volcanic and volcano-sedimentary intercalations (Fig. 5.6c) which is a few tens of meters thick, from the Middle Tortonian.

Continental sedimentation, with which volcanism is associated, is linked to deep fracturing along transverse structural lines (Charrière 1990). This sedimentation is rich in volcanic ash (Fig. 5.6d). Above these volcanic flows is a level of gray clay with small Vallesian mammals (Jaeger and Martin 1971). The volcanic flows encountered in these deposits are dated to 9.7 ± 0.5 Ma (Jaeger et al. 1973). The series ends with white marl-limestones (Fig. 5.6e) which constitute a relatively homogeneous lacustrine unit (Fig. 5.6f) with a thickness of 30–40 m.

The Oued Zra site presents characteristics representative of the first continental and laguno-lacustrine deposits of the Middle Tortonian on a regional scale. These deposits mark the beginning of the transgressive sequence which corresponds to the third post-Paleozoic sedimentary cycle in the Middle Atlas.

5.5.2.2 Oued Mdez

The site of Oued Mdez (Sse14) is located 7.4 km west of Tazouta. It corresponds to fluvial and lagoon-lacustrine sedimentation attributed to the Upper Tortonian (Fig. 5.7).

The deposits of the Oued Mdez site (Figs. 5.8a, b) outcrop on either side of the Oued Mdez. They are (Fig. 5.8c) clastic in nature and show several terms gradually ranging from conglomerates (Fig. 5.8d) to carbonate clays. All of these terms form several positive elementary sequences (Fig. 5.8e) which combine to form a higher-order positive sequence. The base of these conglomeratic terms is underlined by a gully surface. These detritals, with a thickness of 50 m, are heterometric, poorly welded and very channeled. They are formed by the accumulation of clasts, resulting from the erosion of the foundations of the Lias and especially of the Dogger. In the SE part of the Miocene basin of Skoura, the thickness of these fluvial conglomerate deposits is very important and can reach 250 m in thickness.

Concordantly on the conglomeratic deposits, an essentially marly-sandy sedimentation is deposited (Fig. 5.8f) which has a thickness of 50 m. Above, we have deposits, with a thickness of 25 m, of sandy marls (Fig. 5.8g) and which become predominantly sandstone (Fig. 5.8h).

The Oued Mdez site is a good example of sedimentation carried out in an environment that was first fluvio-deltaic, lagoon-lacustrine in the Skoura basin and then marine.

5.5.2.3 Taanint Ou Moudou

The Taanint Ou Moudou site (Sse20) is located 12 km northwest of Aderj. This site (Fig. 5.9a) hosts one of the largest early Messinian reef deposits in the Middle Atlas. The geosite deposits are part of the last Messinian marine episode which is followed by the development of an original reef complex.

The deposits of the Taanint Ou Moudou site correspond to three levels (Fig. 5.10) constituting the Aghram Amellal formation (Sabaoui 1998) of the Upper Tortonian-Messinian:

- the first level corresponds to base molasses (Fig. 5.9b) whose thickness does not exceed 0.5 m.
- the second consists of limestone with reef construction which represents the most dominant facies in this geosite and whose thickness is 3 m (Fig. 5.9c, d).
- the third sedimentary level is represented by sandstone limestone with a thickness of 10 m.

Table 5.5 Degree of deterioration "Sd" of Cenozoic geosites

Cenozoic geosites	Criteria for degree of deterioration (Sd)					Pointing	Final scoring matrix (Sd)					Total (Sd)	Result (Sd)
	Vulnerability	Fragility	Accessibility	Demography	Number of visitors		Vulnerability*1 9%	Fragility *19%	Accessibility* 25%	Demography* 20%	Number of visitors * 17%		
Aderj Plateau	2	2	3	2	1	10	0.38	0.38	0.75	0.4	0.17	2.08	Medium
Aghram Amellal	2	2	2	1	1	8	0.38	0.38	0,5	0.2	0.17	1.63	Medium
Bel Jeraf	2	2	1	1	1	7	0.38	0.38	0.25	0.2	0.17	1.38	Low
Col Touaher	3	2	3	2	1	11	0.57	0.38	0.75	0.4	0.17	2.27	Medium
El Karia	2	2	3	1	1	9	0.38	0.38	0.75	0.2	0.17	1.88	Medium
Foum Khneg	2	1	3	1	1	8	0.38	0.19	0.75	0.2	0.17	1.69	Medium
Ich n'Bouk	2	1	1	1	1	6	0.38	0.19	0.25	0.2	0.17	1.19	Low
Miocène of Bizi	1	2	1	1	1	6	0.19	0.38	0.25	0.2	0.17	1.19	Low
Oued Mdez	1	2	3	2	1	9	0.19	0.38	0.75	0.4	0.17	1.89	Medium
Oued Zra	2	2	2	2	1	9	0.38	0.38	0.5	0.4	0.17	1.83	Medium
Ribat al Khayr	3	2	3	2	1	11	0.57	0.38	0.75	0.4	0.17	2.27	Medium
Silt of Sefrou	2	2	3	1	1	9	0.38	0.38	0.75	0.2	0.17	1.88	Medium
Skoura Travertines	2	2	3	2	1	10	0.38	0.38	0.75	0.4	0.17	2.08	Medium
Tannint Ou Moudou	2	2	3	1	1	9	0.38	0.38	0.75	0.2	0.17	1.88	Medium
Timahdite limestones	3	2	3	2	1	11	0.57	0.38	0.75	0.4	0.17	2.27	Medium

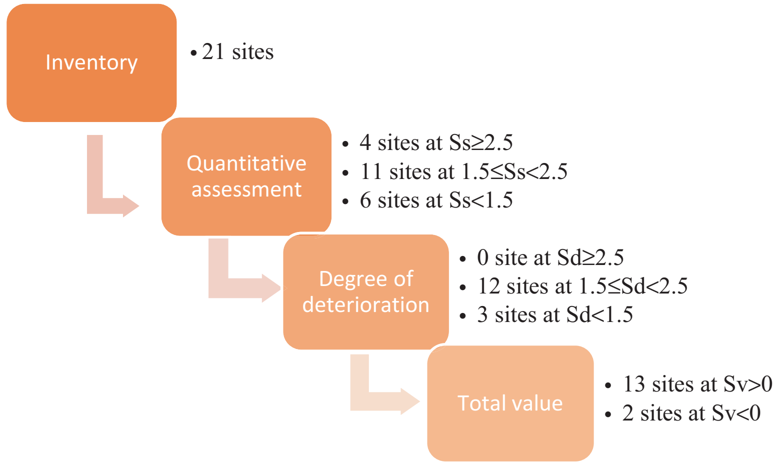

Fig. 5.3 Presentation of inventory and assessment results

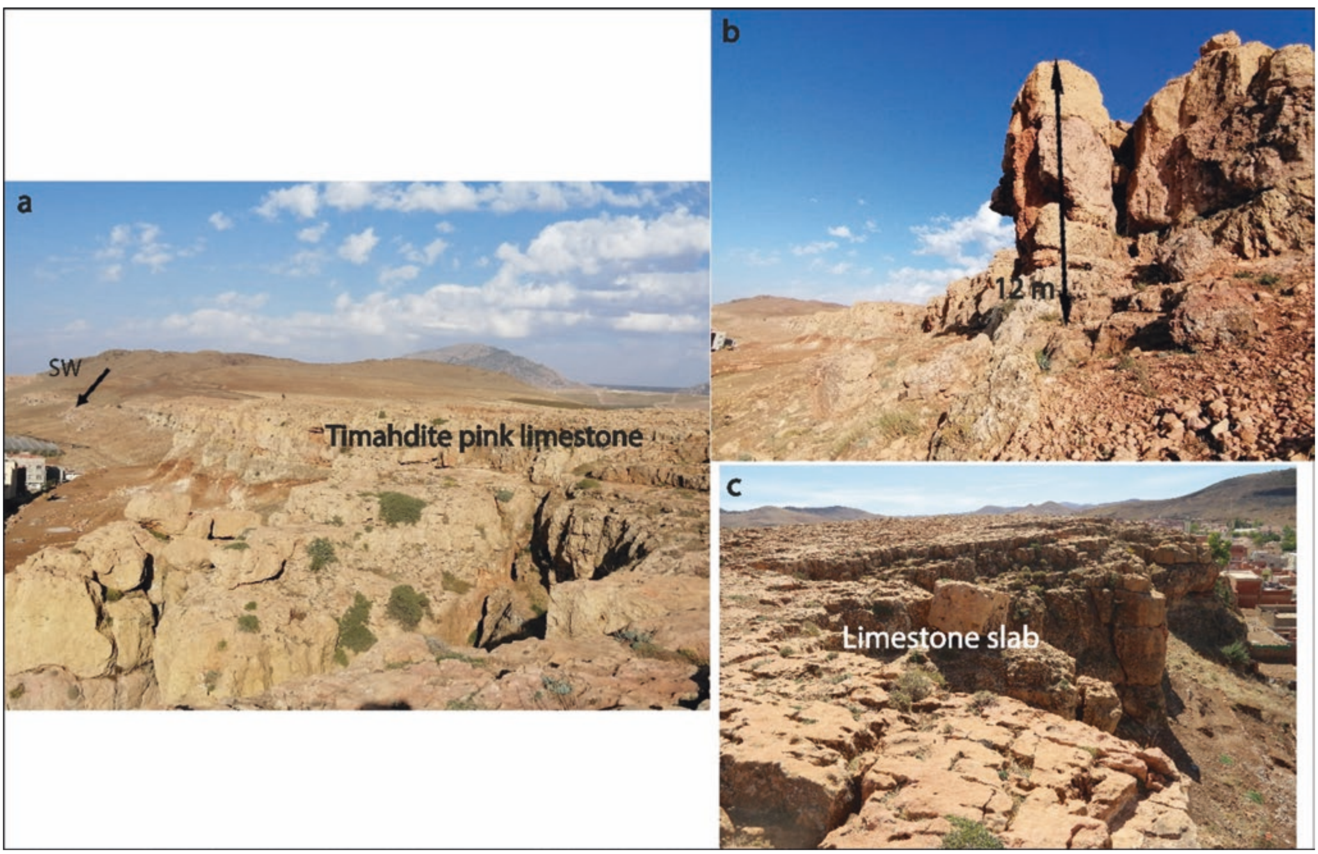

Fig. 5.4 Aspects of the "Timahdite limestones" geosite: (**a**) Timahdite pink limestone slab; (**b**) Middle Eocene pink limestone; (**c**) Limestone slab

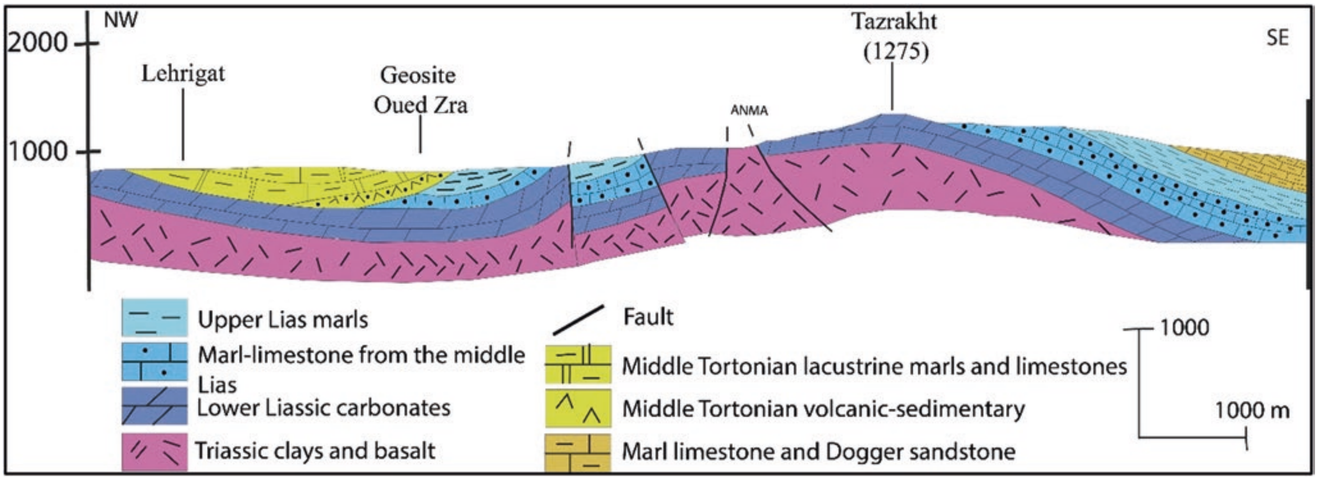

Fig. 5.5 Geological section of the Oued Zra geosite. (Baadi 2021)

The site of Taanint Ou Moudou has the outcrops which constitute the sole of the marine deposits in communication with the Atlantic and the Mediterranean. These deposits underline the importance of the Upper Tortonian-Early Messinian marine intrusion.

5.5.2.4 Ribat al Khayr

The Ribat al Khayr geosite (Sse16) is located in the village of Ribat al Khayr. It shows the terminal deposits of the Middle Atlas Miocene.

The deposits of the Ribat al Khayr geosite essentially correspond to sandy marls which are 30 m thick. They correspond to the formation of the Col de Tazouta of Messinian age (Fig. 5.11). In the NE parts of the Ribat al Khayr plateau, these sandy marls (Fig. 5.12a) overlie the Aghram Amellal formation presented essentially by reef limestones (Fig. 5.12b) which forms a dominant slab to the east of the depression of Zloul. To the west of the Ribat al Khayr plateau, the sandy marls transgress directly onto the Liassic bedrock (Fig. 5.12c).

The presence of Upper Miocene deposits at the level of Ribat al Khayr suggests a marine communication between the two arms of the sea that surround the Tazzeka massif.

5.5.2.5 Col Touaher

The Col Touaher geosite (Sse06) is located 20 km from Taza, at an altitude of 556 m. This geosite (Fig. 5.13a) is located on the border between the Middle Atlas to the south, the South Rifain Corridor to the north, eastern Morocco to the east and western Morocco to the west. This geosite has a particularity where the Paleozoic deposits are in direct contact with the Miocene deposits.

The deposits of the Col Touaher geosite are of two types: Miocene deposits of the South Rif Corridor in the north and Paleozoic deposits of the Tazzeka massif in the south. These two deposits (Fig. 5.13b) constitute a zone of confrontation between the two major structural domains of Morocco: the Atlas domain and the Rifian domain. The Paleozoic schistose soils outcrop largely at Col Touaher and in contact with them, come up against the soils of the pre-Rifan complex which lead, at this place, to the definitive obstruction of the Taza corridor. The latter, at Col Touaher, at the end of the Miocene, caused the cessation of marine communication between the Mediterranean and the Atlantic. This connection ceased during the Messinian, around six million years ago, at Col Touaher (Krijgsman et al. 1999; Krijgsman and Langereis 2000; Dayja and Bignot 2003). Going further north, the white marls with flint from the Miocene, of the Pre-rifan aquifer, rest directly on the Paleozoic shales of the Tazzeka.

By its representativeness, its rarity and its singularity, the Col Touaher geosite presents the only site in Morocco whose deposits communicate between two different Moroccan mountain chains, that of the Middle Atlas and the Rif.

5.5.3 Plio-quaternary Geosites

5.5.3.1 Aderj Plateau

The Aderj plateau geosite (Sse01) is located east of the village of Aderj. This geosite shows travertine deposits and lacustrine limestones. It is known for the quality and significant thickness of its outcrops.

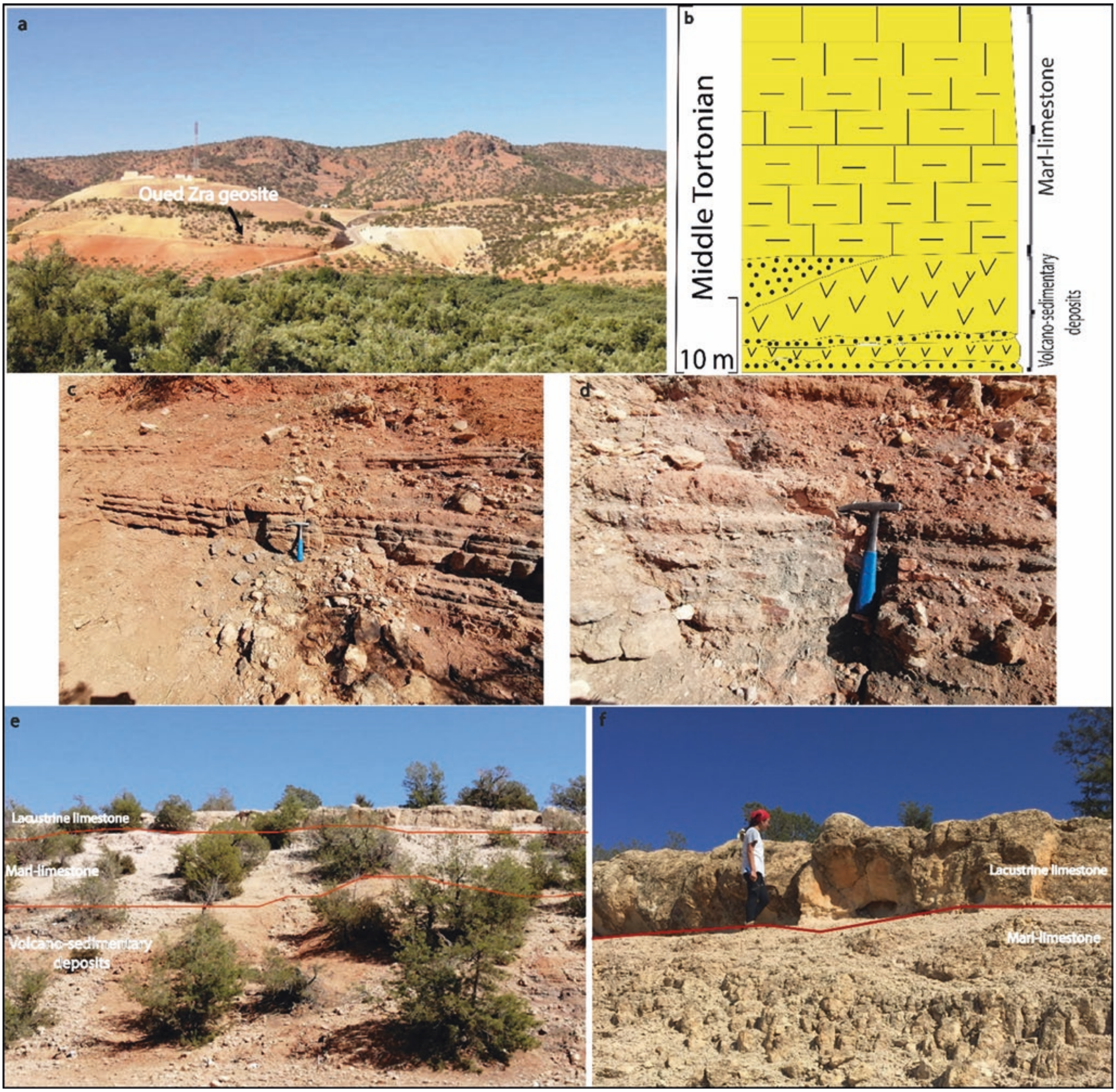

Fig. 5.6 (**a**) General view of the Oued Zra geosite; (**b**) Synthetic stratigraphic log of the deposits of the Oued Zra geosite; (**c**) Intercalation of sedimentary and volcanic deposits; (**d**) Sedimentary deposits covered by volcanic ash; (**e**) Marl-limestone deposits resting directly on the volcano-sedimentary deposits; (**f**) The transition from marl-limestone to lacustrine limestone

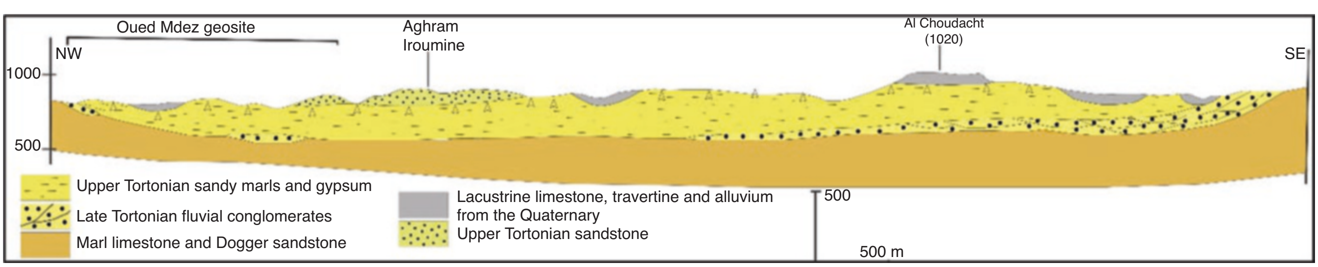

Fig. 5.7 Geological section of the Oued Mdez geosite. (Baadi 2021)

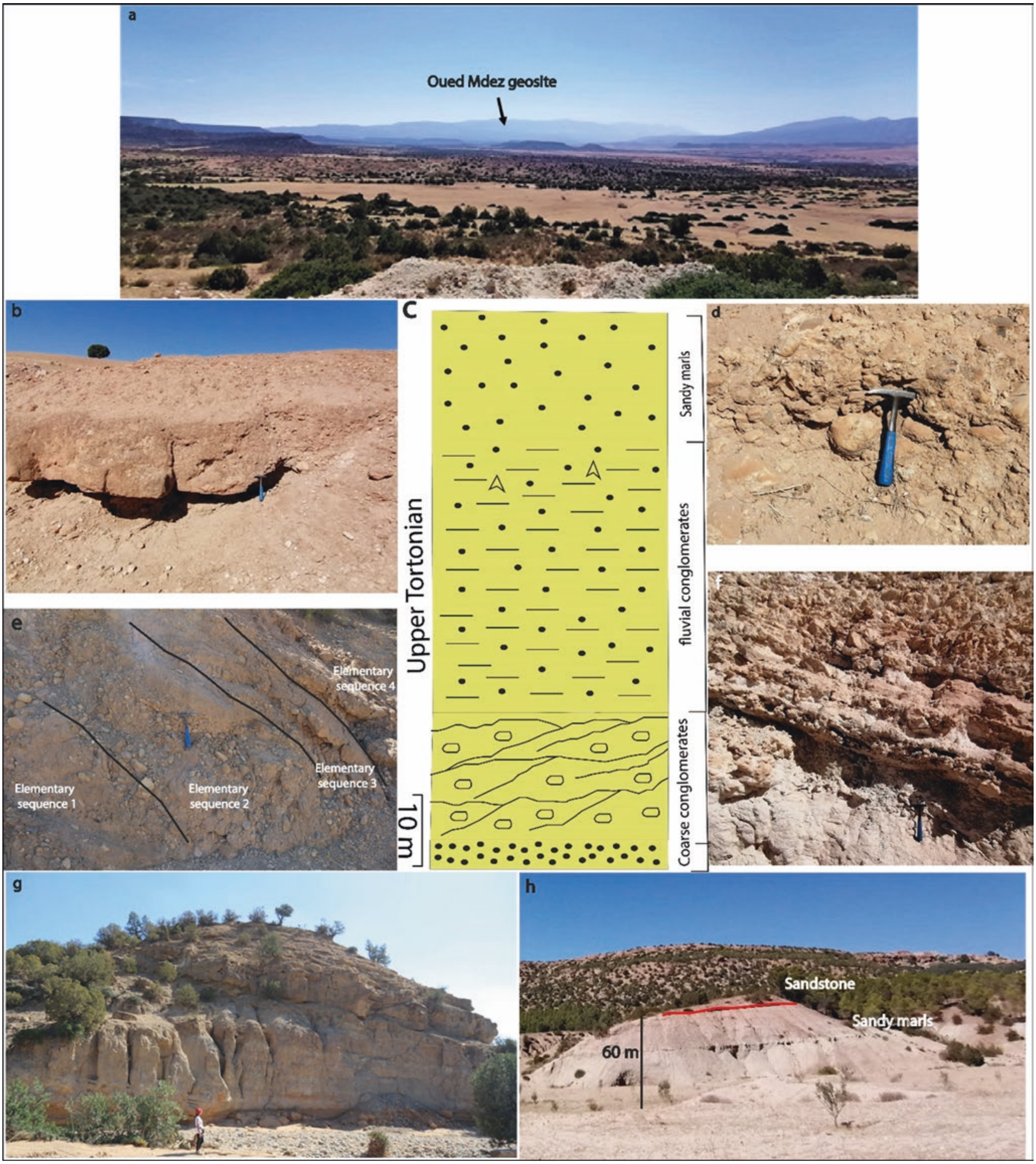

Fig. 5.8 Aspects of the Oued Mdez site. (Baadi 2021): (**a**) General view of the Oued Mdez geosite; (**b**) Fluvial conglomerates of the base of the Upper Tortonian series; (**c**) synthetic stratigraphic log of the main deposits forming the Oued Mdez geosite; (**d**) Conglomerates of the Oued Mdez series; (**e**) Positive elementary sequences of conglomerates; (**f**) Transition of conglomerates to other Upper Tortonian deposits; (**g**) Sandy marls with sandstone dominance; (**h**) Sandstone resting concordantly on sandy marls

Fig. 5.9 (**a**) General view of the Tannint Ou Moudou geosite; (**b**) Limestone with reef constructions resting concordantly on the base molasses; (**c**) Upper Tortonian-Early Messinian reef limestones; (**d**) Reefs of the Taanint Ou Moudou geosite

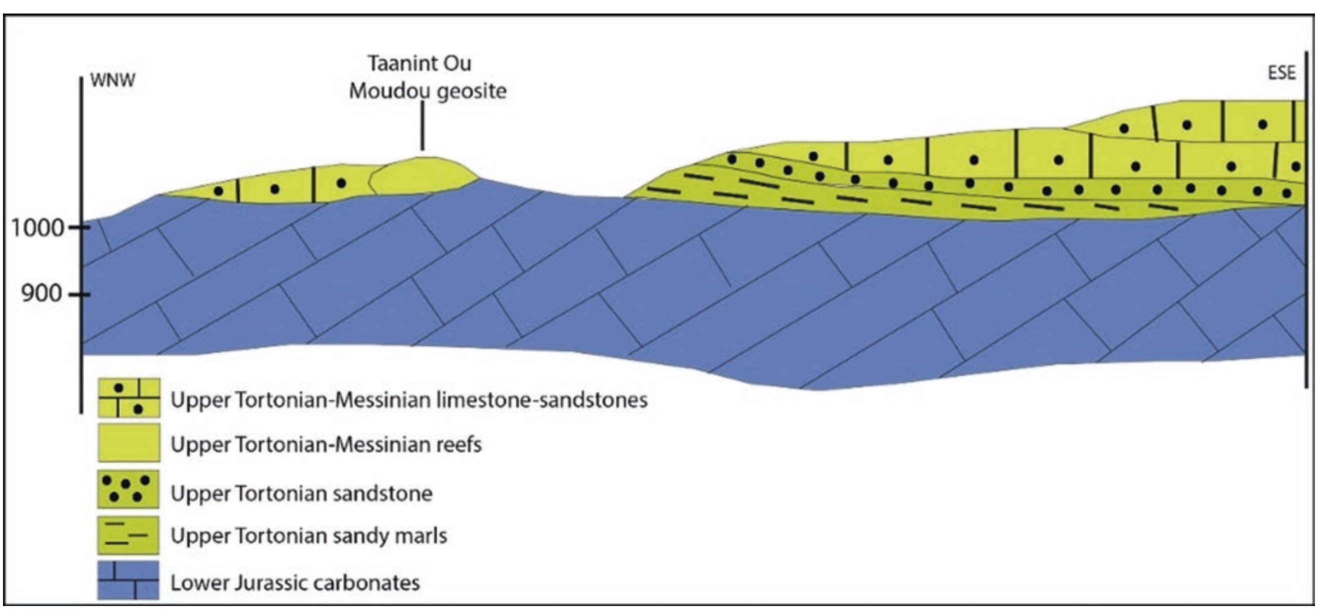

Fig. 5.10 Geological section of the Taanint Ou Moudou geosite

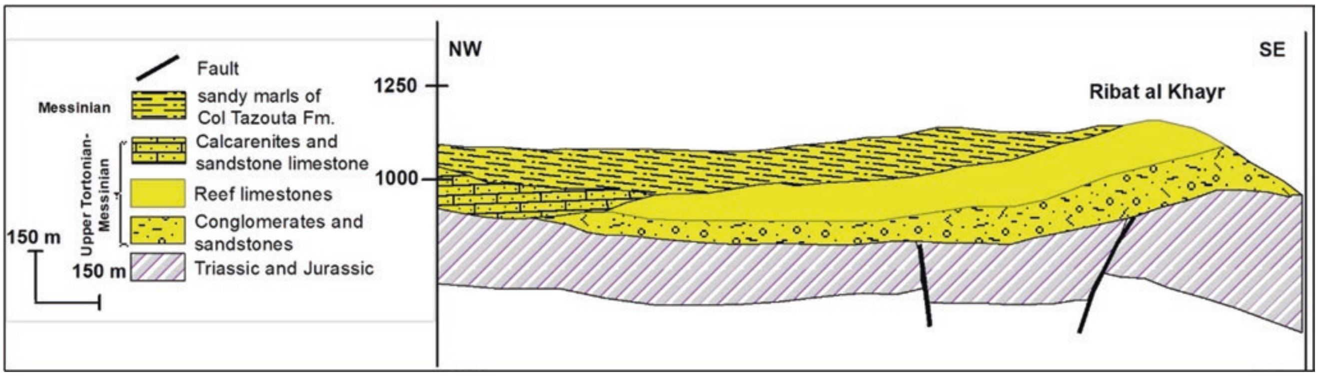

Fig. 5.11 Geological section of the sandy marls of the Col Tazouta

Fig. 5.12 (**a**) Reef limestones of the Aghram Amellal formation; (**b**) Sandy marls of the Col Tazouta formation; (**c**) South-east of the Miocene formations, outcrop the limestone bars with Cancellophycus of Amane Ilila

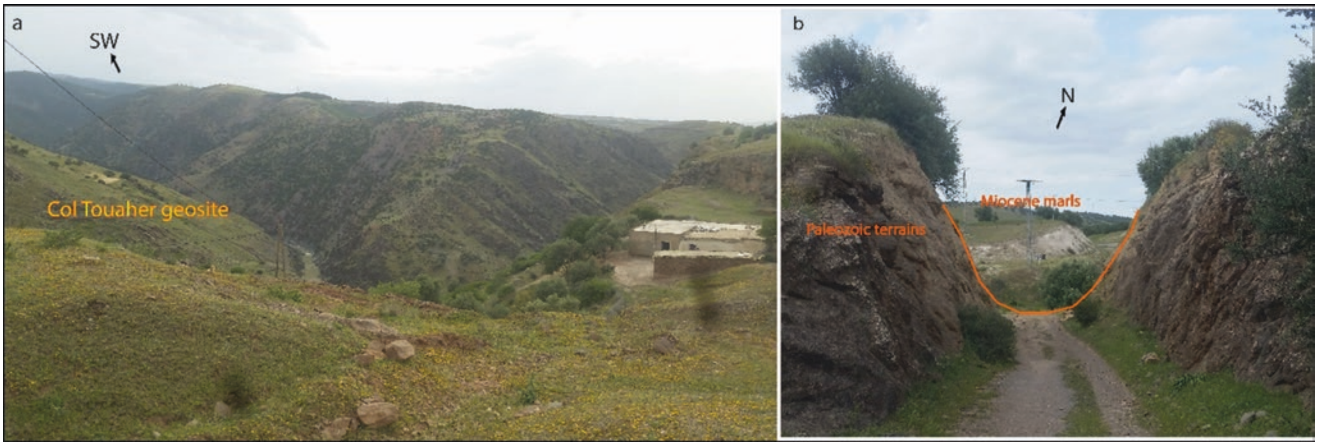

Fig. 5.13 (**a**) General view of the Col Touaher geosite; (**b**) Miocene deposits are in direct contact with Paleozoic terrains

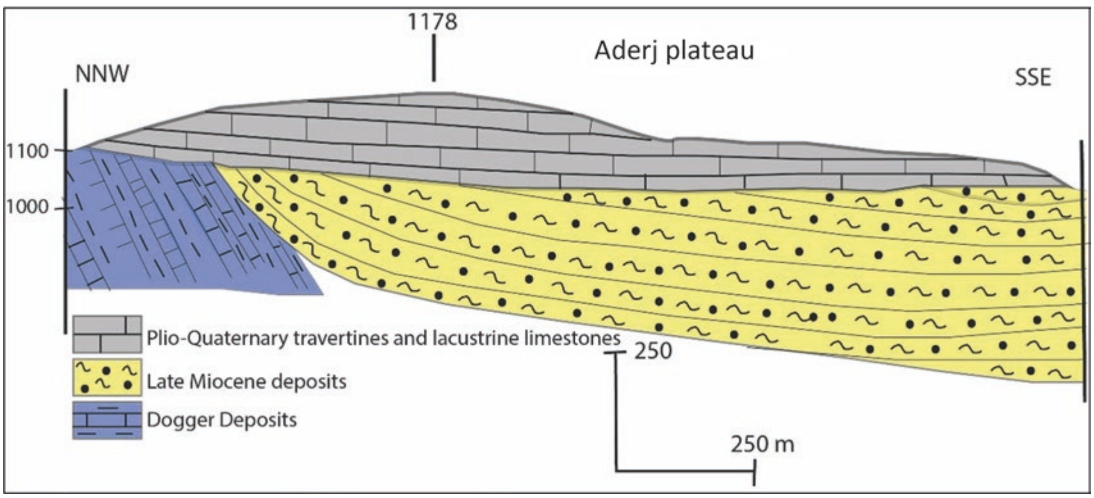

Fig. 5.14 Geological section of Aderj plateau

The outcrops of the Aderj plateau geosite (Fig. 5.14), of Upper Pliocene to Early Quaternary age (Sabaoui 1998), constitute a very large slab (Fig. 5.15a) over an area of about 8 km^2. In the SW part of the geosite, this slab is 20 m thick. On the other hand, to the NE of the Aderj plateau, this thickness reaches 80 m. It is a stack of thick beds of travertines (Fig. 5.15b) which can be separated by layers of white marls and conglomerates. These travertines are followed by lacustrine limestones (Fig. 5.15c).

The deposits of Aderj plateau are contemporary with an extensive NNW-SSE regime, during the Middle-Upper Pliocene which allowed the installation of a lacustrine environment fed by the paleo-river of Oued Mdez (El Fartati et al. 2019). During this period, the hot and humid climate favored the sedimentation of these lacustrine limestones, currently exploited as building materials and ornamental rocks.

The geosite of Aderj plateau represents the largest outcrop of travertines and lacustrine limestones of the Middle Atlas over a large area of 2.25 km^2 and a thickness that reaches 80 m.

5.5.3.2 El Karia

The El Karia geosite (Sse07) is located 8 km southeast of Ribat al Khayr. It presents alluvial terraces (Fig. 5.16) deposited along and in the vicinity of Oued El Karia.

The deposits of the El Karia geosite (Fig. 5.17a) are made up of alluvial deposits which correspond to clay-loam spreading compacting of blocks and pebbles (Fig. 5.17b). These alluvial deposits, whose thickness can reach 100 m, are made up of three terraces staged in a spectacular way and sometimes nested:

– the first terrace, the oldest, seems to have an extension that covers the southern part of the Zloul depression. It shows, in its southern part, coarse conglomerates made up of more or less rolled and fairly consolidated pebbles.

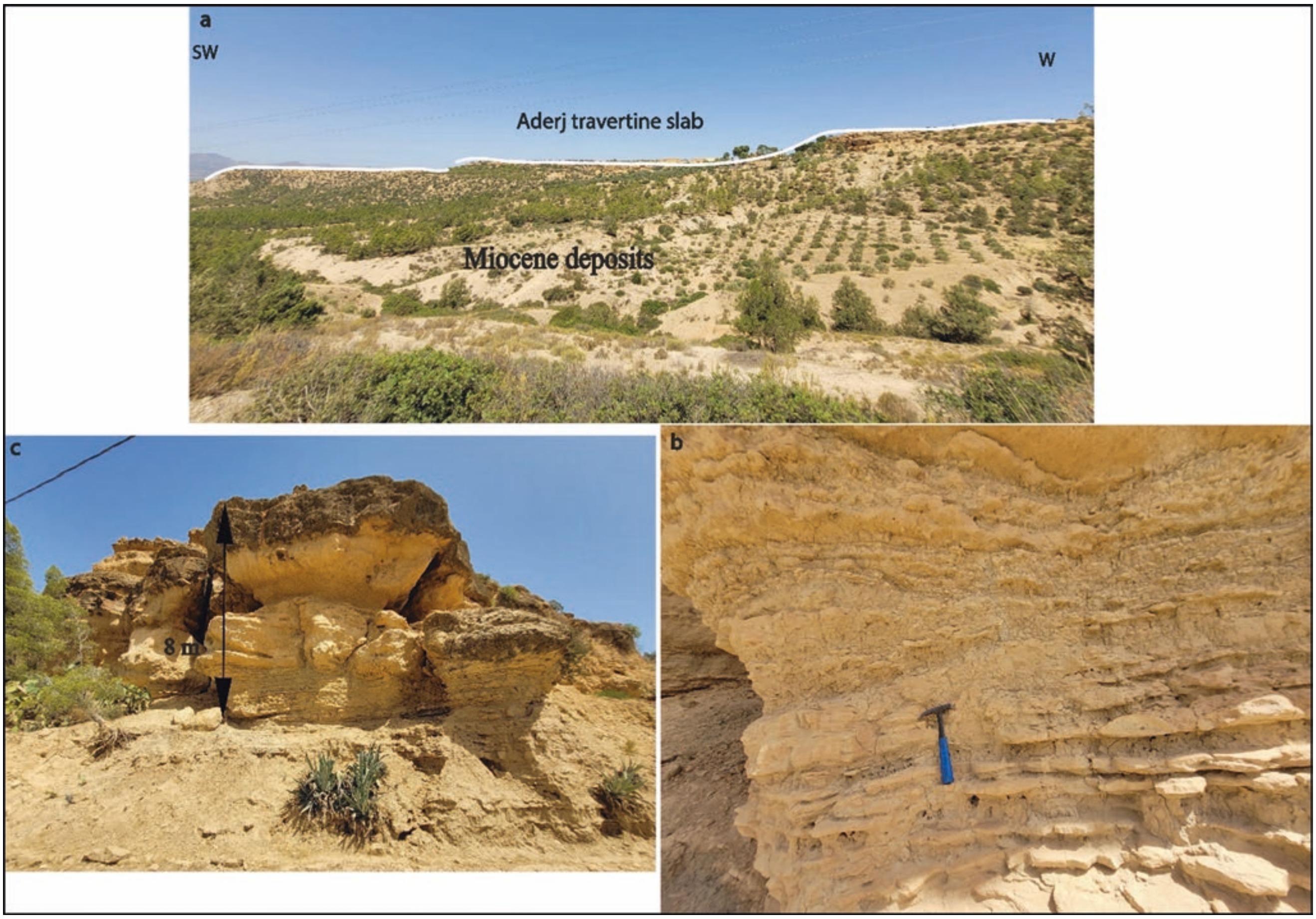

Fig. 5.15 (**a**) Travertine slab of the Aderj plateau geosite; (**b**) Lacustrine and travertine limestone from the Upper Pliocene to Early Quaternary; (**c**) Travertines

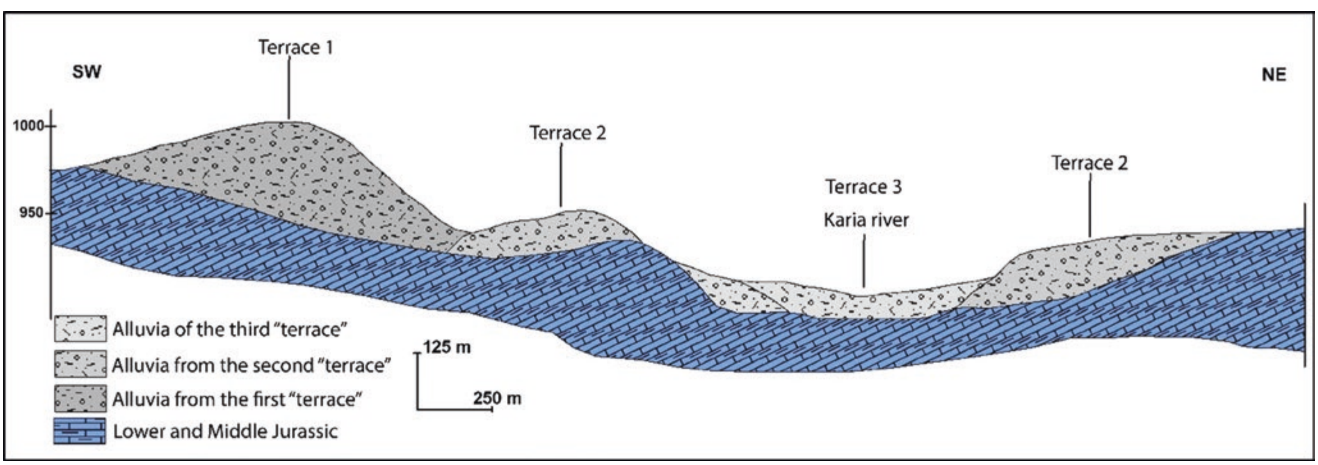

Fig. 5.16 The three alluvial terraces of Oued Karia. (Baadi 2021)

– the second terrace is 40 m lower than the top of the first terrace (Fig. 5.17c).
– the third terrace, the most recent, is at the bottom of the current Oued Karia valley (Fig. 5.17d).

The El Karia geosite is a key geosite with alluvial terraces of significant and unique thickness in the Middle Atlas.

5.6 State of Preservation

Faced with the growing threats to the natural heritage, Morocco has for several years devoted efforts to the preservation and protection of nature, by creating national parks and protected areas, of which the Middle Atlas is home to the greatest number. Beyond these initiatives, the means devel-

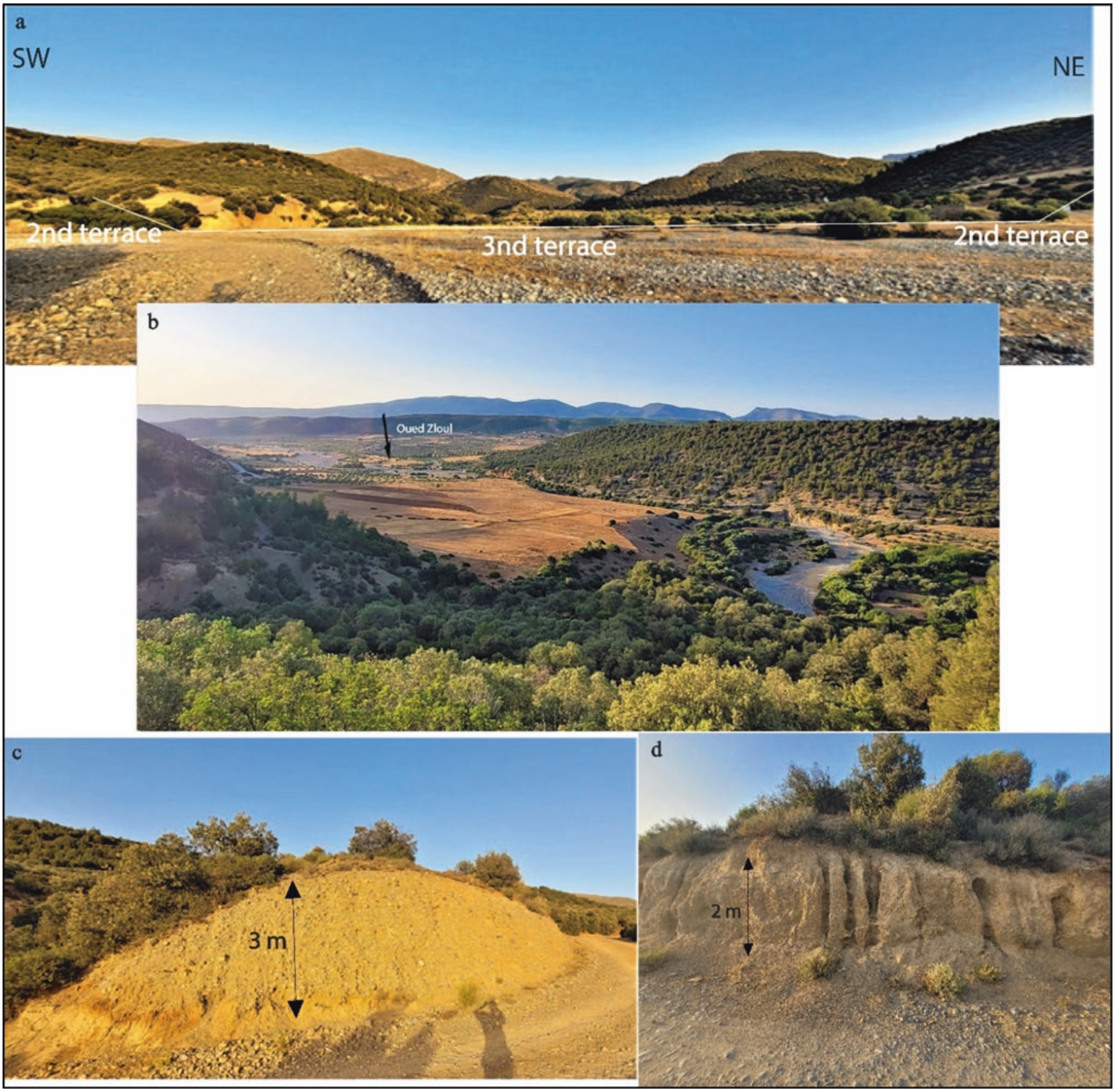

Fig. 5.17 (**a**) The second and third terrace of Oued Karia; (**b**) Overview of the terraces of Oued Karia; (**c**) Alluvium from the second terrace; (**d**) Alluvia of the third terrace

oped for the preservation of the geological heritage are also slow to be put in place in the Middle Atlas.

The Middle Atlas seems to be lagging behind compared to other Moroccan regions in terms of the preservation and protection of geosites. It undeniably harbors a rich lithostratigraphic and sedimentological heritage which requires a presentation of its state of preservation. In this chapter, we have underlined the need to recognize the lithostratigraphic and sedimentological heritage of the Cenozoic age and to stimulate a new dynamic for the dissemination of knowledge and the enhancement of this still little-known heritage. The state of preservation of this heritage is linked to the location of the main geosites in virgin areas far from large cities.

Although no geosite assessed during the deterioration stage had an Sd score ≥ 2.5, we observe in the field that some geosites are threatened by anthropogenic activities. We cite the case of the geosites of Ribat al Khayr (Sd = 2.27) and Timahdite limestones (Sd = 2.27). They suffer abusive exploitation altering their landscape. Regarding the geosite of Ribat al Khayr, the sandy marl deposits of the Messinian are almost completely hidden by constructions obscuring the geological characteristics of these deposits. For the Timahdite limestones geosite, the Eocene pink limestone deposits are overexploited as ornamental rocks. For the rest of the geosites (Aderj plateau (Sd = 2.08), Col Touaher (Sd = 2.27), El Karia (Sd = 1.88), Oued Mdez (Sd = 1.89), Oued Zra (1.83) and Taanint Ou Moudou (Sd = 1.88)), the geological characteristics of the various deposits are preserved thanks, essentially, to their location, which is far from any anthropogenic threat.

Although no geosite has had a high degree of deterioration, it is important that the public authorities pay more attention especially to the control of the overexploitation of quarries which causes the alteration of the Middle Atlas landscapes.

5.7 Conclusion

The Middle Atlas is renowned for its geological history covering three geological eras and recording the structures linked to two orogenies: Hercynian and Alpine. The alpine heritage has covered the geological stages from the Triassic to the present, marking the regional geological history. This heritage has borrowed from the Middle Atlas through various deposits of various persuasions (Tethysian, Atlantic, and Mediterranean).

In this work, the Cenozoic geological heritage, inscribed in all the outcrops and geological events which are distinguished by transgressive and regressive series intersected by significant volcanism, is the subject of a heritage study of the various geosites noting the lithostratigraphic and sedimentological history of the region from the Paleogene to the present. An inventory and a quantitative assessment has been proposed to expose the sum of sites with representative and rare characteristics. In this work, 21 Cenozoic geosites were inventoried of which 15 geosites arrived at the quantitative assessment stage harboring an Ss score ≥ 1.5. These geosites were assessed to determine their degree of deterioration. This step is essential to define the overall value of the sites. The determination of the degree of deterioration led us to specify the sites presenting the greatest risk of deterioration. Eight geosites were studied in detail, revealing the Cenozoic lithostratigraphic and sedimentological history during the Paleogene (geosite of Timahdite limestones), the Miocene (geosites Oued Mdez, Oued Zra, Taanint Ou Moudou, Ribat al Khayr and Col Touaher) and the Plio-Quaternary (geosites Aderj plateau and El Karia).

The Cenozoic lithostratigraphic and sedimentological geosites of the Middle Atlas host unique and diverse geological features illustrating the regional and national geological history of the Alpine heritage. The proposal for the inventory and assessment of these geosites is considered a priority to reveal their state of preservation.

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Part III

Palaeontological Heritage

6 The Palaeontological Heritage of Vertebrates in the Middle Atlas (Morocco): Initiatives of Inventory and Assessment for a Rare Heritage Threatened with Degradation

Khaoula Baadi

Abstract

Recognized by its paleontological sites of *in-situ* and *ex-situ* vertebrates, the Middle Atlas is the subject of increased attention and offers geoscientists and paleontologists a vast field of predilection for one of the richest fossiliferous deposits in the country and even to the world. The paleontological heritage "paleontoheritage" is considered as an indispensable resource in regional and national socio-economic development. In the region, vertebrate paleontological sites are under strong degradation pressure leading to the deterioration of this heritage despite some promotion and preservation initiatives. An inventory and a quantitative assessment of these sites by determining their degree of deterioration is necessary to preserve this paleontoheritage. The inventory resulted in 35 geosites inventoried *in situ*, of which 34.2% of the geosites held medium to high scores during the quantitative assessment (Ss) and the rest of the geosites presented average scores during the assessment of the degree of deterioration (Sd). Among the sum of the geosites, four (Aït Bazza, Ancherif, Boulahfa and El Mers) were chosen and studied due to their high scoring value of representativeness, rarity and geological diversity criteria.

Keywords

Paleontoheritage · Vertebrate paleontological sites · Inventory · Assessment · Middle Atlas

6.1 Introduction

Paleontology has always fascinated geoscientists and paleontologists who have tried to discover, through fossils and their traces, evidence of the evolutionary history of life on Earth. It is a "time machine" that allows other sciences to discover geological time and allows each of us to embark on imaginary adventures in the Earth's past (Ward 1998). Recently, biodiversity has begun to occupy a primordial place in the research of scientists, public opinion and the political world. Its protection and preservation has become an irreversible whose awareness is relatively recent. The study of current biodiversity is inseparable from the paleontological study. To retrace the history of biodiversity and to analyze it, it is necessary to use fossils, which are thus the keys to understanding the evolution of biodiversity (Neagu 2010).

Great interest has been shown in the paleontology of vertebrates in the Middle Atlas, the first studies of which date back to 1927 (Termier 1927). Since that date, several works have appeared (De Lapparent 1942; Jenny et al. 1981; Monbaron and Taquet 1981; Jenny 1982; Monbaron 1983; Monbaron et al. 1999; Allain et al. 2004; Hadri and Pérez-Lorente 2012; Marinheiro et al. 2014; Marinheiro 2015; Maidment et al. 2020, 2021). The vertebrate paleontology of the Middle Atlas, compared to other Middle Jurassic localities (England, United States and Portugal), presents the greatest paleontological diversity (Hadri and Pérez-Lorente 2012). The Middle Atlas is home to a rich and diversified paleontological heritage by holding the most important fossiliferous deposits of vertebrates in Morocco. The paleontological heritage, including fossils and ichnofossils, represents essential witnesses for deciphering and reconstructing the history of our planet through numerous fossiliferous deposits despite their fragility. Through the diversity of its geological history, the Middle Atlas conceals fossiliferous deposits of global importance which have given rise to numerous works attracting the attention of several international paleontologists. Deposits known and described since the beginning of the twentieth century by many authors and have provided material for several collections, the richest fossil collections in the world, in various national and international museums.

Some sites are unique in Morocco and even in the world. The richest areas of the entire Middle Atlas chain, by their

K. Baadi (✉)
Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, Fez, Morocco

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wealth in ichnofossils and bones, are those of El Mers, Boulemane, Imouzzer Marmoucha and Oulad Ali. Even today, several discoveries of bones in the region are made. Examples include the recent discovery of dinosaur footsteps in Jbel Oudiksou (Gandini and Ahalfi 2015) and dinosaur bones in Boulahfa (Maidment et al. 2020, 2021).

The paleontological heritage of Morocco and of the Middle Atlas in particular is subject to considerable pressure, without much of an inventory or basis for legal protection. To achieve a truly respectful sustainable development and its regulatory organization, it has become urgent to carry out an inventory of this heritage in the Middle Atlas.

This present chapter focuses on the paleontological heritage "paleontoheritage"and emphasizes the paleontological heritage of vertebrates and their ichnofossils. The latter are of remarkable importance in paleoecology, providing information that allows paleoenvironmental reconstructions. The paleontological sites of the vertebrates of the Middle Atlas which are presented in this chapter reveal a unique character in Morocco and all the data which can be retained from them are confirmed to be essential for deciphering the stratigraphic and sedimentary history from the Jurassic to the Pleistocene. The objective is therefore multiple, scientific, heritage and preservation.

6.2 Paleontological Heritage of Vertebrates

The paleontological heritage of vertebrates from the Middle Atlas has made a substantial and decisive contribution to understanding and clarifying the evolution of vertebrates and their distribution on a national and international scale. The fossiliferous diversity provided crucial information on the evolution and paleobiogeography of the Middle Atlas chain and also provided some of the most remarkable ichnological sites in Morocco.

The Middle Atlas is today world famous for having provided the richest and most diversified fossil bones in Africa and even in the world. As a result, it is considered the crossroads of new discoveries that attract several researchers around the world. The majority of these discoveries are assembled in the Bathonian deposits of the Boulemane and El Mers region.

6.2.1 Inventory and Assessment

The development of an inventory and an assessment will allow the identification of a series of sites of particular scientific interest. Each site inventoried and assessed will subsequently contribute to the protection and preservation of these sites by enabling them to reveal their heritage value. In this present work, the inventory led to an inventory of 35 paleontological sites of vertebrates (Table 6.1). This inventory will serve as a support presenting the most important fossiliferous deposits of the Middle Atlas chain. These sites present fossiliferous sites that cover a time interval from the Jurassic to the Pleistocene. These are geosites of footprints, bones and fossiliferous skeletons.

During the quantitative assessment (Table 6.2), 5 geosites out of 35 inventoried geosites presented an $Ss \geq 2.5$, 8 sites a $1.5 \leq Ss < 2.5$, and the remaining 22 had an $Ss < 1.5$. The latter were withdrawn from the selection given their low scientific value.

For the degree of deterioration, 13 geosites were therefore selected (Table 6.3). Among these 13 geosites: no site has an $Sd \geq 2.5$, 5 geosites have an $Sd < 1.5$, and 8 geosites have a $1.5 \leq Sd < 2.5$.

As for the results of the calculation of their total value, this was positive for 12 geosites, the only remaining one therefore has an $Sv < 0$.

6.2.2 Paleontological Geosites of Vertebrates

Four vertebrates paleontological geosites are studied. They are chosen among the geosites selected during the quantitative assessment and the degree of deterioration by their high score of criteria of representativeness, rarity and geological diversity as well as their state of preservation.

6.2.2.1 Aït Bazza

Aït Bazza (Pal03) is located 6 km south of Imouzzer Marmoucha. This site (Fig. 6.1a) houses a cemetery which holds the most numerous dinosaur bones in the Middle Atlas. It extends over a length of 3 km and a width of 2 km.

The dinosaur remains of the Aït Bazza geosite are found in the marls of the Lower Bathonian El Mers 1 formation. We find their ribs (Fig. 6.1b) and various bones (Fig. 6.1c).

The geosite of Aït Bazza is an important site and constitutes a reference by its originality, its representativeness and by the extension of the remains of the dinosaurs. Unfortunately, it is seriously degraded and in need of urgent conservation. This geosite has not, until now, known work on the remains of the dinosaurs.

6.2.2.2 Ancherif

Ancherif (Pal04) is located 24 km northwest of Boulemane, at the NW end of the El Mers syncline. This site shows a strong paleontological potential of a relatively little explored area.

The Ancherif geosite (Fig. 6.2a) is located on the edge of Oued Guigou. It is located in Middle Pleistocene deposits.

Table 6.1 Inventory of paleontological geosites of vertebrates

Geosites	Identification code	Type of geosite	Coordinates			Administrative location	Property	Accessibility	Protected area
			X	Y	Z				
Aïn ou N'Jourh	Pal01	*Cetiosaurus* sp.	33°28′30.24″N	4°27′14.37″W	1451	El Mers	Public	Medium	–
Aït Abdellah	Pal02	–	33°25′3.30″N	4°26′35.60″W	1628	El Mers	Public	Medium	–
Aït Bazza	Pal03	*Iguanodon*	33°24′35.75″N	4°18′35.86″W	1463	El Mers	Public	Medium	–
Ancherif	Pal04	*Elephas recki recki*	33°29′1.38″N	4°36′48.31″W	1132	Taghrout	Public	Medium	–
Botane	Pal05	Teleosauridae	33°28′48.62″N	4°27′56.01″W	1597	El Mers	Public	Medium	–
Botane Sud	Pal06	*Steneosaurus* sp.	33°28′27.54″N	4°27′45.55″W	1575	El Mers	Public	Medium	–
Bou Ifraoun	Pal07	*Steneosaurus* sp.	33°24′54.67″N	4°22′34.52″W	1449	El Mers	Public	Medium	–
Bou Ifraoun Ouest	Pal08	*Steneosaurus* sp.	33°24′55.89″N	4°22′51.24″W	1422	El Mers	Public	Medium	–
Boulahfa	Pal09	*Adratiklit boulahfa; Spicomellus*	33°17′48.56″N	4°42′13.76″W	1930	Boulemane	Public	Difficult	–
Darak	Pal10	*Steneosaurus* sp.	33°25′24.34″N	4°27′9.68″W	1709	El Mers	Public	Medium	–
Djmila	Pal11	*Steneosaurus* sp.	33°30′41.97″N	4°26′6.74″W	1359	El Mers	Public	Medium	–
EL Mers	Pal12	*Megalosauripus; Breviparopus*	33°26′49.82″N	4°26′41.61″W	1491	El Mers	Public	Facile	–
Jbel Oudiksou	Pal13	–	33°14′57.86″N	4°49′46.46″W	2110	Boulemane	Public	Medium	–
Ksar Aït Moulay (Tisfoula Tasra)	Pal14	*Steneosaurus* sp.	33°26′37.48″N	4°23′29.45″W	1274	El Mers	Public	Medium	–
Oued Boukamouche	Pal15	–	33°26′48.72″N	4°25′21.25″W	1410	El Mers	Public	Medium	–
Oued Mers	Pal16	*Lepidotes* sp.	33°26′42.10″N	4°18′57.47″W	1410	Imouzzer Marmoucha	Public	Medium	–
Oued Tamemchet	Pal17	*Steneosaurus* sp.	33°25′47.74″N	4°23′50.28″W	1436	El Mers	Public	Medium	–
Oued Tamghilt	Pal18	–	33°26′35.63″N	4°19′2.71″W	1401	El Mers	Public	Medium	–
Oulad Ali	Pal19	Sauropoda; Theropoda	33°27′52.66″N	3°58′17.24″W	1447	Oulad Ali Youssef	Public	Medium	–
Selghert	Pal20	–	33°08.82′N	04°58.82′W	1970	El Mers	Public	Medium	–
Taghit	Pal21	*Cetiosaurus mogrebensis; Megalosaurus mersensis*	33°27′27.07″N	4°27′35.14″W	1536	El Mers	Public	Easy	–
Taghit Aït Youssef	Pal22	–	33°27′22.09″N	4°27′12.51″W	1561	El Mers	Public	Medium	–
Taghit Tissenflet	Pal23	–	33°27′3.18″N	4°25′23.05″W	1540	El Mers	Public	Medium	–
Taghrout	Pal24	*Cetiosaurus* sp.	33°27′0.94″N	4°28′0.06″W	1598	El Mers	Public	Medium	–
Taghzout	Pal25	–	33°27′23.38″N	4°23′24.73″W	1277	El Mers	Public	Medium	–
Tamgert Iktaaïn (Tizi N'Julierh)	Pal26	Teleosauridae; Testudinata	33°28′1.58″N	4°26′58.67″W	1532	El Mers	Public	Medium	–
Tamgert N'Tarit	Pal27	*Cetiosaurus* sp.	–	4°26′3.45″W	1424	El Mers	Public	Medium	–
Tamgert N'Tarit Nord	Pal28	Testudinata; Cetiosaurus; Protocardia; Ostreidae	33°28′1.50″N	4°26′0.40″W	1488	El Mers	Public	Medium	–
Tamguert N'rate	Pal29	–	33°27′14.27″N	4°18′44.32″W	1525	Imouzzer Marmoucha	Public	Medium	–
Tasra	Pal30	Steneosaurus sp.	33°27′35.43″N	4°23′35.06″W	1237	El Mers	Public	Medium	–
Tasra Est	Pal31	Steneosaurus sp.	33°27′34.43″N	4°23′10.71″W	1280	El Mers	Public	Medium	–
Tichniouine	Pal32	*Cetiosaurus* sp.	33°25′36.80″N	4°25′10.59″W	1453	El Mers	Public	Medium	–
Tichou Moulay Said	Pal33	Steneosaurus sp.	33°26′28.11″N	4°23′43.34″W		El Mers	Public	Medium	–
Tirardine	Pal34	*Steneosaurus* sp.	33°26′9.43″N	4°21′32.85″W	1458	Imouzzer Marmoucha	Public	Medium	–
Vértébrés d'El Mers	Pal35	Theropoda	33°27′0.04″N	4°25′59.75″W	1523	El Mers	Public	Medium	–

Table 6.2 Quantitative assessment (Ss) of paleontological geosites of vertebrates

Geosites	Criteria of quantitative assessment (Ss)					Total pointing	Final scoring matrix (Ss)					Total quantitative assessment	Result (Ss)
	Representativeness	Rarity	Geological diversity	State of preservation	Documentation		Representativeness *24%	Rarity *18%	Geological diversity *20%	State of preservation *24%	Documentation *14%		
Aïn ou N'Jourh	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Aït Abdellah	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Aït Bazza	3	3	3	1	3	13	0.72	0.54	0.6	0.24	0.42	2.52	High
Ancherif	3	3	3	1	3	13	0.72	0.54	0.6	0.24	0.42	2.52	High
Botane	2	2	1	1	2	8	0.48	0.36	0.2	0.24	0.28	1.56	Medium
Botane Sud	2	2	1	1	2	8	0.48	0.36	0.2	0.24	0.28	1.56	Medium
Bou Ifraoun	2	2	1	1	2	8	0.48	0.36	0.2	0.24	0.28	1.56	Medium
Bou Ifraoun Ouest	2	2	1	1	2	8	0.48	0.36	0.2	0.24	0.28	1.56	Medium
Boulahfa	3	3	3	1	3	13	0.72	0.54	0.6	0.24	0.42	2.52	High
Darak	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Djmila	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
El Mers	3	3	3	1	3	13	0.72	0.54	0.6	0.24	0.42	2.52	High
Jbel Oudiksou	2	2	1	1	2	8	0.48	0.36	0.2	0.24	0.28	1.56	Medium
Ksar Aït Moulay (Tisfoula Tasra)	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Oued Boukamouche	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Oued Mers	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Oued Tamemchet	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Oued Tamghilt	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Oulad Ali	2	2	1	1	2	8	0.48	0.36	0.2	0.24	0.28	1.56	Medium
Pas d'EL Mers	3	3	3	1	3	13	0.72	0.54	0.6	0.24	0.42	2.52	High
Taghit	2	2	2	1	3	10	0.48	0.36	0.4	0.24	0.42	1.9	Medium
Taghit Aït Youssef	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Taghit Tissenflet	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Taghrout	3	2	1	1	2	9	0.72	0.36	0.2	0.24	0.28	1.8	Medium

Taghzout	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Tamgert Iktaaïn (Tizi N'Julierh)	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Tamgert N'Tarit	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Tamgert N'Tarit Nord	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Tamguert N'rate	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Tasra	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Tasra Est	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Tichniouine	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Tichou Moulay Said	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Tirardine	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Vertébrés d'El Mers	3	3	3	1	3	13	0.72	0.54	0.6	0.24	0.42	2.52	High

Table 6.3 Degree of deterioration (Sd) of paleontological geosites of vertebrates

Geosites	Critera of degree of deterioration (Sd)					Total of pointing	Final scoring matrix (Sd)					Total of Sd	Result (Sd)
	Vulnerability	Fragility	Accessibility	Demography	Number of visitors		Vulnerability *19%	Fragility*19%	Accessibility*25%	Demography*20%	Number of visitors*17%		
Aït Bazza	3	3	3	1	1	11	0.57	0.57	0.75	0.2	0.17	2.26	Medium
Ancherif	3	3	1	1	1	9	0.57	0.57	0.25	0.2	0.17	1.76	Medium
Botane	1	1	2	1	1	6	0.19	0.19	0.5	0.2	0.17	1.25	Low
Botane Sud	1	1	1	1	1	5	0.19	0.19	0.25	0.2	0.17	1	Low
Bou Ifraoun	1	1	1	1	1	5	0.19	0.19	0.25	0.2	0.17	1	Low
Bou Ifraoun Ouest	1	1	1	1	1	5	0.19	0.19	0.25	0.2	0.17	1	Low
Boulahfa	3	3	1	1	1	9	0.57	0.57	0.25	0.2	0.17	1.76	Medium
EL Mers	3	3	3	1	1	11	0.57	0.57	0.75	0.2	0.17	2.26	Medium
Jbel Oudiksou	1	2	2	1	1	7	0.19	0.38	0.5	0.2	0.17	1.44	Low
Oulad Ali	2	2	2	1	1	8	0.38	0.38	0.5	0.2	0.17	1.63	Medium
Taghit	2	2	3	1	1	9	0.38	0.38	0.75	0.2	0.17	1.88	Medium
Taghrout	2	2	2	1	1	8	0.38	0.38	0.5	0.2	0.17	1.63	Medium
Vertébrés d'El Mers	3	3	3	1	1	11	0.57	0.57	0.75	0.2	0.17	2.26	Medium

The deposits of the Ancherif geosite are lacustrine in nature. These deposits contain the remains of fish, continental reptiles, artiodactyls, bones of large mammals, bones of elephants (Fig. 6.2b).

The Ancherif geosite yielded the remains of four elephants and a young adult. This is the species *Elephas recki recki* (Marinheiro et al. 2014). These remains, still well preserved, show shoulder blades (Fig. 6.2c, d), which can reach 1.5 m wide, several bones of the limbs and a pectoral belt (Fig. 6.2e). The presence of these species in colonies is explained by the topographic conditions of the locality. Indeed, it is a mountain lake with steep and slippery edges that could have served as a natural trap (Marinheiro 2015).

The geosite of Ancherif presents a rarity from the paleontological point of view by showing the presence of the first bones of *Elephas* reported in the Middle Atlas and the most recent in Morocco. This geosite testifies to the environment of the region during the Middle Pleistocene.

6.2.2.3 Boulahfa

Boulahfa (Pal09) is located 13 km south of Boulemane. This site presents a singularity in Morocco and even in the world.

The dinosaur bones of the Boulahfa geosite are found at the top of the formation of the versicolored marls of El Mers 2 of Bathonian age (Fig. 6.3a). They correspond to many stegosaur bones (Charroud and Fedan 1992).

Most of the stegosaurs discovered so far have shown that the species lived throughout the Late Jurassic and Cretaceous. The Boulahfa Stegosaurus indicates an age of 168 million years (Bajocian), according to the team of the Museum of Natural History in London. This new specimen (Fig. 6.3b) is named *Adratiklit boulahfa* (Maidment et al. 2020). *Adratiklit boulahfa* is a new species and the oldest of all stegosaurs.

Very recently, in September 2021, a new species was discovered at the site. It is a *Spicomellus afer gen. and sp. Nov.* of Bathonian-Callovian age. This species is the oldest of all ankylosaurs (Maidment et al. 2021). This discovery filled an important gap in the evolution of dinosaurs. The morphology of this *Spicomellus* (Fig. 6.3c) is unprecedented among extinct and extant vertebrates (Maidment et al. 2021) in particular by the discovery of spines attached directly to bones.

Boulahfa holds the oldest stegosaurus discovered so far in the world. The geosite, through its bones, makes it possible to understand the diversity and paleobiogeography of the stegosaurus and ankylosaur dinosaurs.

6.2.2.4 El Mers

El Mers (Pal12) is located in the center of the village of El Mers. It presents the only deposit in the Middle Atlas that shows the footprints of dinosaurs.

Dinosaur ichnites (Fig. 6.4a) are found in deposits of the Bou Akrabène-Ich Timellaline formation (Fig. 6.4b). These are marl-limestone deposits corresponding to alternations of coastal and supratidal marine environments.

In this geosite, there are 101 recorded dinosaur ichnites (Hadri and Pérez-Lorente 2012). They form intersecting tracks or isolated indentations (Fig. 6.4a). They appear on both sides of the Oued Mers (Fig. 6.4a) of which we notice an intense erosion which risks making these imprints disappear. Hadri and Pérez-Lorente (2012) showed the existence of three types of footprints: Those of small theropod dinosaurs with small, narrow and long steps (Fig. 6.4c, d); those of broad-footed theropods with long, broad toes that some authors have associated with the genus *Megalosauripus*. Finally, a third type of footprint attributed to sauropod dinosaurs of the genus *Breviparopus*.

The prints are digitigrade tridactyl or semiplantigrade tetradactyl. The length of the footprints, tridactyle or tetradactyle, varies between 18 and 30 cm, with a depth reaching 10 cm. The most apparent tracks are those of large quadrupeds. The shape and size of these ichnites show that the dinosaurs moved at an average speed of 5 km/h (Hadri and Pérez-Lorente 2012). Further south in the same formation are other dinosaur footsteps, 40 cm wide, with blunt toes.

El Mers is unique in its many dinosaur footsteps from different genera of theropods and sauropods. These ichnites show a variety of morphotypes and structures that help to understand the size, shape and behavior of these dinosaurs.

6.2.3 Paleontoheritage: Between Degradation and Preservation Initiatives

Morocco has for years carried laws protecting the environment, soil and subsoil with more attention to the protection and preservation of water resources due to its importance on all scales: scientific and economic, with less important or even incomplete for the preservation of the paleontological heritage. Like Law 33-13 relating to mines, which regulates all exploitation of Moroccan mineral resources, no law regulates the overexploitation of fossiliferous resources. The lack of a legal framework that adopts protective laws and limits the collection of fossils means that the country and especially the Middle Atlas is subject to uncontrolled exploitation by national and international researchers but also by fossil looters with their action on certain fossils. Have found their way into museums abroad.

Recently, several initiatives have emerged in Morocco to preserve and protect the country's paleontological heritage, considered unique, rare and irreversible. Among these initia-

Fig. 6.1 (**a**) View of the location of one of the bones of the Aïn Bazza geosite; (**b**) Dinosaur rib; (**c**) Well-degraded dinosaur bone

tives, in 2014, the Scientific Institute of Rabat "Israbat" carried out an inventory of a collection of national fossils which presents a century of research in Morocco of more than 12,000 samples. It is an inventory of certain groups of fossils, animals and plants, of the country as well as of the prehistoric industry and ichnofossils (Fedan 2014). The samples presented during this inventory were deprived of certain details of their location, their state of preservation and their current state in the field. The vertebrate samples are not marked with the name of the species found but only with bones. These samples are exhibited in the institute's museum.

In 2016, another initiative was launched in the Middle Atlas with the inauguration of the Middle Atlas Heritage Interpretation Center (CIPMA). It has various facilities with a cultural, scientific and educational vocation. The latter exhibits a set of objects that trace the history of the region from the Lower Palaeolithic to the present day and which cover both the natural, archaeological and ethnographic side. Among the objects exhibited in this center are certain bones of *Elephas* from the geosite of Ancherif (Fig. 6.5a, b).

The paleontological resources of the Middle Atlas are rapidly disappearing as development, construction, industrialization, vandalism and the harvesting of fossils by professionals, amateurs and commercial collectors continues. The majority of the sites visited during the inventory carried out in this work are extremely degraded and even in some sites we find only traces of the fossils collected.

The implementation of a site preservation and protection strategy is essential to guarantee the preservation of this national paleontological treasure. Understanding the history of life on Earth is done through this preservation which provides a framework of understanding of materials for scientific research of the past, today and tomorrow.

Although a serious and reasonable work must be done for a good preservation of the sites on the ground and even in museums. *In-situ* geosites provide other data that cannot or

Fig. 6.2 (**a**) General view of the location of the Ancherif geosite; (**b**) Shoulder blade of Ancherif *Elephas* with part of the rib on top; (**c**) Shoulder blade of *Elephas recki recki*; (**d**) Scapula of a juvenile *Elepha*; (**e**) rib of Ancherif *Elephas*

are not commonly preserved in museums, such as features and structures of sedimentary rocks, associated trace fossils, data from contiguous layers, etc. Therefore, urgent conservation of *in-situ* geosites is a priority.

Authorities need to consider that people are interested in these types of sites and are willing to support them at the local level because of the income, attention and educational opportunities they generate. As a result, they present an economic opportunity that serves to generate considerable income for the local population if this initiative will be accompanied by professionals hired to manage the site.

6.3 Discussion

During the inventory, 35 vertebrate paleontological geosites were inventoried. For the total value of the geosites, only 1 geosite had a total value less than 0 (Sv < 0) and 12 geosites had a positive total value (Sv > 0) which represents 34.2% of all geosites inventoried.

The selection of the four geosites studied in this work is based on the scoring of the criteria of representativeness, rarity and geological diversity (a score of 3). Indeed, the uniqueness of vertebrate paleontological geosites reflects the geographical position of the Middle Atlas chain during the

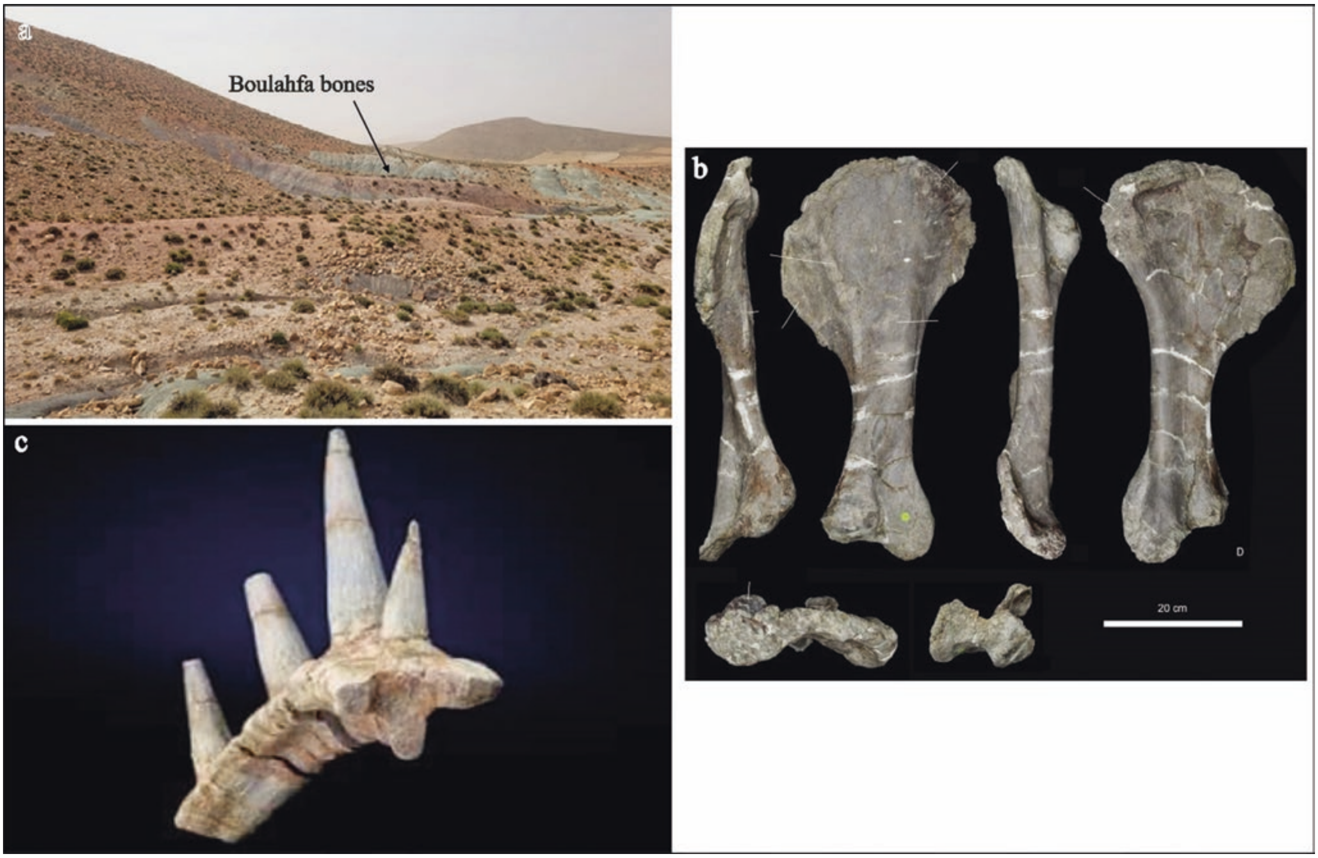

Fig. 6.3 (**a**) General view of the location of the bones of the Boulahfa geosite; (**b**) Left humerus of Boulahfa's stegosaurus. (Maidment et al. 2020); (**c**) *Spicomellus* rib. (Maidment et al. 2021)

Jurassic and Pleistocene. These 4 geosites all had an Ss ≥ 2.5 (Aït Bazza (Ss = 2.52), Ancherif (Ss = 2.52), Boulahfa (Ss = 2.52) and El Mers (Ss = 2.52)).

The sites selected, *in situ*, present footprints, bones of dinosaurs or mammals, from the Jurassic and the Pleistocene. The remaining geosites have been excluded from this description due to their similar intrinsic characteristics, which is why we have not duplicated their description multiple times. On the other hand, *ex-situ* sites have not been included in the inventory of these geosites such as museum collections and reconstitution exhibitions.

Despite the fact that no geosite had a high deterioration score, all the geosites are relatively degraded by human activity, due to the proximity of villages and infrastructures, and inducing the harvesting of the majority of bones (at except for the dinosaur footsteps) currently *ex situ*. These sites are endangered by economic development, construction, extraction and vandalism. Wild harvests unfortunately end up in museums abroad, like the remains of fossils from the Boulahfa geosite, exhibited at the Natural History Museum in London. On the other hand, the natural action has also altered their condition. This is the case of dinosaur footsteps found in the beds of Oueds which are permanently exposed to water erosion.

The results highlight these geosites with top priority for management due to their high scientific value and degree of deterioration. Although the geosites selected during the assessment of the degree of deterioration obtained a positive (Sv), we do not recommend these geosites for tourist uses because of their fragility and the difficulty of their preservation with respect to the action of looters and tourists.

6.4 Conclusion and Perspectives

Recognized for a century, the Middle Atlas is the subject of increased attention and offers geoscientists and paleontologists a vast field of predilection for one of the richest fossiliferous deposits in the country and even in the world. Vertebrate palaeontology in the region has thus made a consistent and decisive contribution to understanding and documenting the origin and evolution of numerous groups of vertebrates from the Jurassic to the Pleistocene.

Fig. 6.4 (**a**) Dinosaur footsteps crossing each other on the limestone slab of the Bou Akrabène-Ich Timellaline formation; (**b**) Location of El Mers dinosaur footsteps; (**c**) and (**d**) Footprints of theropod dinosaurs

Paleontological heritage or "paleontoheritage"is considered an indispensable resource in regional and national socio-economic development. Most paleontological work on vertebrates in the Middle Atlas is insufficiently researched. Faced with the degradation of several fossiliferous sites, it appeared necessary to carry out an inventory, as exhaustive as possible, and to make available as many of these sites as possible. The inventory of vertebrate paleontological geosites led to the inventory of 35 localized sites, almost all of them, in the folded Middle Atlas, 4 of which are described in this work. This inventory revealed a variety and diversity of specimens, bones and ichnites. These are specimens of *Cetiosaurus* sp., *Iguanodon* sp., Teleosauridae (*Steneosaurus* sp.), *Megalosauripus* sp., *Breviparopus* sp., *Lepidotes* sp., *Megalosaurus* sp., Testudinata, *Protocardia* sp., Ostreidae, *Elephas recki* (*recki*), *Adratiklit boulahfa* and *Spicomellus afer*.

Great progress has been made on the study of vertebrate paleontology in the Middle Atlas. Unfortunately, scientific research on these archives of life is often confused by the abusive exploitation that ends up some sites toward destruction. Therefore, it is necessary to restore a protection and conservation status to protect this *in-situ* heritage and limit any action to export *ex-situ* bones.

It is only with full knowledge of the facts that we can take the necessary measures concerning their safeguarding and their enhancement in a dual perspective of scientific and economic development. People must also be made aware of the richness of their heritage and the potential it offers for their development. Professionals, scientists and/or merchants, who know the value of this heritage must be held accountable, particularly in terms of sharing knowledge and specimens: collaborations must be encouraged, and areas of research multiplied.

The best strategy for safeguarding the paleontological heritage of the Middle Atlas is to integrate the local population in the management of paleontological sites through several awareness-raising accompaniments allowing a better knowledge of the scientific, cultural and territorial interest of the region. They are considered with the authorities as the first conservation partners. Their presence in the field is useful for information gathering, but controlling the mobility of heritage objects is a concern. They have a direct link to the conservation and protection of paleontological sites in the region, which requires a vast campaign to raise their awareness of these sites and ignore their interest for the community.

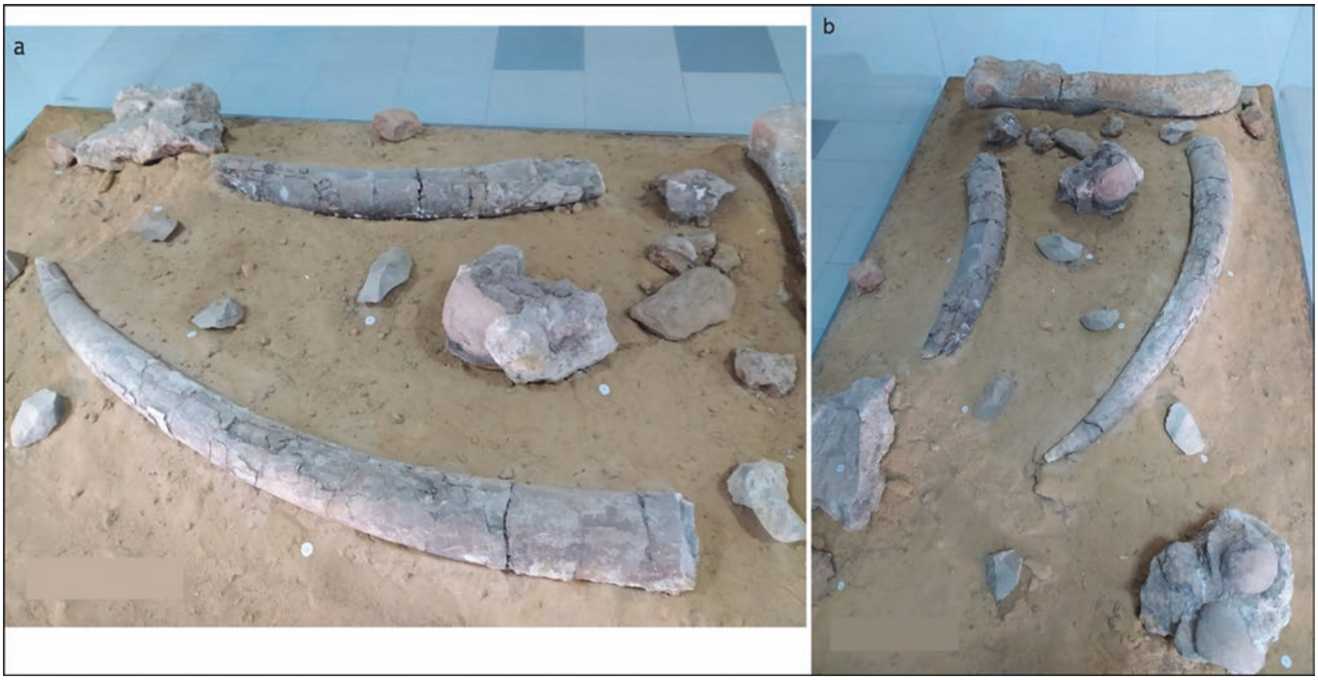

Fig. 6.5 (**a**) and (**b**) Elephas bones preserved in the Middle Atlas Heritage Interpretation Center (CIPMA)

The lack of local or regional museums dedicated to the preservation of paleontological heritage is a cause of anarchy, irregularities and destruction. Thus, the absence of a competent administrative structure, which can make legislative proposals, means that this type of heritage is marginalized and in degradation. However, the authorities must on their part take initiatives to set up a local or regional museum to represent the importance and rarity of this irreversible heritage.

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3D Virtual Visit of the Paleontological Site of Anchrif (Middle Atlas, Morocco): A New Perspective for the Enhancement of Geoheritage

7

Mustapha Amzil and Mostafa Oukassou

Abstract

Anchrif is an important paleontological and archaeological site located about 1.5 km to the West of the Taghrout village in the province of Fez-Boulemane (Middle Atlas, Morocco). It is a Pleistocene paleo-lake that has delivered several vertebrate fossils. Although the most common findings are elephants ascribed to *Elephas*, artiodactyls, turtles, and *in-situ* Acheulean tools were also collected. In this work, we use 3D reality capture solutions for the geomorphological reconstruction of this site. Aerial photogrammetry and terrestrial laser scanning methods will allow to move virtually on the site and access to augmented information. The results constitute a database for online virtual visit of this site and the visualization of the collected fossil specimens. This will bring new perspectives for the valorization of this heritage and its preservation in the form of a digital archive representing a support of value for the scientists and the general public offering varied experiences for education, enjoyment, reflection, and knowledge sharing.

Keywords

Reality capture · Geoheritage · Anchrif · Pleistocene · Middle Atlas · Morocco

7.1 Introduction

The paleontological heritage is increasingly becoming an important component of the cultural heritage. Over the years, the interest was given to purely static-conservative conception of the protection environmental geoheritage that puts everything under protection and that only allows the contemplation of the good. From this dimension, we have moved on to a more dynamic conception, oriented toward an experiential involvement of the public; this is because the cultural heritage, particularly geoheritage, is increasingly considered no longer as a heritage only to be protected but as something destined for public enjoyment and therefore experienced as a tool of cultural, educational, and economic growth of society (Fistola et al. 2020).

But when and how a paleontological site or geosite, in general, emerges from the shadows and anonymity, that the knowledge of a few experts assigns them and manages to enter in the collective cultural heritage, shared and recognized as a good with undisputed value and of which each citizen is a proud holder? In other words, what are the processes that need to be implemented because the promotion of a paleontological site, but also of a concept, a behavior, become effective and permanent and allows for a cultural growth? While it is more immediate to understand the importance of protecting fossils or meteorites or it is not yet sufficiently widespread the awareness of the geological heritage protection, often constituted by nonrenewable resources such as a waterfall, a caver, or a fossil level.

The use of geological heritage, particularly paleontological heritage, as touristic and educational sites, is everywhere an advantage for the local population and promotes scientific knowledge and geoeducation. In this study, we highlight an important paleontological and archaeological site that can significantly contribute to the education and development of geotourism.

Moreover, the paleontological site of Anchrif (Middle Atlas of Morocco) could be an example for all the other paleontological sites that use technological innovation and augmented reality as tools for promoting cultural heritage. The major role of 3D scanning and modeling by the different techniques (photogrammetry and terrestrial laser scanning) does not only lie in its capacity to provide documentation on the sites and objects, but also in its capacity to analyze the

M. Amzil (✉) · M. Oukassou
Faculty of Sciences Ben M'sick, Hassan II University of Casablanca, Casablanca, Morocco

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collected data. It is a real scientific tool, able to create plans and cross-sections, measure and even compare results. To do so, the elements that constitute the virtual visit – from the shooting to the creation of the 3D model – must be accurate. If this is the case, the 3D model and the orthophoto projections can be used as scientific documentation, preservation, and restoration of cultural heritage objects and sites. Technological innovation and augmented reality are even mentioned by UNESCO in their guidelines for World Heritage Sites management (UNESCO 2019).

7.2 Geological Setting

The Anchrif site is located near of the village of Taghrout in the Skoura syncline (Middle Atlas, Morocco) (Fig. 7.1). This area is characterized mostly by Middle Jurassic formations, more specifically of the Bathonian in age. These sediments, although limited throughout the Middle-Atlas accumulate in depressions located around the anticline ridge (Skoura, El Mers, and Marmoucha synclines) (Fig. 7.1b). These Jurassic basins formed due to the extension caused by the opening to the Tethyan Ocean between divergence of Europe and North Africa (Frizon de Lamotte et al. 2008). The uplift of the mountains themselves happened in the Cenozoic, with the possibility of some of that uplift being ante-Miocene (Babault et al. 2008; Charrière et al. 2011).

The Skoura syncline extends between the North Middle Atlas Fault (NMAF) and the Tichoukt anticline ridge and exposes formations ranging from Lower Liassic limestones to late Middle Jurassic regressive deposits (Dresnay 1963, 1969, 1975; Benshili 1989; Charrière 1990; Fedan 1993; Charrière et al. 1994; Oukassou 2018; Oukassou et al. 2016, 2019). In the Skoura syncline, the strata exhibit a gentle dip on the northwestern flank, whereas they are vertical or even overturned on the southeastern flank underlying the Jebel Tichoukt transverse fault. The axis of the Skoura syncline is traversed by the Oued Guigou, which cuts deeply into the Jurassic strata, and the meanders determine picturesque sites such as the perched Kasba of Taferdouste and that Ksar of Taghrout (Aldighieri et al. 2013). The Anchrif area described in this work is located at the west of the syncline axis at about 1.5 km West of Taghrout village (GPS coordinates N33° 28′ 59.79′W4° 37′ 02.76″) (Fig. 7.1b, c).

The Anchrif quarry is a small high-altitude sedimentary basin (50,000 m^2) with paleo-lake deposits, dated to mid-Pleistocene based on mammal material and hominid tools. The outcrops are located in a valley west of a bent in the Guigou river that passes just Southwest of Taghrout (Fig. 7.2a). This valley is around 20 meters higher than the current level of the above-mentioned river. The Quaternary sediments were deposited in the bottom of a paleo-lake whose dimensions should correspond roughly to the size of the valley that we have today, taking into account that is surrounded by modern valley topography of the Jurassic rocks (Marinheiro 2015).

The base of the formation is a detritic rock, a ferruginous conglomerate. The conglomerate is poorly sorted and most of the grains can be classified as fine gravel (not exceeding 3 cm in size). On top of the conglomeratic layer, soft carbonated sediments are found. The limestone strata have several hard concretions made by concentric layers of carbonates (Fig. 7.2b, c).

These concretions are mostly tube-like in shape and many exhibit an empty tube in their center and are more likely rhizoconcretions. It is possible the formation of the carbonated rocks should not be very different than it is today in a waterfall in the nearby town of Skoura (Marinheiro 2015).

In this area, the carbonates in the rocks are accumulated by freshwater algae and are deposited with the development of the algae colonies. The constant accumulation of carbonates forms layers of limestone over time and ends up forming the structures we can see today near the stream that feeds the waterfall. Anchrif concretions could be formed by the accumulation of carbonates using the same method in plant roots, which would explain the tube-like shape of these structures and the hollow interior (Marinheiro 2015).

The carbonated layers have a dip toward the center of the basin. As such the margins of the lake were at the time the carbonates were forming the top of the formation as steep as they are today (Fig. 7.2d, e, f). The inclination of the ground could have provided a natural trap for large mammals such as the elephants.

7.3 History of Anchrif Paleontological Site

In 2003, Mohamed Ikken and other young villagers from Taghrout discovered in Anchrif several large bones which were thought to belong to dinosaurs due to their large size bones and to the known Moroccan Atlas abundance of dinosaur remains. They announced the discovery to local officials and the regional Direction of Cultural Heritage of the Ministry of Culture. The information has quickly spread throughout the village and even beyond, and the rural community decided to ensure the place of discovery a permanent guarding.

At the request of the villagers in 2011, the Director of Moroccan Cultural Heritage accompanied by some specialists in the field visited the site to investigate the findings of 2003. Immediately, the scientific potential of the site was proven and it was decided to set up a multidisciplinary research program to better highlight the paleontological importance of Anchrif deposit, which could be a means of

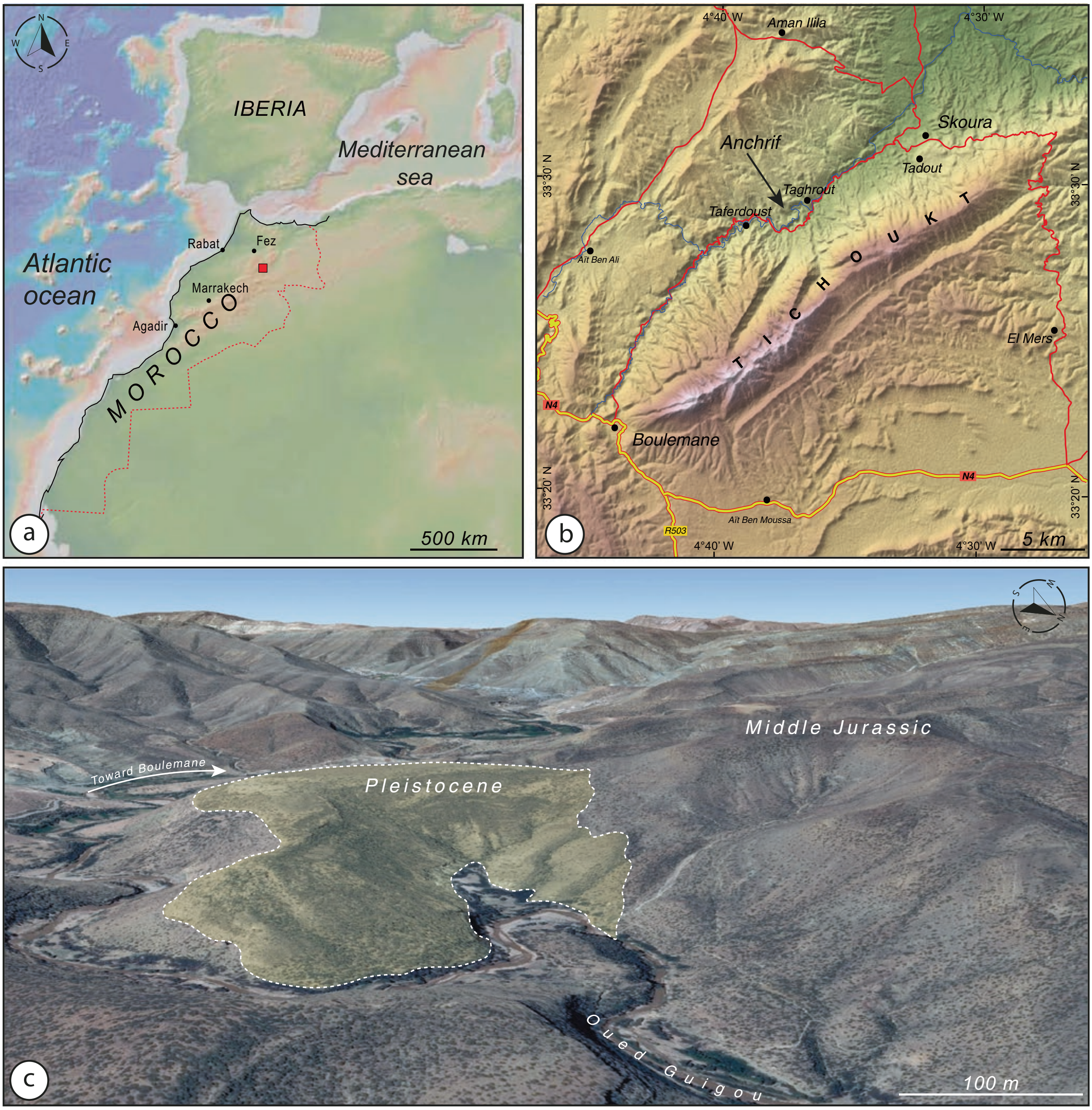

Fig. 7.1 Location of the Anchrif site. (**a**) Geographical map of Morocco. (**b**) Simplified regional geographical map of the vicinity of Anchrif (Middle Atlas, Morocco). (**c**) Landscape view, taken from Google Earth of the study site at Anchrif (Pleistocene paleo-lake) showing aspects of the local geology

raising tourism in the area, adding to a raise of importance to the region, besides the scientific research.

The Direction of Cultural Heritage has, therefore, set up through the *Institut National des Sciences d'Archéologie et du Patrimoine* (INSAP), a research program supported by a cooperation agreement established between INSAP and the Nova University Lisbon of Portugal. The two parties have formed a mixed multidisciplinary team and a preliminary visit to Anchrif was planned and made on March 23rd, 2013.

This field mission of March 2013 consisted essentially of methodical excavations in sectors offering tangible evidence of important paleontological remains. The preliminary results of these investigations have immediately invalidated the hypothesis of the existence of dinosaur bones as previously disclosed, but on the other hand, they have allowed to highlight the existence of paleontological riches in the form of bones of *Proboscideans* (an ancient species of elephants) (Mateus 2013).

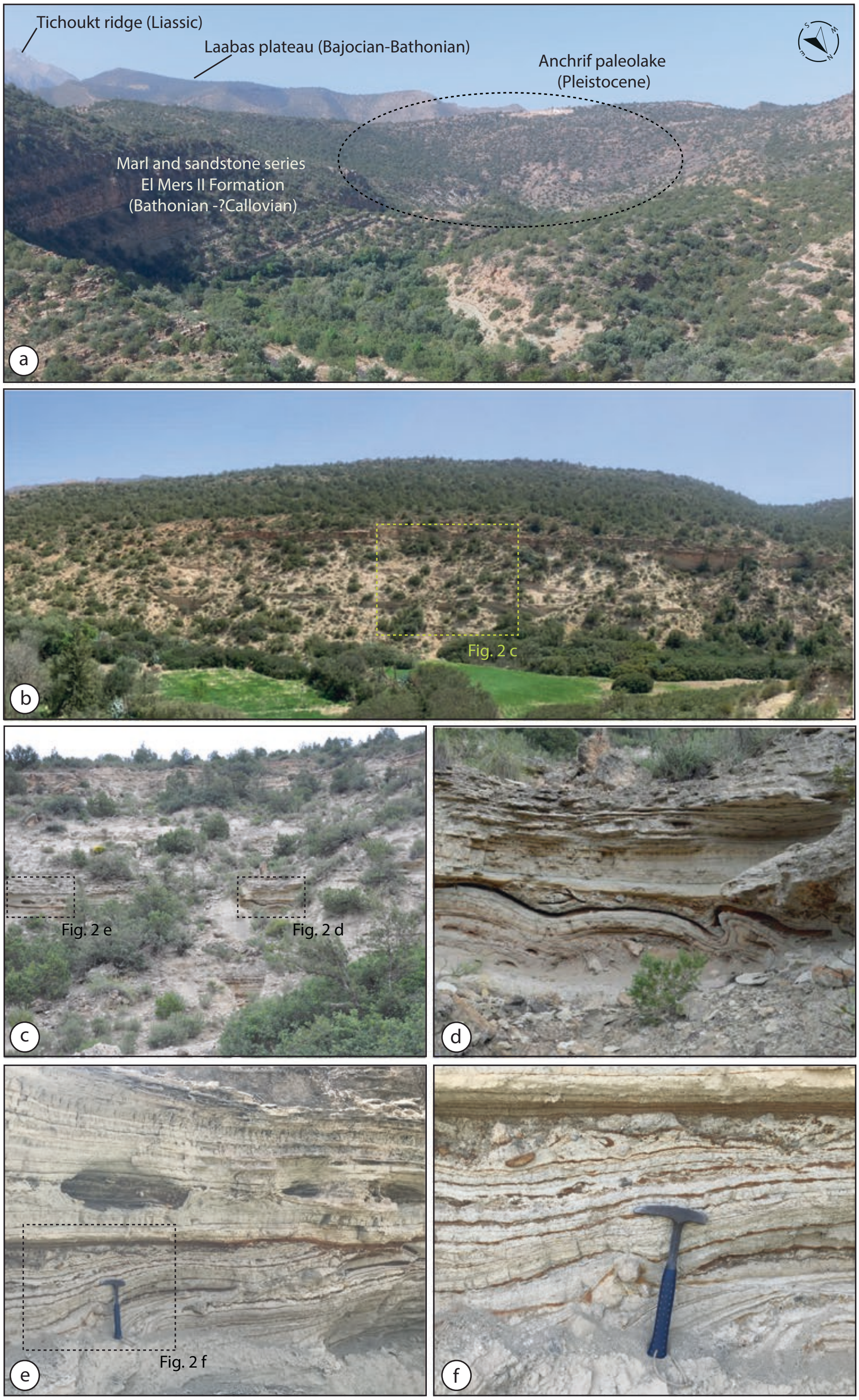

Fig. 7.2 (**a**) Panoramic view from the Northwest over the Anchrif sedimentary basin, near Taghrout, Morocco. (**b**) General view of the Anchrif dig site as seen looking North to South. The whitish beds on the cliff-side correspond to the Pleistocene layers. (**c**), (**d**), (**e**) and (**f**) characteristics of the Pleistocene lacustrine deposits of Anchrif

In September 2013, a protocol was signed between the Direction of Cultural Heritage of Morocco and the Nova University of Lisbon in order to establish the cooperation of the two institutions in the paleontological and archaeological study of the Anchrif locality and the surrounding Middle-Atlas region (Atlas Mémoire Project, Alaoui et al. 2016).

Field work was scheduled for late September (18th–26th) 2013, a Moroccan-Portuguese expedition made excavations on the site with the help of locals from the village of Taghrout (Fig. 7.3a, b). The excavations yielded new bone material from large mammals. The most common findings are elephants ascribed to the genus *Elephas*, but artiodactyls, turtles, and *in-situ* hominid Acheulean tools were also collected.

Partial results of this research were published in form of scientific communications (Marinheiro et al. 2014a, b) and a Master's dissertation (Marinheiro 2015). This site was also part of a geotouristic trail including other geosites reflecting the geological, geomorphological, and environmental history of the Boulemane-Skoura area (Oukassou et al. 2019). Since this time several educational visits of high schools and universities are organized at the site given its importance due to its educational and pedagogical aspects.

After the inauguration in 2016 of the *Centre d'Interpretation du Patrimoine du Moyen Atlas* (CIPMA) housed in the Cultural Center of Azrou (Alaoui et al. 2016; Lazhar 2019), the Elephantidae material collected during the expeditions is part of the permanent public exhibition of the pavilion dedicated to natural heritage (Fig. 7.3d). It should be noted that other bones, some of large dimensions were left in the site to be dug out in a later date (Fig. 7.3c).

Fig. 7.3 (**a**) Moroccan-Portuguese scientific team that provided the excavation work during the 2013 field trip, note the two elephant tusks at the researchers' feet. (**b**) J. Russo and J. Marinheiro (Nova University Lisbon, Portugal) during the 2013 excavation. (**c**) Bones, some of them large, were left at the site until the present day. (**d**) Permanent public exhibition of elephantidae material collected during the expeditions at the *Centre d'Interprétation du Patrimoine du Moyen Atlas* in Azrou, Morocco

7.4 Methods, Equipment, Software, and General Workflow

Terrestrial laser scanning (TLS) in combination with Unmanned Aerial Vehicle (UAV) and modern computer-based photogrammetry is currently the best approach for the acquisition of high-resolution 3D spatial information. Highly realistic 3D spatial data sets are becoming the basis for detailed geological studies, providing a multidisciplinary approach in the study and research of both underground and above-ground sites.

Due to the value and potential of the Anchrif paleontological site, one of its main objectives of the work was to produce comprehensive documentation of the entire site with the highest possible degree of accuracy and detail. The proper selection of technologies, equipment, software, and workflow was fundamental to the success of the 3D virtual visit of the site (the entire site is ca. 50,000 m^2; Fig. 7.1c). In this work, we combined two 3D data acquisition techniques: UAV photogrammetry to generate the digital surface model and TLS to obtain the accurate point cloud and 360° views (Figs. 7.4 and 7.5). Subsequently, the 3D virtual visit of the Anchrif site was realized using the Arskan silo-data platform, which aims to enable the compression, visualization, management and online sharing of massive 3D data.

7.4.1 UAV Photogrammetry

Digital surface model (DSM) generation is essential to recreating the paleo-lake of Anchrif geomorphology. In this work, the DSM is obtained by using unmanned aerial vehicle (UAV) equipped with a stabilized visible light camera for the images to be photogrammetrically correct (Gašparović and Gajski 2016). This approach is efficient and necessary to allow rapid land survey with high accuracy. For this work and the creation of a 3D model of the Paleo-lake, we used the DJI Mavic 2 Pro (MP) aircraft which is of the rotating wing type (Fig. 7.4e). The major advantage of rotating wing drones is the possibility of vertical landing and take-off and the ability to capture terrain and objects with horizontal and oblique measuring axes (Jiménez-Jiménez et al. 2021; Mulahusić et al. 2022). For the flight planning and image acquisition, we used the Pix4D flight application installed in the Android operating system of the controller (Fig. 7.4f). As for the autopilot shooting mode, one regular mission, that took 18 minutes, was made at the height of 150 m above the ground in order to better represent the shape of the paleo-lake, using GSD (Ground Sample Distance) of 3.51 cm/pixel (Fig. 7.6a). A total of 158 photos covering the entire site were taken by the drone in a single acquisition mission. It should be noted that before the flight with the UAV, the calibration of the aircraft was done in terms of checking all the necessary parameters.

After all the necessary data was collected, the photographs were imported into a photo-based 3D reconstruction software package using 3DF Zephyr Aerial Education version 6.5.0 (www.3dflow.net). The processing steps are as follows: firstly, the importing of raw data (images) in the software; and overlapping images by Structure from Motion (SfM) method (Fig. 7.5). Subsequently, camera calibration in the software (determination of internal orientation parameters); and generate a dense point cloud. Then, importing and combining the 3D point cloud of the laser Scanner RTC360 and the drone using Multi-ICP (Iterative closest point), an algorithm employed to minimize the difference between two point clouds. Multi ICP algorithm allows to merge and colorize multiple point clouds as needed (Fig. 7.6b). Finally, after the rough alignment of point clouds has been completed simply we proceed to photogrammetry processing to generate the high-definition textured mesh (Fig. 7.6c).

7.4.2 Terrestrial Laser Scanning

Before starting the scan acquisition mission, we carried out a reconnaissance visit of the Anchrif paleo-lake in order to avoid obstacles and optimize the number of scan setups then to focus on the main excavation areas. The Leica RTC360 Laser Scanner (Fig. 7.4b, c) was used for the 3D terrestrial lasergrammetry mission. This high-speed scanner (up to 2,000,000 pts./s) has a range of up to 130 m and a High-Dynamic Range (HDR) spherical imaging system composed of 3 cameras of 36 Megapixel and a video inertial measurement system VIS (Visual Inertial System). The purpose of this system is to determine the relative position and orientation between two consecutive scan setups. Based on the relative positioning, the point cloud of the second captured setup can be transformed in the coordinate system of the first. The RTC360 was mounted on a carbon tripod, which makes it easy to move from one setup to another (Fig. 7.4d), as there is a lot of vegetation and the terrain is very rough. The scanner was connected, via a Wifi generic network, with Cyclone Field 360 a free mobile application (www.leica-geosystems.com) installed in the smartphone in order to control, check and adjust alignments of the setups point clouds and immersive images in the field (Biasion et al. 2019).

The field registration workflow (Fig. 7.5) of the RTC360 solution allowed to access directly and rapidly to scan registration in the field. 32 scan stations were placed over the entire site in 2 hours. Each station covered a horizontal range of 360° with a resolution of 6 mm at 10 m. This assured proper overlapping of scans and appropriate density of recorded data (Fig. 7.7).

Fig. 7.4 (**a**) Fieldwork at the Anchrif geosite and 3D data acquisition equipment. (**b**), (**c**), and (**d**) 3D terrestrial laser scanning by Leica RTC360. (**e**) and (**f**) Geotagged aerial imagery by the unmanned aerial vehicle DJI Mavic 2 Pro

At the end of the field operations, the collected data is transferred from the RTC360 to an office PC. The multiple scans of the paleo-lake need to be combined and edited. This was done using Leica Register 360 software version 2022.1.0 (www.leica-geosystems.com), with a simple drag and drop and which is used to fine-tune the alignment of scan positions and clean the point clouds by deleting specific sets of unwanted points. During the import, several steps of data processing are running. Filters are applied, as mixed pixels and oversaturated points filter. The raw data is processed, with the creation of the panoramic images overlapped on the colored point clouds. Finally, we performed the alignment check of the scans and the quality of the images (Biasion et al. 2019).

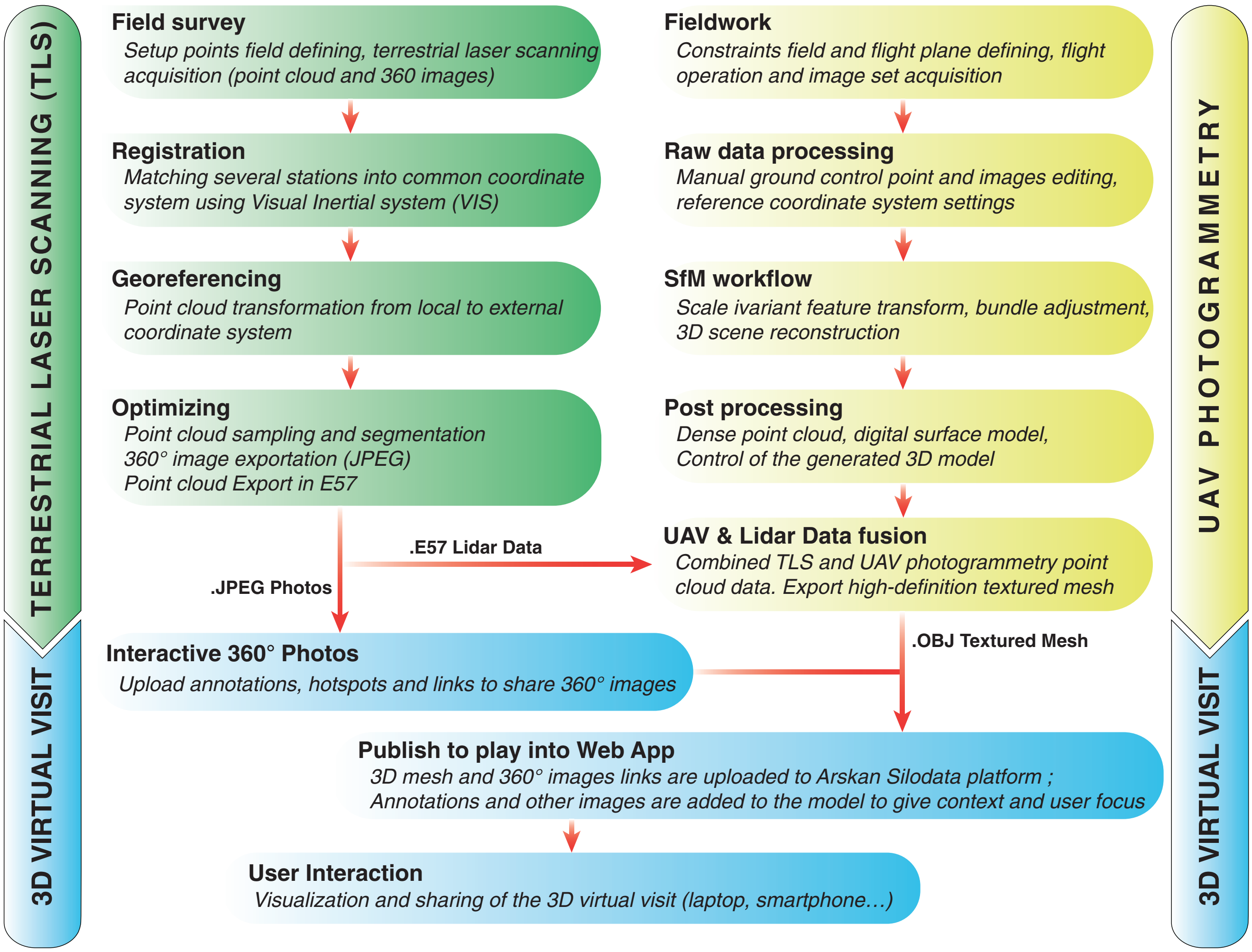

Fig. 7.5 Flowchart showing the workflow for creating the 3D virtual visit of the Anchrif site

7.4.3 3D Virtual Visit

The integration of interactive 360° images in the 3D virtual visit is important, as it allows to have a detailed commented panoramic view of the site. For this, we have used the free online software Momento360 (www.momento360.com). It is the easiest way to make the most of all 360° images and videos through uploading, viewing, and sharing 360° photos and videos all in one place, all from the browser. We have generated links for each 360° image to integrate them into our 3D model of the Anchrif virtual visit.

Finally, to create a 3D Virtual visit model, the textured mesh from 3DF Zephyr was imported into the ARSKAN Silodata platform (www.silodata.arskan.com). It's a collaborative 3D visualization platform to visualize and use massive 3D models; upload and manage 3D data; create secure silos; visualize on PC, Mobile, and VR headset. The imported model is an object file that was combined with the geological data (images, annotations, etc.) extracted from the field investigations, bibliographic review, and from 360° image links, giving a true 3D geological terrain model. Any additional data, such as logs, fossils, and other geological surveys can be added at this stage. The Silodata consists of the scene where digital textured surface models and spatial data are placed to build a virtualized 3D environment which users can interact with. The construction of those scenes varies depending on the visualization context (ground scale, annotations, clipping box, measurements, etc.), to display only relevant information. The main goal of the user interface design is to provide users with a natural interaction experience, including movement dynamics; pointing and selection, immersive data visualization; and scene navigation and measurement tools.

7.5 Results and Discussions

Virtual reality (VR) has been booming since late 2019 after the Covid-19 outbreak and lockdowns, more and more people started to embrace advanced technology in several

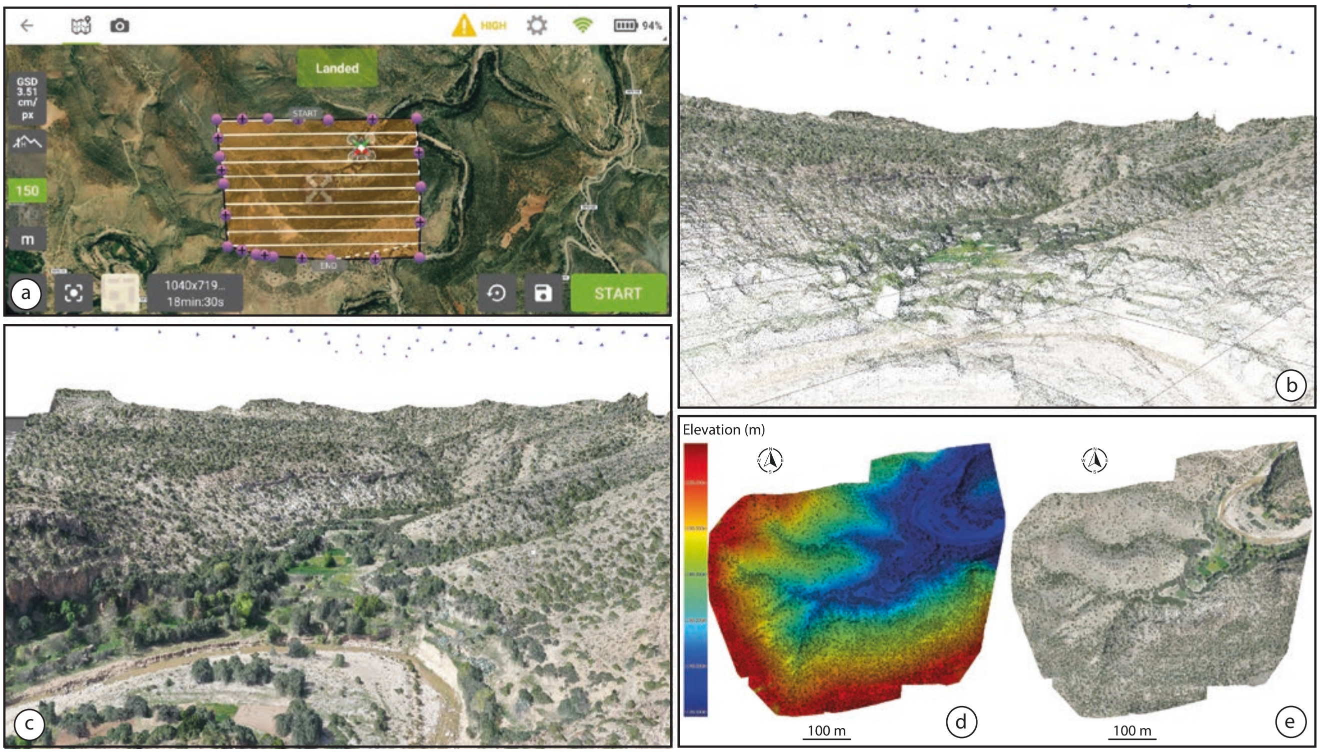

Fig. 7.6 UAV photogrammetry of Anchrif site: (**a**) Screenshot of the pilot application (Pix4D) from the smartphone showing the flight plan and its parameters. (**b**) Colored point cloud. (**c**) High-definition textured mesh. (**d**) Digital surface model. (**e**) Orthophoto

Fig. 7.7 Terrestrial laser scanning of Anchrif site: data preview of survey network and distribution of scanner stations in the import area of Cyclone REGISTER 360

domains. In fact, virtual reality is now one of the prime technologies in demand. The most significant form of VR technology today is virtual reality tours or simply virtual visits. They are frequently used as a tourist and commercial support; however, they offer many possibilities in the field of culture and heritage. Thus, a virtual visit can be a way to discover an exceptional place, a geotouristic site or fossils, meteorites, caves, etc.

In this work, given the difficulty of the relief and the access to Anchrif site, the presence of the guide Mr. Ikken throughout our visit has facilitated us essentially to find the exact location of the excavated areas of fossils. Our focus was to digitize the entire Anchrif paleo-lake and particularly to take 360° views of each excavated area.

The preparation of the site by defining the location of the 3D scanning setups and the location of the launching platform of the Drone allowed us to optimize the time of intervention on the field and to collect reliable and exhaustive data as planned for this project.

The processing of the reality capture data is becoming faster and faster thanks to the improvement of the performance of the processing workstations and in particular of the calculation algorithms. The data collected using the 3D laser scanner Leica RTC360 and the drone DJI Mavic 2 Pro were processed in a workstation with the help of the software Leica cyclone Register 360 and Zephyr 3D Flow, the exploitation of the results of the assembly of lasergrammetric and photogrammetric data after testing several desktops and web applications for sharing and pooling 3D data, we chose the Arskan SiloData platform.

Arskan SiloData provides very advanced 3D model visualization compression features that make it easy for the end user to navigate through his models on any mobile device or computer. In the Anchrif 3D model visualization space, the user can navigate through the 3D model in full immersion, measure, create cross-sections and then use the 360° photos to visit each excavation point. The annotations provide a wealth of information related to the paleo-lake such as scientific articles, videos, and photos of bones taken on the site at the time of excavation and also of the fossils we found on the site during our visit. All this information can be used by scientists and students to make their first visit to discover the history of the site, and it constitutes a non-destructive safeguard of this geological heritage. It is a new tool to raise awareness and promote these sites with online heritage values, which allows and continues to keep alive the legacy left by history.

However, the interest of virtual visits in the heritage and geological heritage in particular, is not only to "show or visit." Virtual visits offer a privileged access to informative content: 3D Models, text documents, Measurements, videos, soundtracks, 360° images, illustrations, photos, plans, dia-

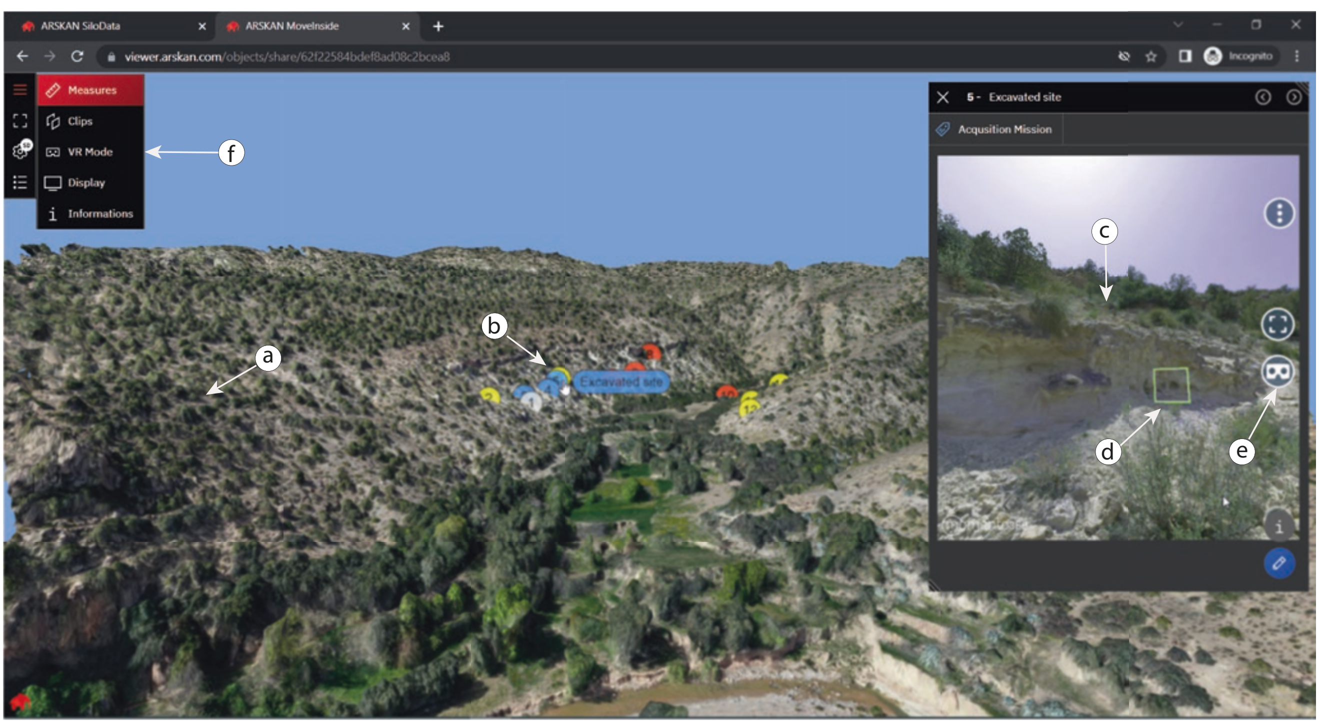

Fig. 7.8 Screenshot of the virtual visit application of Anchrif site via Arskan SiloData platform and these components on the web browser: (**a**) 3D model of Anchrif paleo-lake. (**b**) Annotation. (**c**) 360° image. (**d**) Illustration. (**e**) VR virtual reality mode. (**f**) Tools

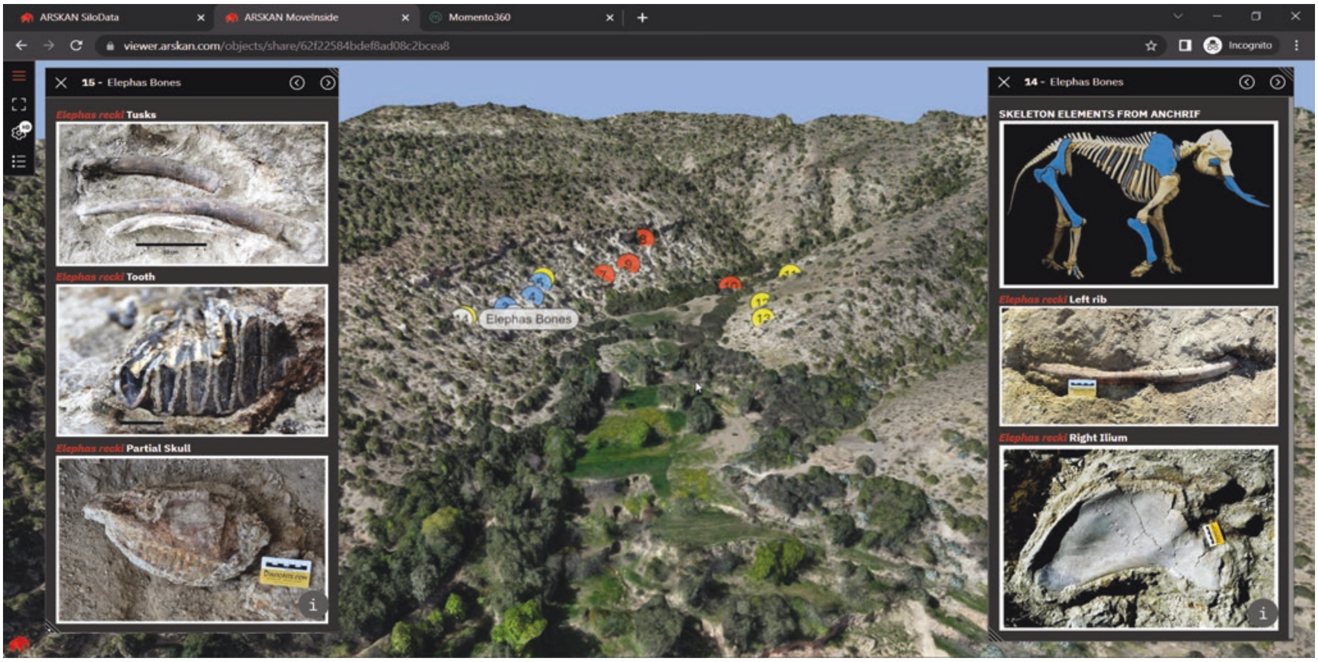

Fig. 7.9 Screenshot of the virtual visit application of Anchrif site via Arskan SiloData platform with example of shared data types

grams, etc. (Figs. 7.8 and 7.9). A lot of scientific information can be added to the visit and enrich it by transforming it into a real interactive guided visit on a simple viewer or by using a VR headset for more immersion and interaction with all the data added.

In this reality, the observer uses more than just sight to experience something real and memorable. Thanks to 3D digital models and new technologies allowing interactive exploration, the "passive" viewer becomes an "active user" who decides what to see and what paths to take, and to interact with objects or virtual environments, sharing their sensations and opinions; in this way, the experience remains in the visitor's memory (Barrile et al. 2022).

Digital preservation can be seen as all those processes aimed at ensuring the continuity of digital heritage materials for as long as they are needed (UNESCO 2002). In fact, using the reality capture solution to digitize geological heritage sites allows them to be timelessly preserved when they may be destined to disappear.

As a perspective of this project, we plan to provide this realization to the Center of Interpretation of the Heritage of the Middle Atlas in Azrou in order to benefit from it as an educational support of the pavilion of the natural heritage of the center and to sensitize and encourage the visitors of the museum and the tourists to go physically on site to discover it, which will create a social and economic dynamics in the region. The 360 virtual visits represent a real benefit for tourism professionals. A virtual tour of this kind will never replace the real trip, but it will give the traveler a taste of the next destination and initiate positive emotions toward it, even before planning the trip.

7.6 Conclusion

Paleontological geosites are privileged windows for scientific studies. In the Middle Atlas, Anchrif paleo-lake comprised of Pleistocene deposits in one site is deeply relevant for its paleontological and archeological heritage.

Generally, permanent exhibitions, teaching, and dissemination activities, fieldtrips, and geotourism are the base for the valorization of geosites. Recently, the use of 3D technological innovation would increase the interest in the public converting paleontological geosite in an open-air virtual museum and opens up immense perspectives for educational activities related to the paleontological heritage.

A 3D virtual visit is here suggested, in order to promote and valorize this site. Based on aerial photogrammetry and terrestrial laser scanning methods, will allow the visitors to move virtually in the museum, in the field, or even at home and access to augmented information projecting virtual reconstructions on the background of a real environment. The platform hosting the virtual visit can be fed with informative and didactic documentations on the site to disseminate information about the history of paleontological discovery at this foremost geosite.

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Part IV

Hydric Heritage

Hydric Geosites of Middle Atlas: A Natural Heritage Under Threat

8

Khaoula Baadi, Bernard Lebreton, and Paulo Pereira

Abstract

Renowned as the 'water tower' of Morocco, the Middle Atlas is the richest Moroccan mountain chain in surface and underground water resources. These resources largely contribute to the water supply essential to the socio-economic development of the region. To reveal these water resources, being part of the natural heritage, 128 water geosites have been inventoried of which 12 (9.3% of all geosites) have been selected as reference sites of the subject in the Middle Atlas. These 12 geosites have characteristic features implementing tourism and educational initiatives, attracting more visitors, while aiming to avoid their degradation through appropriate sustainable management. The irregularity of these resources, in certain areas, constitutes a limiting factor for the socio-economic development of the region due to the unsustainable use and management of the water potential. They are threatened by the effects of climate change on the one hand and irrational use due to human action without a strategy guaranteeing the sustainability of this resource. These threats deteriorate the scientific value of these geosites. It essentially appeared to present different factors altering this irreversible heritage for all the inventoried geosites.

Keywords

Natural heritage · Hydric geosites · Inventory · Threat of degradation · Middle Atlas

K. Baadi (✉)
Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, Fez, Morocco

B. Lebreton
French Speleology Federation, Lyon, France

P. Pereira
University of Minho, Braga, Portugal

8.1 Introduction

The Middle Atlas is considered to be the 'water tower' of Morocco, as it is the richest Moroccan mountain chain in surface and underground water resources. It contributes largely to the supply of water essential to the socio-economic development of the neighbouring plains. On the one hand, in these plains, many rivers originate in the Middle Atlas, and on the other hand, the groundwater is fed mainly from the hydrogeological basins of this chain.

Since the 1950s, the Middle Atlas has been the subject of numerous scientific works that cover water resources topics, such as sedimentological (Baali 1998; Benkhadour et al. 2008; Détriché et al. 2009; Etebaai 2009; Damnati et al. 2016), hydrokarstic (El Khalki and Akdim 2001), hydroclimatic (Benkaddour 1993; Obda 2003; Sayad et al. 2011; El Hamouti 2014; Nourelbait et al. 2016), hydrogeological (El Fartati et al. 2019), hydrochemical (Adallal et al. 2019), tectonic (Hinaje and Ait Brahim 2002; El Fartati et al. 2019), mineralogical (El Fellah Idrissi et al. 2009; El Ouali et al. 2011), ecological (Chillasse et al. 2001; Chillasse and Dakki 2004; El Hamouti et al. 2016), paleoenvironmental (Rhoujjati et al. 2012) and limnological (Gayral 1954; Dumont et al. 1973; Chergui et al. 1999).

Research on the water heritage of the Middle Atlas concerns both the inventory of wetlands (Chillasse et al. 2001) and the inventory of springs and lakes (Malaki 2006; Baadi 2021).

Since 1942, several national parks have been created in order to protect Morocco's natural heritage and more specifically its water resources. Three national parks were created in the Middle Atlas: the Tazzeka National Park (TNP) in 1950, the Ifrane National Park (INP) in 2004 and the Khénifra National Park (KNP) in 2008.

In 1995, national level reforms led to the Water Law (Law 10-95), laying the foundations for integrated and decentralised management of water resources, with the creation of watershed basin agencies. The country's policies regarding

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this law are based on the management and preservation of water resources through the integration, strengthening and adoption of strategies to preserve surface and groundwater resources.

Several attempts to inventory the wetlands (lakes and springs) of the Middle Atlas have been made. In 1996, the Master Plan for Protected Areas initiated an inventory of nineteen wetlands in the Middle Atlas, 16 of which are classified as Sites of Biological and Ecological Interest (SIBE) and three as RAMSAR sites. In 1997, the establishment of a vision for water management was launched at the First World Water Forum in Marrakech. In 2002, a new water policy was defined and a reform of the water sector was launched. This reform focuses on demand management, user participation and de-pollution at the watershed level. In 2009, a new water resources management policy was launched to address the most urgent problems and to make water a decisive factor for sustainable development. This strategy is based on tools such as the National Water Plan, which aims to preserve and protect water resources (safeguarding and replenishing groundwater, protecting the quality of water resources and combating pollution, safeguarding watersheds, oases and wetlands), reducing vulnerability to water-related risks (drought and flooding) and adapting to climate change.

In spite of these strategies and plans, the water resources of the Middle Atlas are, for the time being, in constant decline. The irregularity of these resources, in some areas, constitutes a limiting factor for the socio-economic development of the region due to an unsustainable use and management of the water potential. In this chapter, this valuable resource is presented as a natural heritage that should be valorised through conservation strategies and also through its touristic and educational use in a sustainable context. Water is understood as a fundamental element of geodiversity and the most valuable hydric sites (springs, lakes and waterfalls) from a scientific point of view are considered as geosites.

8.2 Water and Climate in the Middle Atlas

The high altitudes (Fig. 8.1), the particularly favourable climatic factors and the relatively complex structure of the karstified Liassic fields have allowed the genesis of an immense water potential of the Middle Atlas chain.

Essentially on its western and north-western side, the Middle Atlas receives oceanic atmospheric currents charged with humidity, allowing the triggering of rain and snow precipitations. Nevertheless, a decrease in precipitation can be observed from the NW to the SE where semi-arid climate zones are reached with continental influences from eastern Morocco. Karstification, coupled with the fracturing of the carbonate fields and the presence of impermeable Triassic fields, has led to the formation of resurgences and depressions of varying sizes, at the centre of which are endoreic lakes. The hydrosystems of the Middle Atlas are generally characterised by important variations in their level and by their non-negligible underground water flows due to their karstic nature (Lamb et al. 1999). From a structural point of view, four main tectonic episodes from the Upper Miocene to the Middle-Upper Quaternary were responsible for the genesis and evolution of the Middle Atlas fluvio-lacustrine basins (Hinaje 2004; El Fartati et al. 2019). The surface and subsurface hydric flows of the chain were also affected by the presence of volcanism and faults, causing adjustments in flow directions.

All these factors have given rise to a significant water potential, expressed by several springs, rivers, waterfalls and lakes. The predominance of surface water generates a multitude of permanent springs, generally with a high flow rate. Freshwater springs, salty or thermal, emerge on the surface at the level of geological accidents and at the edges of the contact of the Lias carbonates with the impermeable Triassic clays (Bentayeb and Leclerc 1977) in the form of resurgences (for example, Ras El Ma, Sidi-Rached, and Oum Er-Rbia springs). The freshwater springs, rich in calcium carbonates, originating from the Lias carbonate reservoir, have an average flow rate of 11–13 m/s^3 and a salinity of less than 700 mg/l. They are characterised by a high representation of waters with a calcic and magnesium bicarbonate facies (El Ouali et al. 2011). On the other hand, saline water springs, rich in chlorides, sulphates and sodium, are linked to Triassic fields rich in evaporites (Kabbaj and Combe 1977) with a flow rate of 0.5 m/s^3 and cause an increase in the salinity of the mixture (1200–1400 mg/l) (Adallal et al. 2019). Some deep aquifers are the source of thermo-mineral springs (like the Aïn Skhounate springs). These sometimes correspond to mixed circulations, as in the cases of Trias/Lias discharge springs such as Tiguelmamine, Aghbal, Tit Maregh and Aghbalou Maregh emergences (El Khalki and Akdim 2001). Some emergences occurring on Liassic rocks form notable waterfalls like those of Sefrou (30 m), Ras El Ma (30 m), Zaouiat Ifrane (25 m), Aït Smaïl (20 m), Charchoura (20 m), Sabhab (20 m), Skoura (12 m) and Aïn Vittel (10 m).

There are 41 lakes in the Middle Atlas, about half of the permanent and semi-permanent natural lakes in Morocco. Three main types of lakes occur: tectono-karstic lakes (the majority), located in doline or uvala collapse depressions with fluvio-lacustrine filling, where the waters of one or more underground water tables outcrop (Ramdani and Tadili 1980; Charrière 1990); natural dam lakes, such as Guelta Tameda lake, which natural dam resulted from the collapse of Liassic rocks; crater lakes, such as those of Lechmine Ouanou and Lechmine Tajine, which are located in volcanic craters that fill up during rainfall.

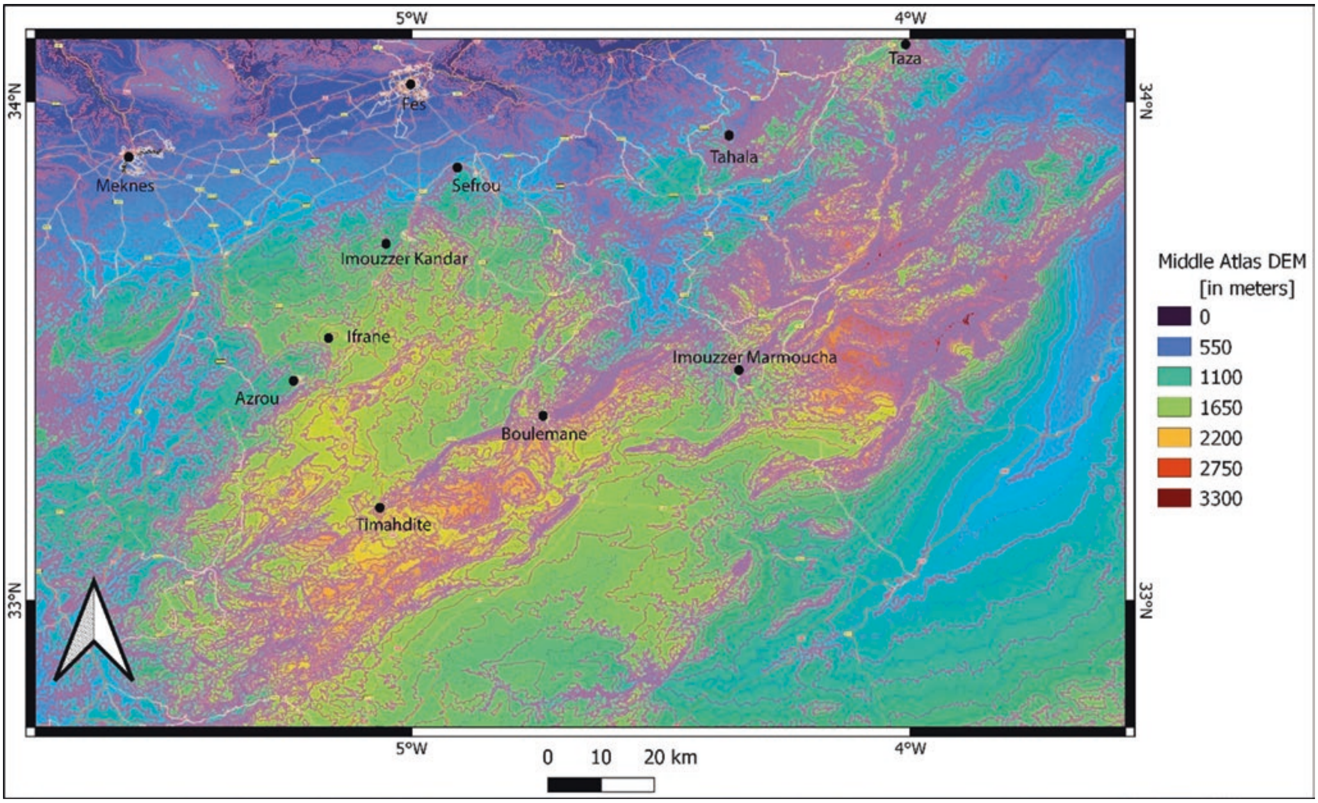

Fig. 8.1 Middle Atlas DEM and contourlines (100 m)

The lakes are located between 1000 m and 2200 m of altitude, in a subhumid and humid bioclimatic stage with a cold winter and a strong Mediterranean influence, which experiences huge precipitation (rain and snow). The high altitude of the Lias carbonate outcrops favours their supply by precipitation and snowmelt. Tectonics, combined with karstification and the presence of evaporite clays, have played a determining role in the construction of the lakes in the Middle Atlas. The main faults, oriented NE-SW and combined with an important network of submeridian fractures, have intimately controlled their formation (Hinaje 2004). The lakes are mostly endoreic and without an outlet, corresponding to speleogenetic overburden basins (Kirat et al. 2016). They are considered as gigantic rain gauges sensitive to climatic variations (Benkaddour 1993), whose water temperature never falls below 10 °C, either at the surface or at the bottom, with a sole period of mixing in the cold season and a period of direct stratification in the warm season.

Recent climate change is well known in the Middle Atlas, evidenced by the variability of the Holocene climate (Cheddadi et al. 1998) and particularly the most recent evolution, during the second half of the twentieth century. The average annual data indicate a warming of about 1.5 °C in 50 years and a significant drop in precipitation, around 100 mm, especially since the end of the 1970s (El Jihad 2016). The consequences of these climatic changes lie in the decrease in river inputs by 20–30% (Chaponniere and Smakhtin 2006; Belhassan et al. 2010) and there are worrying predictions that proclaim a warming of 4–6 °C and a reduction in precipitation of 20–60% by 2071–2099 (El Jihad 2016). Immerzeel et al. (2011) consider that meeting all of Morocco's water needs by 2050 would be problematic regardless of future climate change. The deficit would be critical in the plains and the coasts, where imposing water needs strongly interfere with the river inflows from the Middle Atlas, which are already affected by climate change. Moreover, the mobilisation of river inflows by dams is already affected by the siltation of their reservoirs (Taabni and El Jihad 2012).

Current conditions for the use of water resources are marked by an increasing demand, generated by the demographical and economic development of the country. In addition, the extremely severe and long droughts experienced in the region in 2021 and 2022 are of great consequence on the water resources.

Several streams, springs, lakes and waterfalls were severely affected, resulting in significant drops in water levels, sometimes going as far as total drying up, as in the case of Dayet Aoua and Hachlaf lakes. These changes coincide with the introduction of agriculture using groundwater pumping, and the unsustainable use and overexploitation of groundwater for tourism projects.

The degradation of water resources in the region, accentuated by climate change, is a threat to these elements of geodiversity, raising high concerns on their conservation and sustainable use. It therefore makes sense to consider these water resources from a natural heritage perspective, making an inventory of hydric sites and selecting the best examples due to their importance as a local water resource and for their scientific value. These sites (hydric geosites) are considered as witnesses, at different spatial and temporal scales, of geomorphological, tectonic, hydroclimatic, limnological, anthropic and biodiversity changes in the Middle Atlas. They include information that can explain their functioning and the existing interactions between the numerous biotic (ichthyofauna, macrophytes, invertebrate communities) and abiotic (physical and chemical, water/sediment) compartments. They are also vulnerable systems highlighting the risks for the environment and human health (water level decrease, siltation, acidity, toxic contamination and eutrophication).

The proper management of these sites must therefore recognise their dual importance. On the one hand, they are essential sites for the social and economic development of the region, supporting agricultural, industrial and tourism activities. On the other hand, these same activities and climate change have contributed to their degradation, conferring on them needs for conservation and sustained management. In this sense, its condition as natural heritage sites (more specifically as geosites) will be fundamental for the implementation of conservation and sustainable management measures.

8.3 Hydric Geosites

A total of 128 hydric geosites were inventoried in the Middle Atlas (Fig. 8.2 and Table 8.1), supported by literature research, photography and cartography analyses and by fieldwork. The inventory took into account the importance of the hydrological functioning of the sites, as well as their flow, extent, genesis, morphology and geological and biological diversity. It was carried out in 2020 and was updated in 2021, during which several geosites have been noted to lost some of their scientific value.

A selection procedure was applied to the inventoried sites, using a quantitative methodology supported by scientific value criteria (Table 8.2). Twelve hydric geosites have been selected, regarding the scores obtained in representativeness, rarity, degree of preservation and geological diversity criteria (Fig. 8.2; Tables 8.2 and 8.3).

9 of the 12 selected geosites obtained a scientific value score of Ss ≥ 2.5: Aguelmam Sidi Ali (Ss = 2.76), Guelta Tameda (Ss = 2.76), Oum Er-Rbia (Ss = 2.76), Ras El Ma (Ss = 2.76), Aghbalou Aberchane (Ss = 2.58), Lac Afourgagh (Ss = 2.58), Tiguelmamines (Ss = 2.58), Aïn Sebou (Ss = 2.52) and Aïn Skhounate (Ss = 2.52). The remaining 3 geosites obtained a scientific value score of 1.5 ≤ Ss < 2.5: Dayet Ifrah (Ss = 2.38), Aguelmam Azegza (Ss = 2.34) and Zaouiat Ifrane (Ss = 2.14). Three geosites obtained a deterioration degree score of Sd ≥ 2.5: Oum Er-Rbia (Sd = 2.8), Aïn Sebou (Sd = 2.63) and Dayet Ifrah (Sd = 2.63). The other nine geosites scored 1.5 ≤ Sd < 2.5.

These sites are therefore considered unique in the Middle Atlas and in Morocco, being the best examples of the hydric geoheritage of the region. The value of these geosites lies not only in their water resources but also in the biodiversity they contain, with some endemic species under threat of extinction. At the same time, they have the greatest potential for use as tourist and educational sites associated with water resources, based on criteria such as visibility, accessibility, protection status, prior existence of interpretation, safety, food and accommodation facilities, toilet facilities, or aesthetics (Rybár 2010; Pereira and Pereira 2010; Strba and Rybár 2015).

In this sense, the management of the selected hydric geosites of Middle Atlas should consider actions aimed at preserving the quantity and quality of water resources and other occurring elements of geodiversity and biodiversity, as well as actions that promote tourism attractivity and the use of the sites as educational resources.

8.3.1 Aghbalou Aberchane

Aghbalou Aberchane geosite (Hyd02) is located 12 km south of Timahdite (Fig. 8.2). This geosite shelters one of the coldest springs of the Middle Atlas which gushes out under a bar of basaltic flows, a few metres from the bed of the Oued Guigou which it feeds.

The Aghbalou Aberchane spring (Fig. 8.3a) is of the rheocrene type. Its water, whose temperature varies between 4 °C and 9 °C, comes from infiltrations in the basalts and emerges as a spring (Fig. 8.3b). These basalts come from lava flows generated by the Sidi Ali volcano that followed the Oued Guigou valley for several kilometres. Of massive structure, more or less vacuolar, and with a microlitic texture, these basalts are very fractured and fissured. The hydraulic energy of the Oued digs these basalts in a regressive way from the bottom to the top causing a particular phenomenon, "regressive erosion". Longitudinal fractures running in a NE-SW direction have also strongly conditioned the flow of the Oued Guigou in the region by favouring erosion. The hydrographic network is concentrated in these basalt blocks over a thickness of 4–5 m, digging small canyons in these weak areas, which gives the valley, where the source is located, a meandering shape.

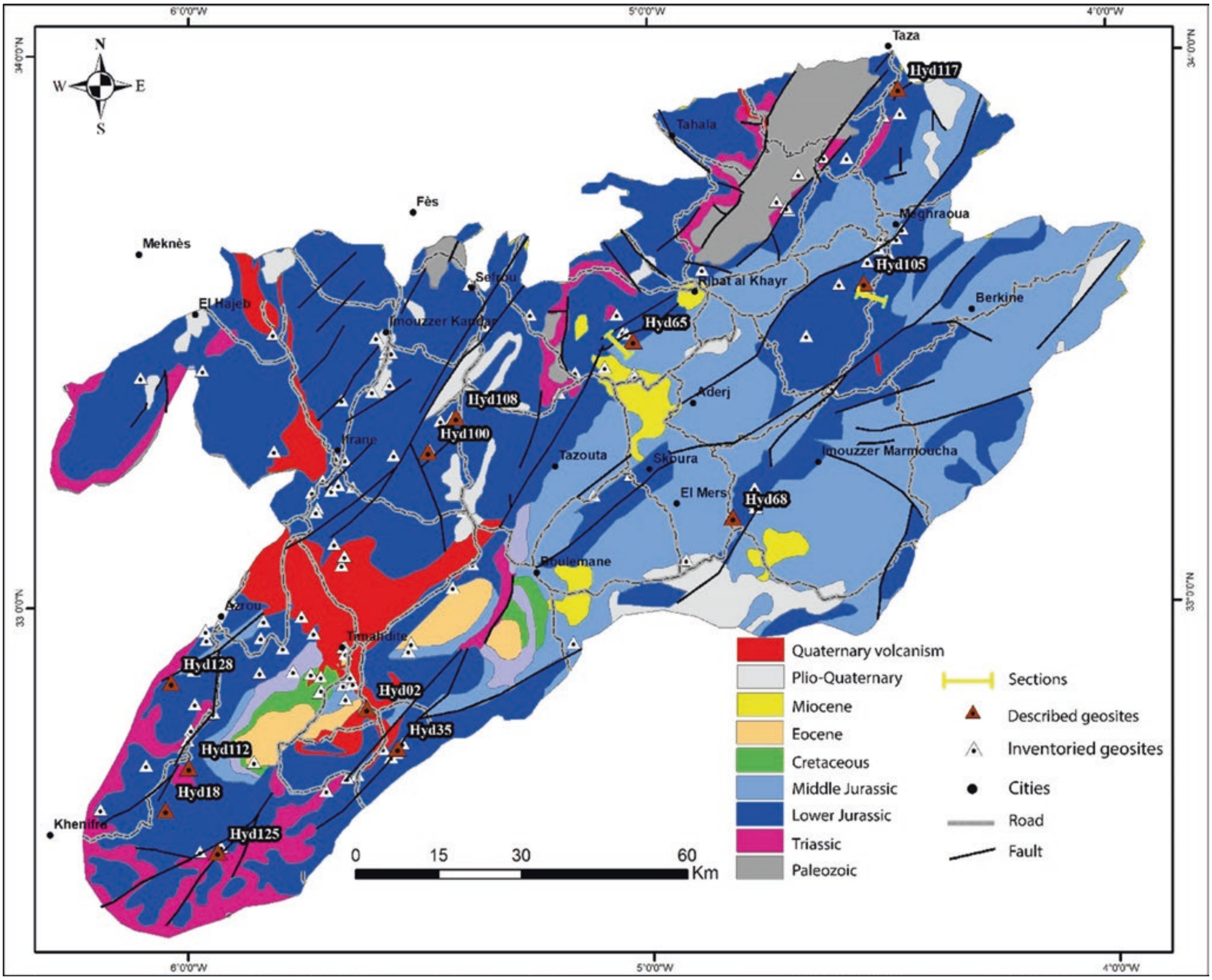

Fig. 8.2 Location of the hydric geosites inventoried in the Middle Atlas. (Baadi 2021)

Species of fish (*Salmo trutta fario*) and crustaceans (*Gammarus gauthieri*) proliferate there. Livestock farming, especially sheep and goats, also has a special place here. The flora is also well represented: *Helosciadium nodiflorum*, *Juncus bufonius*, *Myriophyllum spicatum*, *Ranunculus* sp. group *aquatilis*, *Rumex pulcher*, *Scirpus lacustris*, *Eleocharis palustris*, *Tolypella hispanica.*

8.3.2 Aïn Sebou

The Aïn Sebou geosite (Hyd65) is located 18.6 km south of El Menzel (Fig. 8.2). It is located on the SE slope of Jbel Hamda which is part of the first anticlinal wrinkle. This geosite presents, in its genesis, a multitude of phenomena giving this site a representativeness at the regional and even national scale. Its rarity can be summed up in the location of the Aïn Sebou spring at the lowest altitude of the folded Middle Atlas.

The Aïn Sebou spring is a typical Vauclusian spring, probably originating from more than 100 m depth. This spring appears in a Domerian marlstone level (Fig. 8.4), in the vicinity of a vertical branch of the NMAF. The emergence of the spring (Fig. 8.5a) is located at an altitude of 700 m, which corresponds to the lowest altitude of the Upper Sebou basin upstream of Aïn Sebou. The spring is fed by surface water that infiltrates the surface of the Liassic carbonates on most of the major ridges and anticlinal folds, including a large part of the Bou-Iblane fold (Akdim et al. 2012).

With an average flow of 2500 l/s, which can reach 5375 l/s (case of April 1997) (Akdim et al. 2012), influenced by karst, climate and morphostructure, it is the most important spring of the Northern Middle Atlas. However, it dries up in periods of long droughts and is transformed into a well for absorbing surface water following the phenomenon of siphoning which evolves from an outlet to a karstic ponor. This spring feeds the Oued Sebou directly (Fig. 8.5b).

Table 8.1 List of the hydric geosites inventoried in the Middle Atlas (RAMSAR: wetland site designated to be of international importance under the Ramsar Convention; SIBE: Site of Biological and Ecological Interest; APM: Moroccan Protected Areas)

Hydric geosite	Identification code	Type of geosite	Coordinates			Administrative location	Property	Extended	Accessibility	Protected area
			X	Y	Z					
Aari Aguelmam	Hyd01	Lake	33°10′5.18″N	5°8′29.22″W	1889	Timahdite	Public	0.09 km2	Easy	
Aghbalou Abrechane	Hyd02	Spring	33°8′22.74″N	5°3′24.98″W	1910	Timahdite	Public	–	Easy	SIBE/RAMSAR
Aghbalou n'Bou Harch	Hyd03	Spring	3°14′59.61″N	5°21′52.21″W	1540	Ain Leuh	Public	–	Easy	–
Aghbalou n'Brahim	Hyd04	Spring	33°1′45.37″N	5°4′15.93″W	2139	Timahdite	Public	–	Easy	–
Aghbalou n'Talouat	Hyd05	Spring	33°11′21.84″N	5°5′8.27″W	1885	Timahdite	Public	–	Easy	–
Aghbalou n'Toumit	Hyd06	Lake	33°8′25.03″N	5°3′6.33″W	1927	Timahdite	Public	–	Easy	–
Aghbalou Ou Mançour	Hyd07	Spring	33°4′55.28″N	4°59′1.70″W	2090	Timahdite	Public	–	Easy	–
Aghbalou Oumlil	Hyd08	Lake	33°13′38.39″N	5°5′37.33″W	1838	Timahdite	Public	–	Easy	–
Aghbalou Taddat	Hyd09	Spring	33°4′50.60″N	4°59′0.39″W	2089	Timahdite	Public	–	Easy	–
Aghbalou Tagma	Hyd10	Spring	33°15′52.70″N	5°21′55.17″W	1424	Ain Leuh	Public	–	Easy	–
Aghbaloun Assounane	Hyd11	Spring	33°13′53.86″N	4°58′18.17″W	2136	Almis Guigou	Public	–	Easy	–
Aguelmam Abekhane	Hyd12	Lake	32°54′43.87″N	5°20′9.33″W	1670	Khénifra	Public	0.24 km2	Easy	–
Aguelmam Admar Izam	Hyd13	Lake	33°11′22.69″N	5°8′31.13″W	1878	Timahdite	Public	0.27 km2	Easy	–
Aguelmam Afiroua	Hyd14	Lake	33°6′11.03″N	5°23′40.04″W	1551	Al Hammam	Public	0.34 km2	Easy	–
Aguelmam Aghbalou Oumlil	Hyd15	Lake	33°13′38.39″N	5°5′37.33″W	1838	Ifrane	Public	0.33 km2	Easy	–
Aguelmam Ait Said	Hyd16	Lake	33°14′35.85″N	4°39′4.95″W	1752	Boulemane	Public	0.67 km2	Easy	–
Aguelmam Almis Guigou	Hyd17	Lake	33°22′21.43″N	4°50′49.75″W	1491	Almis Guigou	Public	0.27 km2	Easy	–
Aguelmam Azegza	Hyd18	Lake	32°58′23.46″N	5°26′36.63″W	1489	Khénifra	Public	0.50 km2	Easy	APM et SIBE
Aguelmam Azougouarh	Hyd19	Lake	33°1′26.97″N	5°5′28.49″W	2059	Timahdite	Public	0.13 km2	Easy	–
Aguelmam Bou Youssef	Hyd20	Lake	33°45′40.66″N	5°17′48.80″W	844	El Hajeb	Public	–	Easy	–
Aguelmam Boucherouidene	Hyd21	Lake	33°15′38.86″N	5°9′22.46″W	1900	Azrou	Public	3.85 km2	Easy	–
Aguelmam Dial Tachnkourt	Hyd22	Lake	33°29′37.99″N	5°7′15.36″W	1665	Azrou	Public	0.30 km2	Easy	–
Aguelmam Ifrighraoune	Hyd23	Lake	33°8′44.02″N	5°23′10.90″W	1592	Ain Leuh	Public	1.53 km2	Medium	–
Aguelmam Mertissiliouine	Hyd24	Lake	33°17′18.10″N	5°10′45.31″W	1878	Azrou	Public	0.15 km2	Medium	–
Aguelmam Miammi	Hyd25	Lake	32°54′15.19″N	5°22′24.93″W	1477	Khénifra	Public	0.09 km2	Medium	–
Aguelmam Nad'Adim	Hyd26	Lake	33°10′43.69″N	5°4′48.53″W	1883	Timahdite	Public	0.15 km2	Medium	–
Aguelmam n'Harcha	Hyd27	Lake	33°7′52.40″N	5°21′4.43″W	1617	Al Hammam	Public	0.1 km2	Medium	–
Aguelmam n'Tghallouine	Hyd28	Lake	33°23′10.03″N	5°5′45.41″W	1856	Azrou	Public	0.18 km2	Easy	–
Aguelmam Ntifounassine	Hyd29	Lake	33°9′15.04″N	5°5′37.79″W	1912	Timahdite	Public	0.6 km2	Medium	RAMSAR et SIBE
Aguelmam Ou Houli	Hyd30	Lake	33°7′46.62″N	5°21′35.61″W	1631	El Hammam	Public	0.1 km2	Medium	–
Aguelmam Sidi Abderahman Ou Said	Hyd31	Lake	33°5′7.48″N	5°24′3.30″W	1543	Al Hammam	Public	0.19 km2	Medium	–
Aguelmam Taanzeoult	Hyd32	Lake	33°4′18.78″N	5°1′16.79″W	2086	Timahdite	Public	0.41 km2	Easy	–
Aguelmam Ticharat	Hyd33	Lake	33°0′13.74″N	5°7′53.88″W	2068	Timahdite	Public	0.20 km2	Easy	–
Aguelmam Tidouit	Hyd34	Lake	33°14′37.78″N	5°5′46.02″W	1828	Timahdite	Public	0.14 km2	Easy	–
Aguelmame Sidi Ali	Hyd35	Lake	33°4′23.80″N	4°59′40.91″W	2100	Timahdite	Public	2.92 km2	Easy	RAMSAR et SIBE
Ain Aberchaou	Hyd36	Spring	33°53′51.40″N	4°0′52.22″W	1360	Meghraoua	Public	–	Easy	–
Ain Aghbal	Hyd37	Spring	33°26′22.09″N	5°15′7.48″W	1177	Ifrane	Public	–	Easy	–

Ain Ait Meziane	Hyd38	Spring	33°39′59.71″N	5°0′23.15″W	1451	Imouzzer Kandar	Public	–	Easy	–
Ain Ajaabou	Hyd39	Spring	33°16′20.22″N	5°20′28.13″W	1629	Ain Leuh	Public	–	Easy	–
Ain Akadous	Hyd40	Spring	33°18′30.84″N	5°18′43.80″W	1457	Ain Leuh	Public	–	Easy	–
Ain Amernoud	Hyd41	Spring	33°41′4.46″N	4°38′39.14″W	1037	Tazouta	Public	–	Difficult	–
Ain Atshernat	Hyd42	Spring	33°51′36.09″N	4°4′16.58″W	1046	Meghraoua	Public	–	Difficult	–
Ain Ba Ahmed	Hyd43	Spring	33°3′29.28″N	5°0′21.31″W	2172	Timahdite	Public	200l/s	Easy	–
Ain Ben Smime	Hyd44	Spring	33°29′25.89″N	5°9′31.07″W	1589	Azrou	Public	–	Easy	–
Ain Dem	Hyd45	Spring	33°39′1.56″N	4°40′33.92″W	1267	Tazouta	Public	–	Difficult	–
Ain El Aouda	Hyd46	Spring	34°5′50.96″N	4°2′13.61″W	1489	Bab Boudir	Public	–	Easy	–
Aïn Erreha	Hyd47	Spring	34°0′15.91″N	4°12′17.33″W	1036	Kaouane	Public	–	Easy	–
Ain Guenaz	Hyd48	Spring	33°49′26.38″N	4°7′38.55″W	1959	Meghraoua	Public	–	Difficult	–
Ain Ighlfoun	Hyd49	Spring	33°51′51.96″N	4°1′31.63″W	1396	Meghraoua	Public	–	Difficult	–
Ain Ighoul	Hyd50	Spring	33°40′35.37″N	4°31′40.94″W	822	Tazouta	Public	–	Difficult	–
Ain Ighouzaz	Hyd51	Spring	33°54′46.43″N	4°0′10.78″W	1317	Meghraoua	Public	–	Difficult	–
Ain Jerjoub	Hyd52	Spring	34°1′49.02″N	4°6′34.00″W	1412	Ademame	Public	–	Difficult	–
Ain Jerrah	Hyd53	Spring	33°44′35.06″N	5°1′57.61″W	1173	Imouzzer Kandar	Public	–	Easy	–
Ain Jorf	Hyd54	Spring	33°36′37.56″N	4°52′48.37″W	1446	Aïn Leuh	Public	–	Easy	–
Ain Kahla	Hyd55	Spring	33°14′13.83″N	5°12′58.42″W	2006	El Hammam	Public	–	Easy	–
Ain Kahla 2	Hyd56	Spring	33°14′36.30″N	4°58′0.66″W	2018	Almis Guigou	Public	–	Easy	–
Aïn Khadem	Hyd57	Spring	33°41′20.66″N	5°22′17.04″W	1002	Ifrane	Public	–	Easy	–
Ain Larais	Hyd58	Spring	33°3′55.27″N	4°59′45.90″W	2163	Timahdite	Public	200l/s	Easy	–
Ain Maarouf	Hyd59	Spring	33°40′38.39″N	5°29′33.48″W	801	Agourai	Public	–	Difficult	–
Ain Melzit	Hyd60	Spring	33°48′36.31″N	4°4′13.09″W	1841	Meghraoua	Public	–	Difficult	–
Ain Mezdou	Hyd61	Spring	33°45′42.43″N	4°49′13.82″W	1231	Sefrou	Public	–	Difficult	–
Ain Mghirta	Hyd62	Spring	33°40′52.49″N	4°31′45.17″W	855	Tazouta	Public	–	Difficult	–
Aïn n'Tislit	Hyd63	Spring	33°56′45.08″N	4°13′28.51″W	1343	Kaouane	Public	–	Difficult	–
Ain Ouamender	Hyd64	Spring	33°44′48.69″N	4°32′35.00″W	692	Tazouta	Public	–	Difficult	–
Ain Regrag	Hyd65	Spring	33°46′44.89″N	4°43′56.12″W	1042	Sefrou	Public	–	Difficult	–
Ain Sebou	Hyd66	Spring	33°44′13.02″N	4°31′58.68″W	678	El Menzel	Public	–	Difficult	–
Ain Sidi Rached	Hyd67	Spring	33°27′29.91″N	5°9′2.31″W	1543	Azrou	Public	–	Easy	–
Ain Skhounate	Hyd68	Spring	33°26′56.70″N	4°20′20.46″W	1420	Imouzze Marmoucha	Public	–	Difficult	–
Ain Sultane	Hyd69	Spring	33°43′4.24″N	5°0′10.99″W	1376	Imouzzer Kandar	Public	–	Medium	–
Ain Takeltount	Hyd70	Spring	33°36′41.33″N	4°53′3.27″W	1440	Aïn Leuh	Public	–	Easy	–
Ain Takhouwat	Hyd71	Spring	33°41′33.69″N	4°35′13.25″W	1038	Tazouta	Public	–	Difficult	–
Ain Talghoulat	Hyd72	Spring	33°22′17.54″N	5°6′4.36″W	1856	Azrou	Public	–	Medium	–

(continued)

Table 8.1 (continued)

Hydric geosite	Identification code	Type of geosite	Coordinates			Administrative location	Property	Extended	Accessibility	Protected area
			X	Y	Z					
Ain Tamzirt	Hyd73	Spring	33°29′34.44″N	4°17′47.47″W	1450	Imouzzer Marmoucha	Public	–	Difficult	–
Ain Tassiwine	Hyd74	Spring	33°48′57.12″N	4°4′4.89″W	1799	Meghraoua	Public	–	Difficult	–
Ain Tataw	Hyd75	Spring	33°27′40.61″N	4°17′44.32″W	1609	Imouzzer Marmoucha	Public	–	Difficult	–
Ain Tidouit	Hyd76	Spring	33°14′14.87″N	5°5′51.87″W	1814	Timahdite	Public	–	Difficult	–
Ain Tifratine	Hyd77	Lake	33°11′54.35″N	5°11′45.70″W	1956	Al Hammam	Public	–	Difficult	–
Ain Timedrine	Hyd78	Spring	33°44′56.05″N	4°33′2.76″W	696	El Menzel	Public	–	Difficult	–
Ain Vital	Hyd79	Spring	33°32′47.18″N	5°6′43.28″W	1580	Ifrane	Public	–	Easy	–
Ain Zerrouka	Hyd80	Spring	33°32′38.07″N	5°5′39.92″W	1611	Ifrane	Public	–	Easy	–
Aioun Imettassene	Hyd81	Spring	33°29′57.84″N	5°4′43.75″W	1686	Azrou	Public	–	Easy	–
Aioun Ras El Ma	Hyd82	Spring	33°27′55.05″N	5°8′54.82″W	1573	Azrou	Public	–	Easy	–
Ait Athia	Hyd83	Spring	33°22′36.32″N	4°25′51.00″W	1522	Serghina	Public	–	Medium	–
Amane Imellaline (Ain Joua)	Hyd84	Spring	33°39′15.49″N	4°8′38.36″W	2110	Bou-Iblane	Public	–	Difficult	–
Anzar Oufounas	Hyd85	Lake	33°9′52.09″N	5°8′42.86″W	1888	Timahdite	Public	0.18 km2	Difficult	–
Cascade d’Aït smail	Hyd86	Waterfall	33°52′55.66″N	4°2′59.59″W	936	Taza	Public	–	Difficult	–
Cascade des vierges	Hyd87	Waterfall	33°31′53.20″N	5°6′32.43″W	2006	Ifrane	Public	–	Difficult	–
Cascade d’Imouzar Marmoucha	Hyd88	Waterfall	33°28′0.88″N	4°17′44.16″W	1560	Imouzze Marmoucha	Public	–	Difficult	–
Cascade d’Imouzer Kandar	Hyd89	Waterfall	33°43′5.50″N	5°0′51.64″W	1360	Imouzzer Kandar	Public	–	Medium	–
Cascade Hawai	Hyd90	Waterfall	33°12′2.55″N	5°23′21.24″W	1475	Ifrane	Public	–	Difficult	–
Cascade Ras El Ma	Hyd91	Waterfall	34°8′41.53″N	4°0′37.06″W	1028	Taza	Public	–	Easy	–
Cascade Sefrou	Hyd92	Waterfall	33°49′41.68″N	4°50′58.44″W	890	Sefrou	Public	–	Easy	–
Cascade Sidi Bou Shaq	Hyd93	Waterfall	33°3′1.11″N	5°16′17.90″W	1654	Bekrit	Public	–	Difficult	–
Cascade Skoura	Hyd94	Waterfall	33°30′57.66″N	4°32′15.83″W	1278	Skoura	Public	–	Easy	–
Cascade Tagoute	Hyd95	Waterfall	33°29′1.40″N	4°36′37.44″W	1116	Boulemane	Public	–	Difficult	–
Dayet Aoua	Hyd96	Lake	33°39′17.20″N	5°2′28.10″W	1466	Imouzze Kandar	Public	1.50 km2	Easy	–
Dayet El Jerane	Hyd97	Lake	33°33′49.97″N	4°59′49.97″W	1693	Ifrane	Public	8 Ha	Easy	–
Dayet Hachlaf	Hyd98	Lake	33°33′3.41″N	4°59′58.69″W	1667	Ifrane	Public	0.60 km2	Easy	–
Dayet Iffer	Hyd99	Lake	33°36′24.25″N	4°54′28.39″W	1517	Ifrane	Public	0.12 km2	Easy	–
Dayet Ifrah	Hyd100	Lake	33°33′35″N	4°55′48″W	1616	Ifrane	Public	1.73 km2	Easy	–
Dayet Lakbira	Hyd101	Lake	33°27′31.86″N	4°51′51.83″W	1555	Imouzzer Kandar	Public	0.75 km2	Easy	–
Dayet Maasker	Hyd102	Lake	33°38′31.25″N	5°5′54.30″W	1374	Imouzzer Kandar	Public	0.62 km2	Easy	–

Dayet Moucherkour	Hyd103	Lake	33°30′10.41″N	5°6′24.75″W	1673	Ifrane	Public	0.32 km2	Easy	–
Dayet Tichout	Hyd104	Lake	33°30′35.62″N	5°8′13.44″W	1637	Ifrane	Public	0.06 km2	Easy	–
Guelta Tameda	Hyd105	Lake	33°49′42.53″N	4°4′44.24″W	1462	Meghraoua	Public	0.62 km2	Difficult	SIBE
Ifri Ou Berid	Hyd106	Spring	33°15′10.76″N	5°15′31.90″W	1858	Ain Leuh	Public	–	Medium	–
Lac Afnourir	Hyd107	Lake	33°16′49.40″N	5°15′10.90″W	1799	Ain Leuh	Public	0.83 km2	Easy	–
Lac Afourgagh	Hyd108	Lake	33°36′49.19″N	4°52′41.48″W	1420	Ain Leuh	Public	0.12 km2	Easy	–
Lac Agoulmame	Hyd109	Lake	33°39′54.14″N	4°51′7.74″W	1394	Anouceur	Public	0.05 km2	Easy	–
Lac Ajdir	Hyd110	Lake	32°57′46.70″N	5°26′5.30″W	1622	Ajdir	Public	0.1 km2	Easy	–
Lac Tighboula-Laachoure	Hyd111	Lake	33°10′33.18″N	5°5′56.19″W	1909	Khénifra	Public	0.08 km2	Easy	–
Oum Er-Rbiaa	Hyd112	Spring	33°3′5.72″N	5°24′43.73″W	1275	Khenifra	Public	–	Medium	–
Ouoouchène	Hyd113	Lake	33°24′30.82″N	4°54′42.40″W	1656	Almis Guigou	Public	0.24 km2	Difficult	–
Rabiaa-Bitit	Hyd114	Spring	33°33′28.93″N	5°13′56.10″W	1452	Ifrane	Public	–	Easy	–
Ras Adrar Izem	Hyd115	Lake	33°11′40.08″N	5°9′41.64″W	1874	Timahdite	Public	0.06 km2	Medium	–
Ras El Ain	Hyd116	Spring	33°28′21.96″N	4°16′43.99″W	1659	Imouzzer Marmoucha	Public	–	Difficult	–
Ras El Ma	Hyd117	Spring	34°8′41.53″N	4°0′37.06″W	1029	Taza	Public	–	Easy	–
Résurgence d'Ademame	Hyd118	Spring	34°1′53.52″N	4°9′17.60″W	1260	Ademame	Public	–	Easy	–
Sabhab	Hyd119	Waterfall	33°53′54.62″N	4°2′43.71″W	1170	Meghraoua	Public	–	Difficult	–
Sidi Yahia	Hyd120	Spring	33°44′26.79″N	4°11′32.38″W	1840	Ribat al Khayr	Public	–	Difficult	–
Tabhirte	Hyd121	Waterfall	33°57′40.58″N	4°14′49.95″W	1184	Tabehirte	Public	–	Easy	–
Taguelmant Yéj	Hyd122	Spring	32°58′20.78″N	5°34′8.59″W	1297	Khénifra	Public	–	Easy	–
Tibakhbakhine	Hyd123	Spring	34°6′8.48″N	4°0′14.48″W	1519	El Ansar	Public	–	Medium	–
Tiguelmamine (El Hajeb)	Hyd124	Lake	33°44′54.03″N	5°14′2.82″W	967	El Hajeb	Public	–	Easy	–
Tiguelmamines	Hyd125	Lake	32°54′20.78″N	5°20′35.42″W	1650	Timahdite	Public	0.15 km2	Difficult	SIBE
Tit Maregh	Hyd126	Spring	4°14′49.95″O	4°13′44.37″W	1313	Madegh	Public	–	Easy	–
Tit-Zill	Hyd127	Spring	33°20′3.24″N	4°53′6.56″W	1523	Boulemane	Public	–	Easy	–
Zaouiat Ifrane	Hyd128	Waterfall	33°11′38.09″N	5°25′9.00″W	1304	Ifrane	Public	–	Easy	–

Table 8.2 Results of the quantitative assessment for the selection of the most relevant hydric geosites in the Middle Atlas

	Criteria of quantitative assessment (Ss)						Final scoring matrix (Ss)						
Geosites	Representativeness	Rarity	Geological diversity	State of preservation	Documentation	Total of pointing	Representativeness*24%	Rarity *18%	Geological diversity*20%	State of preservation*24%	Documentation*14%	Total of Ss	Result (Ss)
Aari Aguelmam	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aghbalou Abrechane	3	2	3	2	3	13	0.72	0.36	0.6	0.48	0.42	2.58	High
Aghbalou n'Bou Harch	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aghbalou n'Brahim	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aghbalou n'Talouat	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aghbalou n'Toumit	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aghbalou Ou Mançour	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aghbalou Oumlil	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aghbalou Taddat	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aghbalou Tagma	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aghbaloun Assounane	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aguelmam Abekhane	1	1	1	2	2	7	0.24	0.18	0.2	0.48	0.28	1.38	Low
Aguelmam Admar Izam	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aguelmam Afiroua	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aguelmam Aghbalou Oumlil	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aguelmam Ait Said	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aguelmam Almis Guigou	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aguelmam Azegza	2	2	3	2	3	12	0.48	0.36	0.6	0.48	0.42	2.34	Medium
Aguelmam Azougouarh	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aguelmam Bou Youssef	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aguelmam Boucherouidene	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aguelmam Dial Tachnkourt	1	1	1	2	1	6	0.24	0.18	0.2	0.48	0.14	1.24	Low
Aguelmam Ifrighraouine	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low

Aguelmam Mertissiliouine	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aguelmam Miammi	1	2	2	1	1	7	0.24	0.36	0.4	0.24	0.14	1.38	Low
Aguelmam Nad'Adim	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aguelmam n'Harcha	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aguelmam n'Tghallouine	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aguelmam N'tifounassine	1	2	3	2	3	11	0.24	0.36	0.6	0.48	0.42	2.1	Medium
Aguelmam Ou Houli	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aguelmam Sidi Abderahman Ou Said	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aguelmam Taanzeouit	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aguelmam Ticharat	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aguelmam Tidouit	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aguelmame Sidi Ali	3	3	3	2	3	14	0.72	0.54	0.6	0.48	0.42	2.76	High
Ain Aberchaou	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Aghbal	1	1	1	2	1	6	0.24	0.18	0.2	0.48	0.14	1.24	Low
Ain Ait Meziane	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Ajaabou	1	1	1	2	1	6	0.24	0.18	0.2	0.48	0.14	1.24	Low
Ain Akadous	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Amernoud	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Atshernat	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Ba Ahmed	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Bn Smime	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Dem	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain El Aouda	1	1	2	1	1	6	0.24	0.18	0.4	0.24	0.14	1.2	Low
Aïn Erreha	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Guenaz	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Ighlfoun	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Ighoul	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Ighouzaz	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Jerjoub	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Jerrah	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Jorf	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Kahla	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Ain Kahla	1	1	1	1	3	7	0.24	0.18	0.2	0.24	0.42	1.28	Low
Aïn Khadem	1	1	1	1	1	1	0.24	0.18	0.2	0.24	0.14	1	Low

(continued)

Table 8.2 (continued)

Ain Larais	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Maarouf	1	1	1	2	1	6	0.24	0.18	0.2	0.48	0.14	1.24	Low
Ain Melzit	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Mezdou	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Mghirta	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aïn n'Tislit	1	1	2	1	1	6	0.24	0.18	0.4	0.24	0.14	1.2	Low
Ain Ouamender	2	2	2	1	3	10	0.48	0.36	0.4	0.24	0.42	1.9	Medium
Ain Regrag	1	1	1	1	3	7	0.24	0.18	0.2	0.24	0.42	1.28	Low
Ain Sebou	3	3	3	1	3	13	0.72	0.54	0.6	0.24	0.42	2.52	High
Ain Sidi Rached	1	1	1	2	2	7	0.24	0.18	0.2	0.48	0.28	1.38	Low
Ain Skhonate	3	3	3	1	3	13	0.72	0.54	0.6	0.24	0.42	2.52	High
Ain Sultane	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Ain Takeltount	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Takhouwat	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Talghoulat	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Tamzirt	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Tassiwine	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Tataw	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Tidouit	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Tifratine	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ain Timedrine	2	2	2	1	3	10	0.48	0.36	0.4	0.24	0.42	1.9	Medium
Ain Vital	2	2	2	2	2	10	0.48	0.36	0.4	0.48	0.28	2	Medium
Ain Zerrouka	1	1	1	2	2	7	0.24	0.18	0.2	0.48	0.28	1.38	Low
Aioun Imettassene	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aioun Ras El Ma	2	2	2	2	2	10	0.48	0.36	0.4	0.48	0.28	2	Medium
Ait Athia	1	1	2	1	1	6	0.24	0.18	0.4	0.24	0.14	1.2	Low
Amane Imellaline (Ain Joua)	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Anzar Oufounas	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Cascade d'Aït smail	2	2	2	1	1	8	0.48	0.36	0.4	0.24	0.14	1.62	Medium
Cascade d'Imouzar Marmoucha	2	2	2	1	1	8	0.48	0.36	0.4	0.24	0.14	1.62	Medium
Cascade d'Imouzer Kandar	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Cascade Hawai	1	1	2	1	1	6	0.24	0.18	0.4	0.24	0.14	1.2	Low
Cascade Ras El Ma	1	1	1	2	2	7	0.24	0.18	0.2	0.48	0.28	1.38	Low
Cascade Sefrou	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Cascade Sidi Bou Shaq	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Cascade Skoura	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low

Cascade des vierges	1	1	2	2	1	7	0.24	0.18	0.4	0.48	0.14	1.44	Low
Cascade Tagoute	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Dayet Aoua	1	1	2	2	3	9	0.24	0.18	0.4	0.48	0.42	1.72	Medium
Dayet El Jerane	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Dayet Hachlaf	1	1	2	2	3	9	0.24	0.18	0.4	0.48	0.42	1.72	Medium
Dayet Iffer	2	2	2	2	3	11	0.48	0.36	0.4	0.48	0.42	2.14	Medium
Dayet Ifrah	3	2	2	2	3	12	0.72	0.36	0.4	0.48	0.42	2.38	Medium
Dayet Lakbira	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Dayet Maasker	1	1	1	2	1	6	0.24	0.18	0.2	0.48	0.14	1.24	Low
Dayet Moucherkour	1	1	1	2	1	6	0.24	0.18	0.2	0.48	0.14	1.24	Low
Dayet Tichout	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Guelta Tameda	3	3	3	2	3	14	0.72	0.54	0.6	0.48	0.42	2.76	High
Ifri Ou Berid	2	2	2	1	2	9	0.48	0.36	0.4	0.24	0.28	1.76	Medium
Lac Afnourir	2	1	2	2	3	10	0.48	0.18	0.4	0.48	0.42	1.96	Medium
Lac Afourgagh	3	2	3	2	3	13	0.72	0.36	0.6	0.48	0.42	2.58	High
Lac Agoulmame	1	1	2	1	1	6	0.24	0.18	0.4	0.24	0.14	1.2	Low
Lac Ajdir	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Lac Tighboula-Laachoure	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Oum Er-Rbiaa	3	3	3	2	3	14	0.72	0.54	0.6	0.48	0.42	2.76	High
Ouoouchène	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Rabiaa-Bitit	2	2	1	1	3	9	0.48	0.36	0.2	0.24	0.42	1.7	Medium
Ras Adrar Izem	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ras El Ain	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ras El Ma	3	3	3	2	3	14	0.72	0.54	0.6	0.48	0.42	2.76	High
Résurgence d'Admame	2	1	1	1	1	6	0.48	0.18	0.2	0.24	0.14	1.24	Low
Sabhab	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Sidi Yahia	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Tabhirte	1	1	2	1	1	6	0.24	0.18	0.4	0.24	0.14	1.2	Low
Taguelmant Yéj	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Tibakhbakhine	2	2	2	1	2	9	0.48	0.36	0.4	0.24	0.28	1.76	Medium
Tiguelmamine (El Hajeb)	2	1	1	2	1	7	0.48	0.18	0.2	0.48	0.14	1.48	Low
Tiguelmamines	3	2	3	2	3	13	0.72	0.36	0.6	0.48	0.42	2.58	High
Tit Maregh	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Tit-Zill	1	1	1	1	3	7	0.24	0.18	0.2	0.24	0.42	1.28	Low
Zaouiet Ifrane	3	2	2	1	3	11	0.72	0.36	0.4	0.24	0.42	2.14	Medium

The geosite of Aïn Sebou presents karstic, climatic and morphostructural characteristics which make this site an educational reference of the hydro-karstic system of the Middle Atlas.

Table 8.3 Main importance of the selected hydric geosites in the Middle Atlas

Hydric geosites	Main importance
Aghbalou Aberchane	It is one of the coldest springs of the Middle Atlas which gushes out under a bar of basaltic flows.
Aïn Sebou	It is located at the lowest altitude of the folded Middle Atlas with an average flow of 2500 l/s.
Aïn Skhounate	It is the only thermo-mineral source of the Middle Atlas with a temperature of 35.7 °C.
Ras el Ma	It is a resurgence of a particular hydrokarstic functioning connected with the underground karstic network of Chiker and Friouato.
Oum Er-Rbia	It is a unique complex of fresh and salty springs in Morocco.
Zaouiat Ifrane	It is one of the most important waterfalls of the Middle Atlas.
Lake Afourgagh	It is a reference site for paleoclimatic and sedimentological studies of the Middle Atlas lakes.
Aguelmam Azegza	It is an important alkalitrophic lake in the Middle Atlas.
Aguelmam Sidi Ali	It is the only volcanic dam lake in the entire Middle Atlas chain.
Dayet Ifrah	It is an important lake with calc-magnesium waters in the Middle Atlas.
Guelta Tameda	It is the only natural dam lake in the Middle Atlas whose origin is linked to the collapse of Liassic carbonate masses.
Tiguelmamines	It is a lake with unique characteristics corresponding to the juxtaposition of three tectono-karstic lakes.

8.3.3 Aïn Skhounate

The Aïn Skhounate geosite (Hyd68) is located 12.2 km west of Imouzzer Marmoucha (Fig. 8.2). It is located at the foothills of the Liassic fields of the Oul Masqir mountain (Fig. 8.6). This geosite constitutes the only thermo-mineral source in the Middle Atlas.

The geosite of Aïn Skhounate corresponds to a thermo-mineral spring reaching a temperature of 35.7 °C. Its flow rate is 5 l/s (Sabri et al. 2019). The spring gushes out in the Lower Lias limestones of the NW slope of Oul Masqir (Figs. 8.7 and 8.8a). Taking into account the geothermal gradient of the region which is 35 °C/km (Zarhloule 2004) and the depth of the reservoir located at 50 m (Sabri et al. 2019), the depth of the water circulations of the spring would be 1.6 km. This depth is justified by the richness of its waters in alkaline earths, sulphates and chlorides (Giudicelli and Dakki 1984). Controlled by several factors on a regional or local scale (Barkaoui et al. 2015), the underground circuit of the spring is linked to deep circulation in areas where the geothermal gradient is abnormally high (>35 °C) (Zarhloule 2004).

The thermo-mineral spring of Aïn Skhounate (Fig. 8.8b) has recently become of crucial interest to the local authorities. The development of the spring (Fig. 8.8c) has made the site very accessible (Fig. 8.8d). The water from this spring can be used to generate electrical energy.

8.3.4 Ras El Ma

The geosite of Ras El Ma (Hyd117) is located 14 km south of Taza (Fig. 8.2). This geosite is the most important resurgence of the Taza region by its flow and its hydrokarstic functioning.

Fig. 8.3 (**a**) Aghbalou Aberchane spring located at the foot of the basaltic flows on the bank of the Oued Guigou; (**b**) Aghbalou Aberchane spring developed

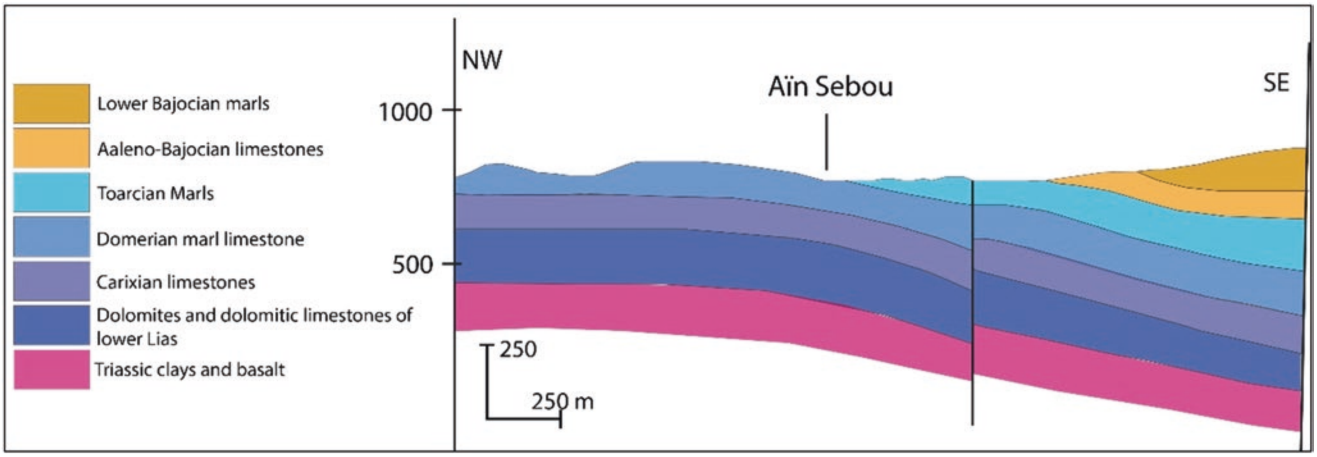

Fig. 8.4 Geological section of the Aïn Sebou geosite

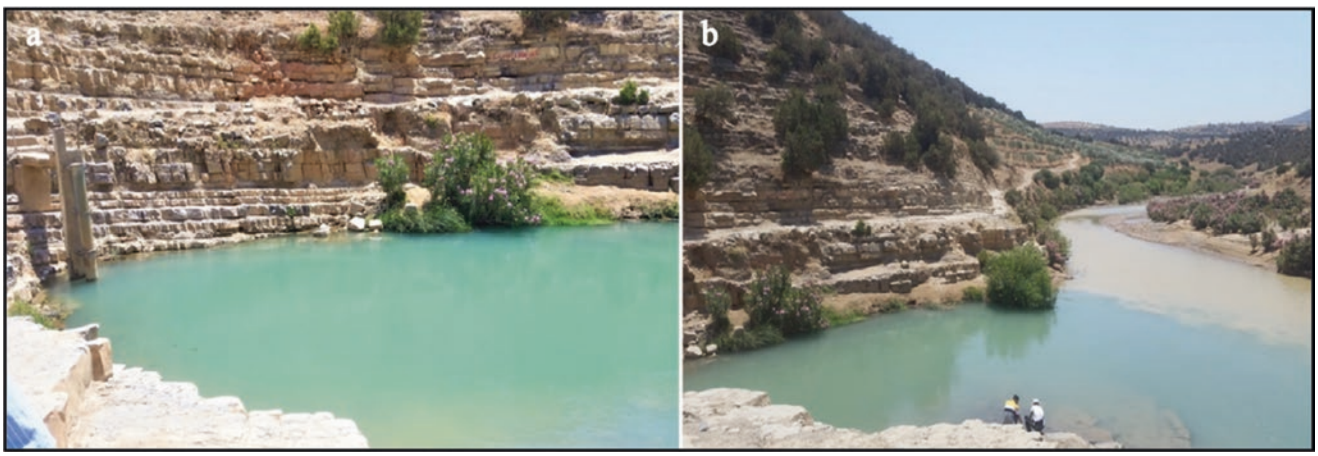

Fig. 8.5 (**a**) Aïn Sebou spring gushing out of the Domerian marl limestone; (**b**) Water coming from the Aïn Sebou spring and feeding, downstream, the Oued Sebou

The Ras El Ma resurgence gushes out at the contact between the dolomitic limestones of the Lower Lias (Fig. 8.9a) and the impermeable Triassic formations. Its gushing is closely related to the Daya Chiker-Gouffre Friouato system. The supply of this resurgence comes, on the one hand, from the waters and flows absorbed at the level of the Chiker cave and, on the other hand, from the waters infiltrating in different ponors located around the Daya Chiker, through the lapies, dolines, ouvalas and fractured structural surfaces of the surrounding mountain massifs (Jbels Bou Adli, Bou Slama and Bou Massoud). These waters follow the main drain of the Gouffre Friouato gallery (Ek and Mathieu 1964; Robillard 1978; Sabaoui et al. 2009; Taous et al. 2009). The waters of this resurgence (Fig. 8.9b) give rise to several waterfalls downstream.

The Ras El Ma geosite provides an educational example of the hydrogeological functioning of the karsts affecting the Middle Atlas chain.

8.3.5 Oum Er-Rbia

The Oum Er-Rbia geosite (Hyd112) is located 45 km northeast of Khénifra (Fig. 8.2). This geosite has a complex of springs unique to the Middle Atlas (Fig. 8.10). The water is fresh for some and salty for others.

The Oum Er-Rbia springs are 40 in number and the hydrogeological basin is considered to be the largest in the Causse with an outcrop of the karst landscape of about 1020 km^2 (Bentayeb and Leclerc 1977). The cumulative flow of these springs, largely related to the NE-SW trending underground river running through the area, gives 118 m/s^3 (Kirat et al. 2016). The flow of all these springs is towards the Oum Er-Rbia Oued. Along the river, waterfalls have developed (Fig. 8.10a) and summering points are set up (Fig. 8.10b).

Located in a transition zone, highly fractured, between the folded Middle Atlas and the subtabular Causse, the

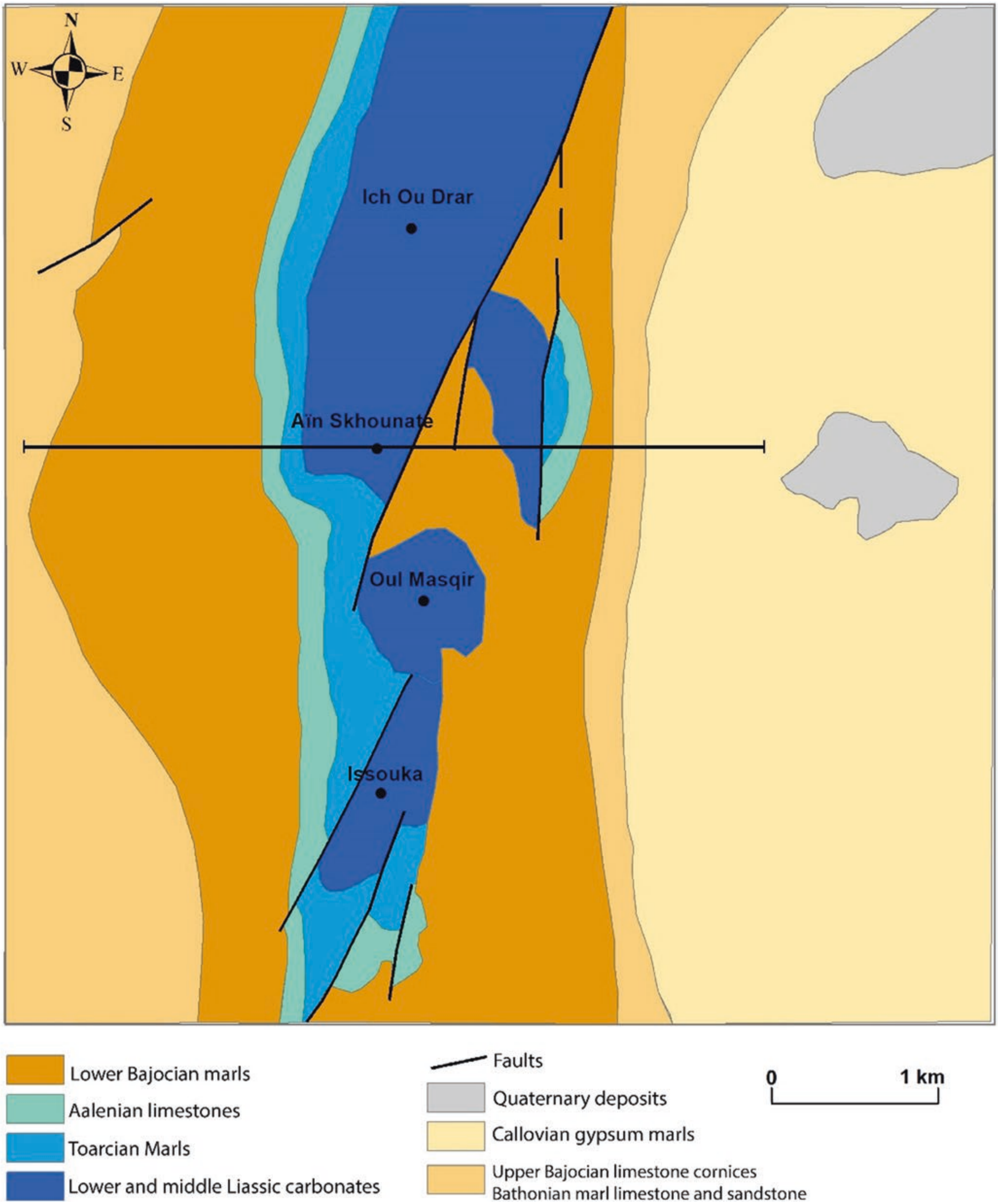

Fig. 8.6 Geological map of the Aïn Skhounate geosite. (Fedan 1988; Baadi 2021)

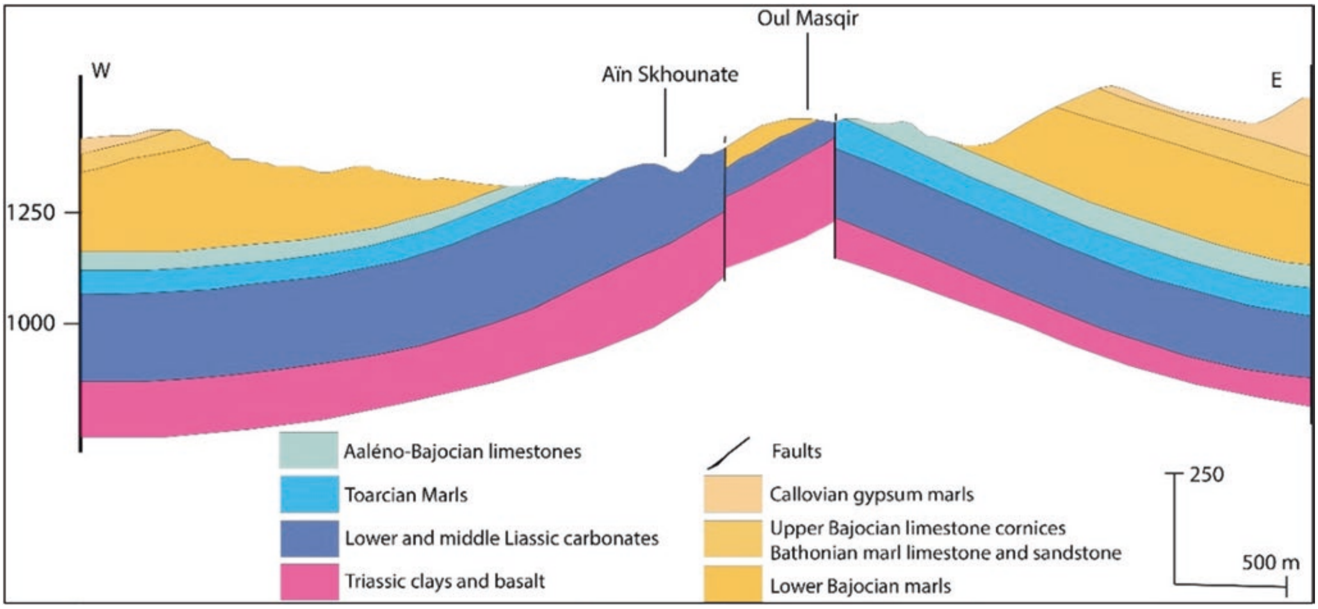

Fig. 8.7 Geological section of the Aïn Skhounate geosite. (Baadi 2021)

springs of Oum Er-Rbia gush out at the level of the Liassic carbonates or in contact with the Triassic saliferous clays. The waters that gush out in contact with the Liassic carbonates and Triassic clays are brackish and have a low flow rate. On the other hand, the springs that gush out of the carbonate formations are soft and have a high flow rate (Bentayeb and Leclerc 1977).

The springs of the Oum Er-Rbia geosite are among the most important springs in Morocco. These springs supply the region with drinking water which is also used for agriculture.

8.3.6 Zaouiat Ifrane

The geosite of Zaouiat Ifrane (Hyd128) is located 47 km north-east of Khénifra (Fig. 8.2). This geosite is composed of waterfalls among the most important in the region, by their flow and their travertine formations.

The geosite of Zaouiat Ifrane corresponds to springs that waterfall down (Fig. 8.11a). These waterfalls flow over ancient Quaternary travertines (Martin 1981). These travertines form steps and draperies on the slope that veil the structure (Fig. 8.11b). They are favoured by the agitation of the water and the presence of a significant plant diversity composed essentially of climbing plants, algae and mosses.

The geosite of Zaouiat Ifrane is an educational site because of its height, its flow and its important travertine precipitation.

8.3.7 Lake Afourgagh

The Lake Afourgagh geosite (Hyd108) is located 36 km north-east of Ifrane (Fig. 8.2). This geosite is a good example for paleoclimatological and sedimentological studies of a lake system.

The Lake Afourgagh geosite is an oval-shaped endoreic lake (Fig. 8.12a) with an area of about 12 ha. Its depth, which varies according to the year and the season, is on average 6 m. This lake is fed by snowmelt, runoff from the catchment area and the springs of Aïn Jorf and Aïn Takeltount. It is located in Liassic dolomite field, below the escarpment of the Tizi n'Tretten accident.

The lake, of tectono-karstic origin, is located within a depression occupied by alluvial cones and travertine formations (Fig. 8.12b). The genesis of this lake would be linked to an intense karstification and to the vertical play of the Tizi n'Tretten accident and the N130, N80 and N170 fault sets (Hinaje 2004).

Until the 1980s, Lake Afourgagh was the most important site in the Middle Atlas for breeding and wintering migratory birds (Thévenot 1995). Up to 300 Red-headed Shelducks were recorded in November 1978 and the Crested Coot was breeding there (Thévenot 1995). Fish are represented by *Esox lucius* and *Micropterus salmoides* (Chergui et al. 1999). The vegetation consists of *Ranunculus millifoliatus*, *Polygonum amphibium*, *Myriophyllum spicatum*, *Typha* sp. and *Phragmites communis*.

Fig. 8.8 (**a**) General view of the Liassic terrain of the Oul Masqir mountain; (**b**) Aïn Skhounate spring gushing out of the lower Liassic limestone; (**c**) Aïn Skhounate spring; d) Spring water flowing into a basin

Fig. 8.9 (**a**) Ras El Ma resurgence; (**b**) Ras El Ma spring water flows

8.3.8 Aguelmam Azegza

The geosite of Aguelmam Azegza (Hyd18) is located 46 km west of Khénifra (Fig. 8.2). This geosite hosts one of the most important alkalitrophic lakes in the Middle Atlas.

The Aguelmam Azegza geosite (Fig. 8.13a) is an endoreic lake with an area of about 50 ha and a maximum depth of 16 m. In August 2021, the lake shrank considerably

Fig. 8.10 (**a**) Water from the Oum Er-Rbia springs forming a waterfall; (**b**) Summering points at the edge of the Oum Er-Rbia

Fig. 8.11 (**a**) Zaouiat Ifrane waterfall with a 25 m high waterfall; (**b**) Travertine draperies of the Zaouiat Ifrane waterfall

(Fig. 8.13b). This lake belongs to the upper hydrological basin of the Oum Er-Rbia. It occupies a deep tectonic polje (Martin 1981) lying in a NW-SE direction. The fields that constitute this lake are Lower Liassic carbonates (Fig. 8.13c). In its south-eastern part, the lake is dominated by dolomitic walls affected by large detachment cracks (El Khalki and Akdim 2001). Indeed, the waters of the lake are slightly alkaline (pH = 8.3) with calcic and magnesium bicarbonate facies reflecting the carbonate nature of the enclosure (Adallal 2019). These waters can freeze frequently, at least partially at the edges, during short winter periods.

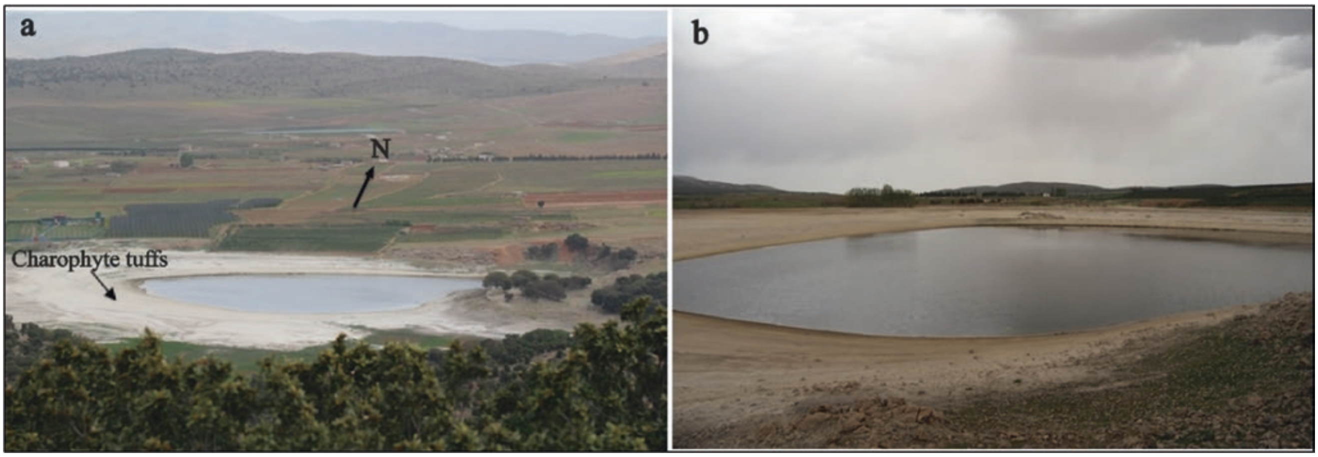

Fig. 8.12 (**a**) Lake Afourgagh geosite occupies a depression in its margins are filled with Charophyte tuffs; (**b**) Overview of the Lake Afourgagh geosite

Fig. 8.13 (**a**) The Aguelmam Azegza lake occupying a SE-NW oriented polje; (**b**) Lake appearing within the carbonate formations of the Lower Lias; (**c**) A sudden decrease of the lake level (October 2021)

In the region where this lake is located, the average precipitation is 1150 mm/year, largely in the form of snow, which can sometimes persist on the high slopes until April. The absence of an outlet and the relative durability of this lake can be explained by a more or less direct relationship with the water table that develops at the contact between the Lias and the Trias (El Khalki and Akdim 2001).

This geosite is classified by the Moroccan Protected Areas (APM) in the list of Sites of Biological and Ecological Interest (SIBE). It is known for the breeding of rainbow trout

(*Oncorhynchus mykiss*), European pike (*Esox lucius*), perch (*Perca fluviatilis*), common carp (*Cyprinus carpio*) and roach (*Rutilus rutilus*). The aquatic vegetation is composed of *Myriophyllum spicatum*, *Polygonum amphibium*, *Ceratophyllum demersum*, *Glygeria fluitans* and especially *Ranunculus aquatilis* and *Chara* sp. (Chillasse et al. 2001). Several species of mammals (monkeys, wild boars, hares, etc.) and several species of birds (ravens, thrushes, jays, magpies, etc.) can be found in the vicinity of the lake.

8.3.9 Aguelmam Sidi Ali

The geosite of Aguelmam Sidi Ali (Hyd35) is located 26 km north of Timahdite (Fig. 8.2). It is located at the NW foothills of the Jbel Sidi Ali anticline (2338 m).

This geosite (Fig. 8.14a) is the largest natural lake in the Middle Atlas by area and depth and also the only volcanic dam lake in the range. The lake is located at the NW foothills of the anticlinal fold of the Jbel Sidi Ali (Fig. 8.14b). Its NW flank is affected by the SMAF (South Middle Atlas Fault). The crest of this fold shows the Triassic salt formation. The bottom of the lake is covered by basalts emitted by the Sidi Ali volcano north of the lake (Fig. 8.14c).

The Aguelmam Sidi Ali lake is an endoreic type lake with a length of 3254 m and a width of 1010 m. It is 36 m deep. This lake is part of a complex of wetlands formed on the one hand by a main lake and on the other hand by a large wet plain (the Taânzoult plain) criss-crossed by streams from different springs. The lake is fed by meteoric water, karstic springs (Aghbalou Ou Mançour and Aghbalou Taddat) and by a few intermittent streams. Its waters are alkalitrophic (Chillasse et al. 2001) and its level is subject to very strong annual variations under the influence of climatic conditions. This lacustrine depression has a drainage corridor intersected by the present valleys (Drech 1952).

The Aguelmam Sidi Ali lake is an exceptional and very important site for Morocco. Indeed, its genesis is different from that of the other Moroccan lakes which are, for the most part, of tectono-karstic origin. It corresponds to a volcanic dam lake (Martin 1981). Its collapse is linked to the dissolution of coalescing pockets of salts in the underlying Triassic saliferous layers (Martin 1981). The tectonic play of two main NE-SW trending faults and other submeridian trending faults have guided the elongated shape of this lake (Hinaje 2004).

This geosite also has ecological values of great interest, which is why it has been included in the SIBE and RAMSAR lists of wetlands at international level since 1980. The site is also important for the wintering of certain species. Several fish species such as *Esox lucius*, *Rutilus rutilus*, *Oncorhynchus mykiss* and *Salvelinus fontinalis*. Several bird species live together on this geosite. Only the south-eastern side of the lake is covered by Cedar (*Cedrus atlantica*), Holm oak (*Quercus rotundifolia*), Oxycene juniper (*Juniperus oxycedrus*), Phoenician juniper (*Juniperus phoenicea*) and Thuriferous juniper (*Juniperus thurifera*).

8.3.10 Dayet Ifrah

The Dayet Ifrah geosite (Hyd100) is located 25 km east of Ifrane (Fig. 8.2). This geosite is one of the lakes of the Middle Atlas that has a significant geological and biological diversity typical of the whole chain.

Dayet Ifrah is a sub-rounded endoreic lake with a surface area of 250 ha and a depth of 8 m. It is fed mainly by groundwater discharge, direct precipitation (snow and rain) and surface runoff during the wet season (Etebaai 2009). It is fed mainly by the emergence of groundwater, direct precipitation (snow and rain) and surface runoff during the wet season (Etebaai 2009). The stagnant and eutrophic waters of the lake are calc-magnesium, relatively alkaline, well oxygenated and supersaturated in alkaline earths (Etebaai 2009).

The lake is situated on Lower Lias dolomitic-limestone and also shows Quaternary alluvial fans. It occupies a flat-bottomed depression (Fig. 8.15a) which is filled with decalcification residues and lacustrine alluvium (Martin 1981). To the south (Fig. 8.15b) and north, the lake is bounded by ENE-WSW faults. The western side is characterised by the Tizi n'Tretten fault zone, whose plays are syn- and post-sedimentary. In addition to the tectonic factor, surface karst excavation has operated in conjunction with tectonic movements since the end of the Tertiary and during the Quaternary to give rise to the Dayet Ifrah lake (Martin 1981). During the Quaternary, erosion reinforced the karst action in the lake (Martin 1981).

The Dayet Ifrah lake is rich in fish such as *Esox lucius*, *Rutilus rutilus*, *Phoxinus phoxinus* and *Perca fluviatilis* (Chergui et al. 1999). The flora is mainly composed of *Ranunculus millifoliatus*, *Potamogeton pectinatus* and *Tolypella hispanica*. A very sparse holm oak (*Quercus rotundifolia*) forest cover begins at some distance from the south-eastern edges of the lake. The invertebrate fauna of the lake is very diverse, although its abundance is low compared to other lakes (Morgan 1982).

8.3.11 Guelta Tameda

The Guelta Tameda geosite (Hyd105) is located 28 km south of Meghraoua (Fig. 8.2), SE of Jbel Nerkibat (2120 m) which is part of the second anticlinal rift (Fig. 8.16). Guelta Tameda corresponds to a reservoir of superficial water that occupies the Souf Igrane valley located upstream of the Oued Tmourhout valley. This geosite presents singular characteris-

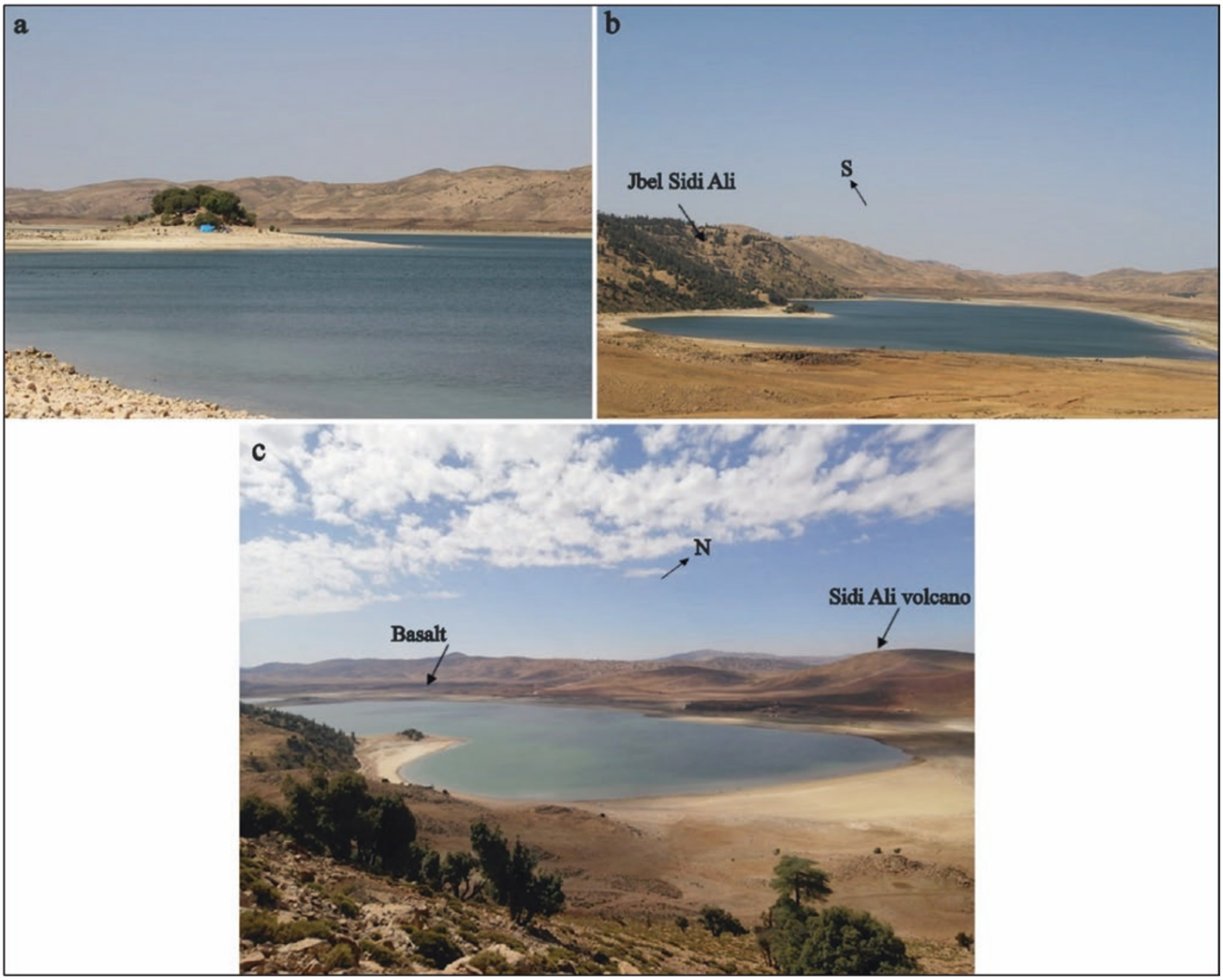

Fig. 8.14 (**a**) Aguelmam Sidi Ali lake at the foothills of Jbel Sidi Ali; (**b**) Whitish sands deposited on the edges and around a small islet in the middle of the lake; (**c**) Basalt on the edge of the lake from the Sidi Ali volcano to the north

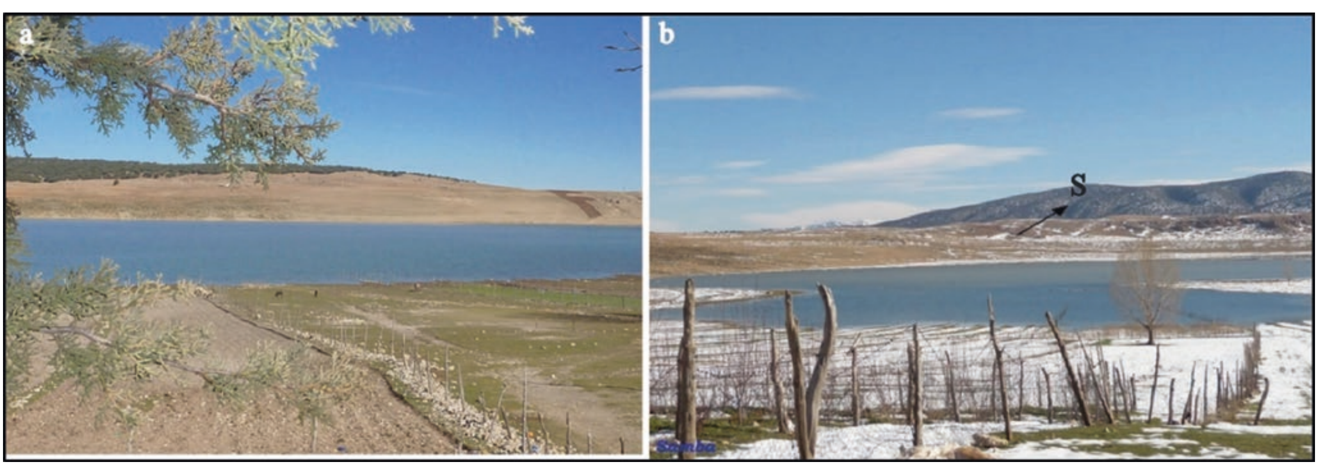

Fig. 8.15 (**a**) and (**b**) Dayet Ifrah lake occupying a large flat-bottomed depression

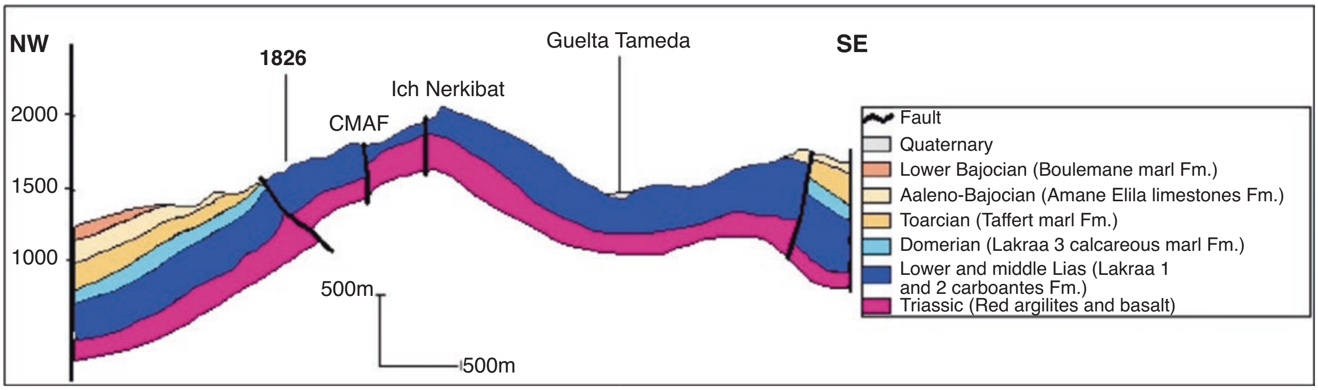

Fig. 8.16 Geological section of the Guelta Tameda geosite. (Baadi et al. 2021)

tics of the only natural dam lake in the Middle Atlas whose origin is linked to the collapse of large masses of Liassic carbonates.

Guelta Tameda is located in a karstified geomorphological context. It is essentially formed by Liassic calcaro-dolomitic outcrops (Fig. 8.16) which characterise the framework of the second Ich Nerkibat rift (Fig. 8.17a). The NW slope of the lake is fractured and destabilised by the effect of karstification and the abundance of different CMAF (Central Middle Atlas Fault) branches. A seismic event (El Fellah 1994) linked to a quaternary replay of the ACMA affecting Jbel Nerkibat, caused a collapse of large masses of Liassic rocks and gave rise to a natural dam lake. These masses block the deep valley of Souf Igrane and stand as a chaotic bulge at the bottom of the valley. The distance covered by the debris varies between 500 and 1500 m. Its volume is estimated on the average surface of the lake of about 80 ha.

The lake is known to fill up seasonally during the rainy months and also during the snowmelt period (Fig. 8.17b). It empties almost completely during the summer (Fig. 8.17c) by evaporation and especially by karstic losses that probably feed the Aïn Bared spring through an underground karstic network.

The geosite is one of Morocco's protected areas and is included in the list of SIBE sites. It is original in its genesis, its dynamics and the beauty it offers to the steep valley it occupies. It is also the only lake in the northern Middle Atlas. The lake is surrounded by cedar forests (*Cedrus atlantica*) and holm oak (*Quercus rotundifolia*). Numerous species of birds, including Bonelli's Eagle (*Aquila fasciata),* naturally find favourable environments for maintaining their populations in the region.

8.3.12 Tiguelmamines

The Tiguelmamines geosite (Hyd125) is located 26 km southwest of Timahdite (Fig. 8.2). This geosite corresponds to the juxtaposition of three tectono-karst lakes.

The three lakes of the Tiguelmamines geosite (Fig. 8.18a) are located in the Lower Lias dolomitic limestone formation (Fig. 8.18b). They belong to a small catchment area of about 7.45 km^2. These lakes are called: North Lake, Central Lake and Southern Lake. They are connected to each other by swampy areas. The North Lake has the smallest surface area. The Southern Lake is 20 m deep and has the deepest basin. It is extended to the south by a ravine which constitutes an outlet. The Central Lake is 18 m deep and has a marshy area with dense vegetation around its edges. The water of the Tiguelmamines geosite has an average mineralisation that is among the lowest of the Middle Atlas lakes (Chillasse et al. 2001).

This geosite is located in a humid climate zone (average temperature 10 °C). It receives approximately 930 mm/year of rainfall. During rainy periods, the watercourses surrounding the geosite temporarily feed it. During heavy rainfall, the lakes and swamps overflow, and the surplus water is evacuated through the outlet to the south to join the Oued Srou (a tributary of the Oum Er-Rbia Oued) (Adallal 2019).

The slopes of the Tiguelmamines geosite are planted with different species dominated by Holm oak (*Quercus rotundifolia*) and Atlas cedar (*Cedrus atlantica*). *Myriophyllum spicatum*, *Ranunculus aquatilis* and *Chara* sp. are abundant in some places, and the emergent riparian vegetation consists of *Juncus bufonius* (Chillasse et al. 2001).

8.4 Conclusion

Recent works have warned of the effect of climate change on geoheritage (Gordon et al. 2022; Selmi et al. 2022). These effects are also more easily noticed in geosites where water is the most valuable element of geodiversity. In regions like the Middle Atlas, where the increase of air temperatures is accompanied by the reduction of precipitation, climate change may further accelerate degradation of hydric geosites.

By comparing the data on the existing maps and aerial photography and their current state in the field, we have

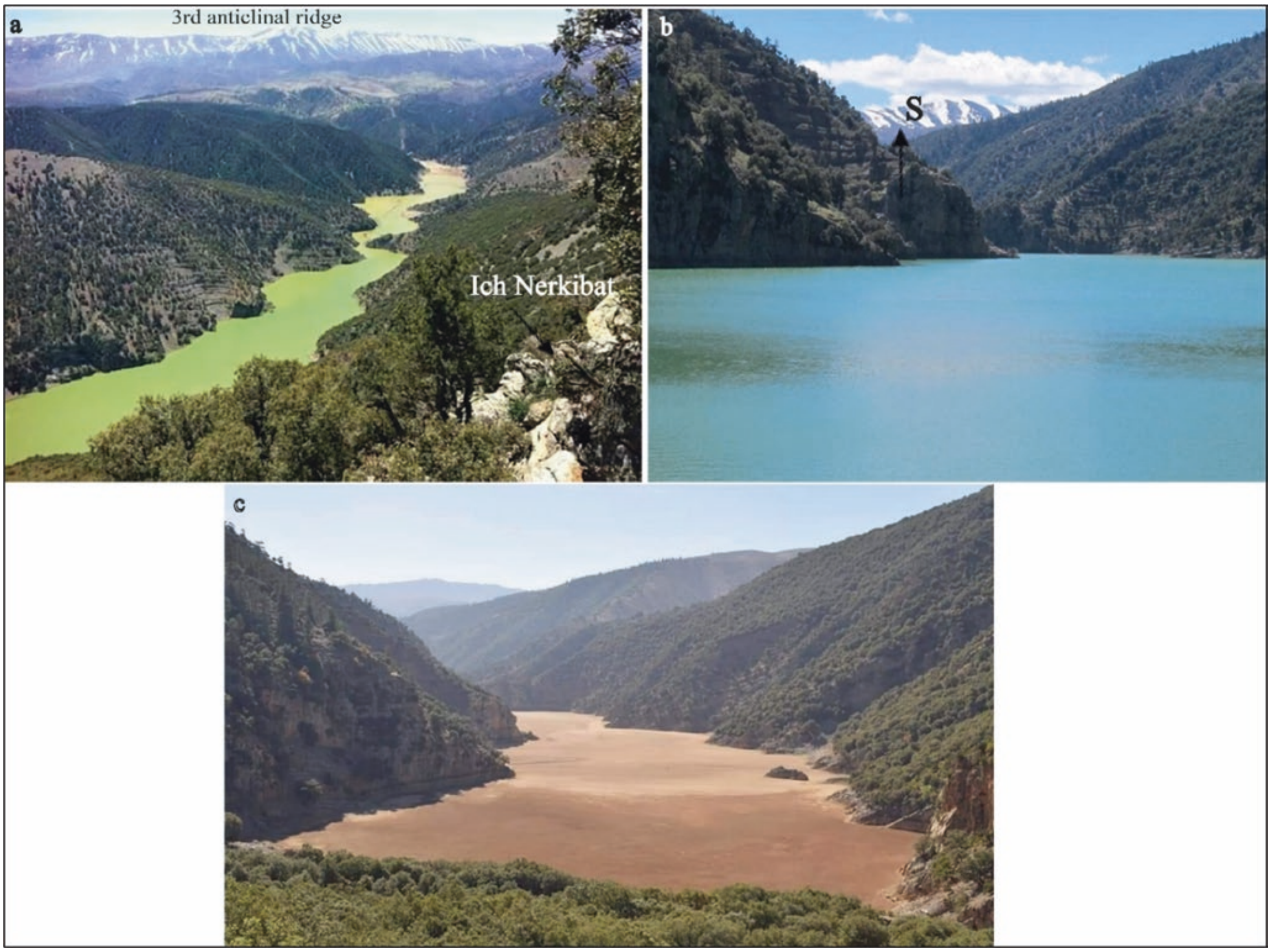

Fig. 8.17 (**a**) Guelta Tameda lake at the foothills of the second Ich Nerkibat rift; (**b**) Guelta Tameda natural reservoir; (**c**) Guelta Tameda lake empties almost completely in summer (Credit photo (c): Hakim Bouhlala)

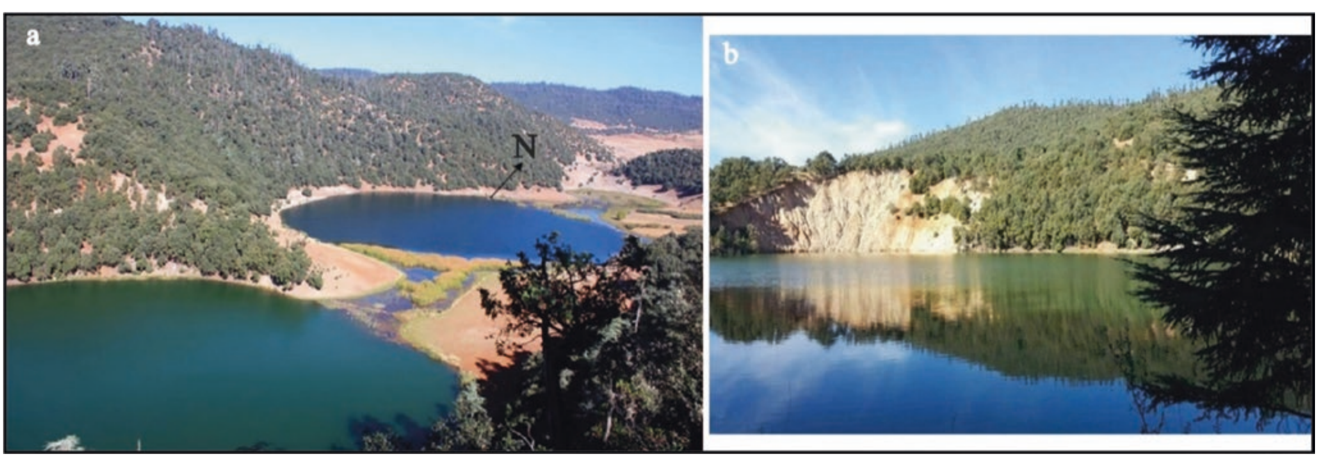

Fig. 8.18 (**a**) Tiguelmamines lakes aligned in an N-S direction; (**b**) Location of the lakes within the lower Lias carbonate formations

noticed that some springs and lakes are experiencing a significant reduction in their levels or even a total drying up, with their location been identified only by means of topographic maps.

Anthropic activities lead also to the deterioration of these geosites. Groundwater is the main source of the springs and lakes of the Middle Atlas, being overexploited by arboriculture. Tourism activities are concentrated mainly in the regions of Imouzzer Kandar and Ifrane, in order to meet the excessive water needs generated by leisure activities (swimming pools and water games) and gardening, and the local lodges and hotels are also important water consumers.

This is thus a situation where the natural resource (water) that is essential to human activities and socio-economic development is, at the same time, the main element of this type of geoheritage and that could sustain local geotourism and educational activities. These human activities should be managed so as not to compromise the sustainability of this social, economic and tourism resource, while avoiding its deterioration.

With the expected decrease in precipitation due to the ongoing climate change and the increased human pressure on this resource, it is important to rethink some activities that require large amounts of water resources, such as leisure activities. The deterioration of this heritage may be irreversible if this sustained management is not done, besides that without this value, the viability of many leisure and tourism activities may be compromised.

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Fluvial Heritage of the Middle Atlas (Morocco): An Essential Element for Regional Sustainable Development

9

Khaoula Baadi

Abstract

Sheltered by its three largest rivers in the country (Sebou, Oum Er-Rbia and Moulouya), the Middle Atlas is the most diversified region of Morocco by its river landscapes reflecting the integration of several geological characteristics. These characteristics are an essential element for sustainable development. The production of an inventory and an assessment of the fluvial heritage is one of the essential axes of this development. It is based on a field study of multitudes of potentially unique geological features and on the analysis of literature data favoring the fluvial landscape of the region. The latter is home to unique and rare sites across the country. A total of 23 fluvial geosites, representing valleys and canyons, have been inventoried. Given the diversity of fluvial morphology elements present in the region, a quantitative assessment and determination of the degree of deterioration of all geosites was carried out. Seven geosites have reached the stage of usage values and are to be exploited for geoeducational and geotourism purposes out of a total of 23 geosites, which represents 30.4% of the sites listed. Three geosites (Bizi, Taffert and Taferdoust) have been chosen for a possible detailed study hosting rare and unique characteristics on a regional and even national scale.

Keywords

Fluvial heritage · Inventory · Assessment · Sustainable development · Middle Atlas

K. Baadi (✉)
Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, Fez, Morocco

9.1 Introduction

The term geological heritage has been widely used over the past three decades to define geological features that are important to society because of their uniqueness (Gray 2008; Henriques et al. 2011; Wimbledon and Smith-Meyer 2012; Henriques and Brilha 2017; Reynard and Brilha 2018). The term fluvial heritage has not taken hold by geoscientists despite the fact that it designates an important element of geoheritage and which can be used for sustainable uses. This type of heritage provides important information on unique geological phenomena serving social and economic purposes.

The Middle Atlas has a hydric potential which is manifested by the most important rivers in the country which flow over hundreds of kilometers. Its flows have shaped the Middle Atlas fluvial landscape giving a remarkable morphology of valleys (Fig. 9.1), meanders, canyons, etc. The fluvial heritage is exceptional in this chain due to a combination of several geomorphological, lithological and structural elements. These elements have given rise to a multitude of forms, controlled by erosion, which are among the most spectacular in the country.

Despite the existence of numerous works on the field, an inventory and an assessment of the geosites based on scientific and tangible criteria has not been carried out. Thus, the region lacks a recent study on the evolution of fluvial forms in the Middle Atlas and an absence of a census of the canyons in the region. In this work, an inventory and an assessment of fluvial geosites were carried out taking into account several criteria (Baadi 2021). The geosites were selected to represent 2 main elements of the Middle Atlas landscape: (i) valleys and (ii) canyons. Representativeness, rarity, geological diversity, state of preservation and documentation were the criteria used for the selection of fluvial geosites. The degree of deterioration of geosites and their usage values were also assessed in order to determine management priorities.

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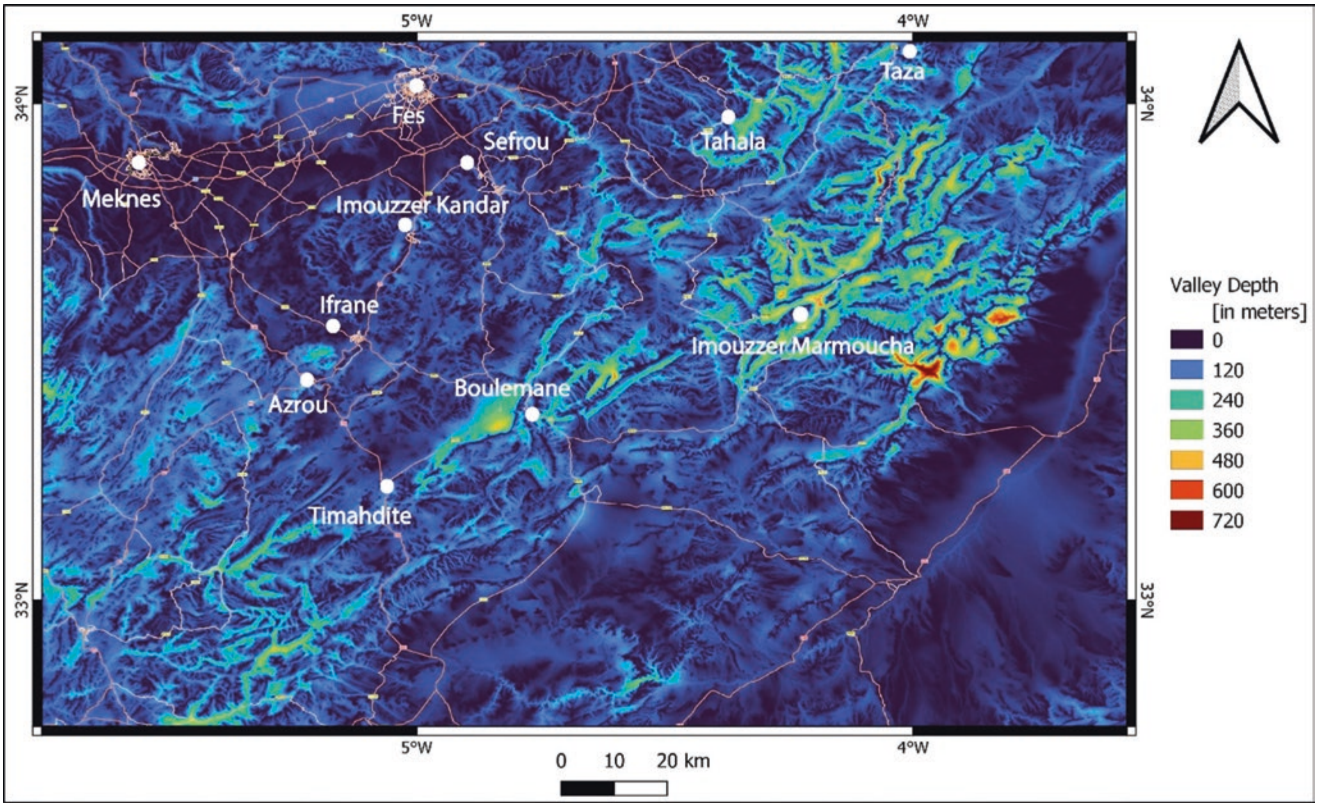

Fig. 9.1 Valley depth map of the Middle Atlas was created on the basis of SRTM 30-m resolution digital terrain model (DEM) using SAGA Next Generation software within QGIS 3.26.3 (Buenos Aires) environment

The need to carry out an inventory and assessment of the fluvial heritage is considered as a need for a better understanding of the diversity of the Middle Atlas fluvial landscape as well as its usefulness for economic development.

9.2 Fluvial Landscape

The lithological diversity, the influence of tectonics during the Alpine orogeny, the morphology of the land, the hydric potential and the karst had a strong implication on the current fluvial morphology. Because of all these elements, the river landscape provides an important database of Earth history, especially as indicators of tectonic, climatic and eustatic events. The digging and the incision of the rivers (Fig. 9.1), which are of order three (the Sebou in the northeast, the Oum Er-Rbia in the southwest and the Moulouya in the south and are the largest rivers in the country which originate in the Middle Atlas), have created innumerable forms. Volcanism has also left its mark on the river landscape. The lava flows profoundly altered the river landscape filling in the old thalwegs and forcing the rivers to erode their new valleys by incising winding canyons in the basalts.

9.3 Fluvial Heritage

The fluvial heritage presents lithological, structural, hydrological, karstic and even volcanic characteristics. This heritage is representative in the folded Middle Atlas due to greater diversity and geomorphological and structural complexity of the terrain compared to the subtabular Causse. This heritage diversity revolves around innumerable river sites composed of canyos and valleys. By applying the methodology of Baadi et al. (2020), 23 geosites "Flu" were inventoried according to well-defined criteria (Table 9.1). There are 21 canyon type geosites and 2 valley type geosites.

During the quantitative assessment "Ss," 2 geosites out of 23 inventoried geosites presented an Ss $\geq$ 2.5, 5 had a 1.5 $\leq$ Ss $<$ 2.5, and the remaining 16 had an Ss $<$ 1.5 (Table 9.2). The latter were withdrawn from the selection due to their low scientific value.

Seven geosites were therefore selected for the "Sd" degree of deterioration stage (Table 9.3). Among these seven geosites, no geosite has an Sd $\geq$ 2.5, four had a 1.5 $\leq$ Sd $<$ 2.5 and three had an Sd $<$ 1.5. As for the results of the calculation of their total "Sv" value, this was positive for the seven geosites, which indicates that the scientific value exceeds the

Table 9.1 Inventory of fluvial geosites

Fluvial geosites	Identification code	Type of geosite	Coordinates			Administrative location	Property	Extended	Accessibility	Protected area
			X	Y	Z					
Aghbal	Flu01	Canyon	33° 2′41.85″N	5°28′51.10″W	1252	Khénifra	Public	–	Medium	No
Aït Ou Hammou	Flu02	Canyon	33° 3′27.30″N	5°22′44.59″W	1346	Al Hammam	Public	–	Difficult	No
Assaka	Flu03	Canyon	33°28′25.49″N	4°38′19.29″W	1216	Boulemane	Public	–	Difficult	No
Bizi	Flu04	Canyon	33°57′37.32″N	3°57′43.74″W	1160	Meghraoua	Public	–	Difficult	No
El Aouinate	Flu05	Canyon	33°35′55.26″N	4°46′28.40″W	1487	Guigou	Public	–	Difficult	No
El Herahir	Flu06	Canyon	33°38′29.98″N	4°59′28.23″W	1504	Imouzer Kandar	Public	–	Easy	No
Fellat	Flu07	Canyon	33° 3′2.69″N	5°16′50.26″W	1616	Bekrit	Public	–	Difficult	No
Gorge d'Issouka	Flu08	Canyon	33°26′58.14″N	4°20′17.37″W	1358	nouzer Marmouch	Public		Medium	No
Gorges d'El Mahssere	Flu09	Canyon	33°32′30.59″N	4°24′36.70″W	1031	Tilmirate	Public	–	Difficult	No
Hayane	Flu10	Canyon	33°43′19.61″N	4°13′37.40″W	1235	Ribat al Khayr	Public	–	Difficult	No
Issoumat	Flu11	Canyon	33°27′48.13"N	4°40′56.14"W	1375	Boulemane	Public	–	Difficult	No
Jbel Lbghel	Flu12	Canyon	33°28′51.76″N	4°42′56.16″W	1437	Boulemane	Public	–	Difficult	No
Jider	Flu13	Canyon	33°43′42.55″N	4°14′17.81″W	1147	Ribat al Khayr	Public	–	Difficult	No
Oudiksou	Flu14	Canyon	33°15′0.02"N	4°50′10.90"W	2269	Achlouj	Public	–	Difficult	No
Qalaa	Flu15	Canyon	33°56′26.84″N	3°59′33.74″W	1005	Meghraoua	Public	–	Difficult	No
Taferdoust	Flu16	Valley	33°28′16.86″N	4°39′4.00″W	1285	Boulemane	Public	–	Easy	No
Taffert	Flu17	Canyon	33°44′0.66″N	4°14′21.98″W	1187	Ribat al Khayr	Public	–	Difficult	No
Taghzout	Flu18	Canyon	33°29′36.62″	4°44′5.38″W	1695	Boulemane	Public	–	Difficult	No
Tazemmakt	Flu19	Canyon	33° 10′3.61 ″N	5°10′37.41″W	1741	Timahdite	Public	–	Difficult	No
Teminte	Flu20	Canyon	33°45′44.03″N	5° 8′38.36″W	1084	El Hajeb	Public	–	Medium	No
Tiguelmamine	Flu21	Canyon	33°46′17.63″N	5°11′45.66″W	888	El Hajeb	Public	–	Easy	No
Tijma	Flu22	Canyon	33°29′16.58″N	4°48′23.42″W	1577	Imouzer Kandar	Public	–	Medium	No
Tmourhout	Flu23	Valley	33°54′19.99″N	4° 1′37.31″W	887	Meghraoua	Public	–	Difficult	No

Table 9.2 Quantitative assessment of fluvial geosites

Fluvial geosites	Critera of quantitative assessment (Ss)					Total of pointing	Final scoring matrix (Ss)					Total of Ss	Result (Ss)
	Representativeness	Rarity	Geological diversity	State of preservation	Documentation		Representativeness *24%	Rarity *18%	Geological diversity*20%	Estate of preservation*24%	Documentation*14%		
Aghbal	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Aït Ou Hammou	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Assaka	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Bizi	3	3	2	1	1	10	0.72	0.54	0.4	0.24	0.14	2.04	Medium
El Aouinate	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
El Herahir	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Fellat	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Gorge d'Issouka	1	1	2	1	1	6	0.24	0.18	0.4	0.24	0.14	1.2	Low
Gorges d'El Mahssere	1	1	2	1	1	6	0.24	0.18	0.4	0.24	0.14	1.2	Low
Hayane	1	2	2	1	2	8	0.24	0.36	0.4	0.24	0.28	1.52	Medium
Issoumat	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Jbel Lbghel	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Jider	2	2	2	1	2	9	0.48	0.36	0.4	0.24	0.28	1.76	Medium
Oudiksou	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Qalaa	2	3	3	1	1	10	0.48	0.54	0.6	0.24	0.14	2	Medium
Taferdoust	3	3	3	1	3	13	0.72	0.54	0.6	0.24	0.42	2.52	High
Taffert	3	3	3	1	3	13	0.72	0.54	0.6	0.24	0.42	2.52	High
Taghzout	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Tazemmakt	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Teminte	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Tiguelmamine	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Tijma	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Tmourhout	2	2	2	1	2	9	0.48	0.36	0.4	0.24	0.28	1.76	Medium

Table 9.3 Degree of deterioration of fluvial geosites

Fluvial geosites	Critera of degree of deterioration (Sd)					Total of pointing	Matrice de notation finale (Sd)					Total of Sd	Result (Sd)
	Vulnerability	Fragility	Accessibility	Demography	Number of visitors		Vulnerability *19%	Fragility *19	Accessibility *25%	Demography *20%	Number of visitors *17		
Bizi	2	3	1	1	1	8	0.38	0.57	0.25	0.2	0.17	1.57	Medium
Hayane	2	2	1	1	1	7	0.38	0.38	0.25	0.2	0.17	1.38	Low
Jider	2	3	1	1	1	8	0.38	0.57	0.25	0.2	0.17	1.57	Medium
Qalaa	2	2	1	1	1	7	0.38	0.38	0.25	0.2	0.17	1.38	Low
Taferdoust	3	2	2	1	1	9	0.57	0.38	0.5	0.2	0.17	1.82	Medium
Taffert	2	3	1	1	1	8	0.38	0.57	0.25	0.2	0.17	1.57	Medium
Tmourhout	2	2	1	1	1	7	0.38	0.38	0.25	0.2	0.17	1.38	Low

value of the degree of deterioration of the geosites and means that the geosites have a significant overall value.

Finally, for the “Su” usage values (Table 9.4), the seven geosites had a $1.5 \leq Su < 2.5$.

9.3.1 Fluvial Geosites

3 fluvial geosites are studied below and are chosen among the geosites selected by their high score of criteria of representativeness, rarity and geological diversity.

9.3.1.1 Bizi

Bizi (Flu04) is located 8 km east of Meghraoua. This geosite corresponds to canyons with its vertical and vertiginous walls and its deep waters. These canyons correspond to a lock of NW-SE direction which crosses the relief of Jbel Lahmar. The latter is part of the second anticline affected by the CMAF (Central Middle Atlas Fault). The NW flank of this anticline shows, here, reverse thrust faults toward the NW (Fig. 9.2).

The Bizi canyons (Fig. 9.3a), which are 4 km long, correspond to a set of three sections of canyons. They are much deeper than wide (Fig. 9.3b). In places, they do not exceed 8 m in width (Fig. 9.3c). Between each of them there are small lakes whose depth can reach 4 m in April. The canyons are dug in the carbonate terrains of the Lower Lias to a depth of 100 to 150 m, which illustrates the long periods of fluvial erosion which affect these rocks.

The canyons are in a region with a subarid to subhumid climate. The important flow and the permanence of the flows of the Oued influenced the formation of these canyons. The flow of the Oued crossing the canyons decreases during the summer and becomes important in the spring which is the period of snowmelt.

9.3.1.2 Taffert

Taffert (Flu17) is located 32 km southeast of Ribat al Khayr. This geosite shows the longest canyons (Fig. 9.4) in the Middle Atlas and probably in Morocco.

The Taffert canyons have vertiginous and rugged walls up to 300 m high (Fig. 9.5a). With a length of 10 km, their width, in places, does not exceed 1 m. Along their course, the Taffert canyons are joined by six secondary canyons (Baadi et al. 2021). Three of them are wider (40 m) and are dug in Domerian marl-limestone and the other three, very narrow (1 m), are dug in Lower Lias carbonates.

The narrow canyons of Taffert have subvertical walls (Fig. 9.5b). They are dug in an alternation of competent levels (hard limestone of the Lower Lias) and others easily altered (marl-limestone of the Domerian) by the Oued Tnidilt. Their formation is the result of a fairly rapid sinking by dissolution and very weak lateral erosion. Along these canyons, three waterfalls have been recognized (Fig. 9.5c).

The canyons of the Taffert geosite are part of the unique geosites of Morocco and are very little known to the general public as well as to geoscientists. It should be noted that the geosite is home to the presence of a population of Magots or Barbary Macaques (*Macaca sylvanus*). This geosite is also known for the harvesting of medicinal plants by the population of the Taffert sector.

9.3.1.3 Taferdoust

Taferdoust (Flu16) is located 18 km northeast of Boulemane. This geosite is one of the most important meandering valleys of the Middle Atlas.

The meander of Taferdoust (Fig. 9.6a) is narrowed and incised in the deep and winding valley of Oued Guigou. It is hosted in the Recifa formation which is composed of Upper Bajocian cornice limestones (Fig. 9.6b). This meander bypasses the perched Douar of Taferdoust (Fig. 9.6c) which is built on the limestone cornices showing a cliff. On the left bank of the valley are several alignments of cuestas corresponding to the oolitic bars of the Bou Akrabène-Ich Timellaline formation.

The geosite of the Meander of Taferdoust is a representative site due to its valley and its layers of limestone cornices where the Douar is perched, which testifies to the history of the region.

9.4 Importance of Fluvial Heritage on Sustainable Development

The Middle Atlas chain is endowed with a particular fluvial potential with a characteristic socio-economic power. The realization of an inventory of fluvial geosites and their assessment contribute to promote the fluvial heritage of the Middle Atlas through the sustainable economic development of the territory. They also help improve society’s recognition of diversity and the importance of preserving and conserving this unique heritage for the country. They serve as an important tool in the organization and hosting of educational and training activities at all levels of education in the enhancement of this heritage and in sustainable development policies.

The Middle Atlas fluvial heritage is important for conservation and exploitation for purposes of research, education and tourism. Geopedagogical and geotourism projects are currently among the main axes of regional sustainable development. Examples in the region of Taza and Ifrane are impressive on the educational and tourist level with awareness companies supervised by several associations which aim to make known the natural resources which abound in

Table 9.4 Usage values of fluvial geosites

Fluvial geosites	Criteria of usage values														Total de pointage	Total of pointing matrix (Su)												Total of Su	Result (Su)
	Geological diversity	Accessibility	Reputation	Ecological value	Cultural value	Infrastructure	Visibility	Terms of use			Number of visitors	Demography	Access restriction	Security		Geological diversity *8%	Accessibility *12%	Reputation *12%	Ecological value*4%	Cultural value*4%	Infrastructure *10%	Visibility *8%	Terms of use (a + b)/2*6%	Number of visitors *13%	Demography *4%	Access restriction *14%	Security *9%		
								a. Geotouristic	b. Geopedagogic	(a + b/2																			
Bizi	2	1	1	2	1	1	2	2	3	2.5	1	1	3	1	18.5	0.16	0.12	0.12	0.08	0.04	0.1	0.16	0.15	0.13	0.04	0.42	0.09	1.61	Medium
Hayane	2	1	2	2	1	1	2	2	3	2.5	1	1	3	1	19.5	0.16	0.12	0.24	0.08	0.04	0.1	0.16	0.15	0.13	0.04	0.42	0.09	1.73	Medium
Jider	2	1	2	2	1	1	2	2	3	2.5	1	1	3	1	19.5	0.16	0.12	0.24	0.08	0.04	0.1	0.16	0.15	0.13	0.04	0.42	0.09	1.73	Medium
Qalaa	3	1	1	2	1	1	2	2	3	2.5	1	1	3	1	19.5	0.24	0.12	0.12	0.08	0.04	0.1	0.16	0.15	0.13	0.04	0.42	0.09	1.69	Medium
Taferdoust	3	2	3	2	2	2	3	2	3	2.5	1	1	3	1	25.5	0.24	0.24	0.36	0.08	0.08	0.2	0.24	0.15	0.13	0.04	0.42	0.09	2.27	Medium
Taffert	3	1	3	2	1	1	2	2	3	2.5	1	1	3	1	21.5	0.24	0.12	0.36	0.08	0.04	0.1	0.16	0.15	0.13	0.04	0.42	0.09	1.93	Medium
Tmourhout	2	1	2	2	1	1	2	2	3	2.5	1	1	3	1	19.5	0.16	0.12	0.24	0.08	0.04	0.1	0.16	0.15	0.13	0.04	0.42	0.09	1.73	Medium

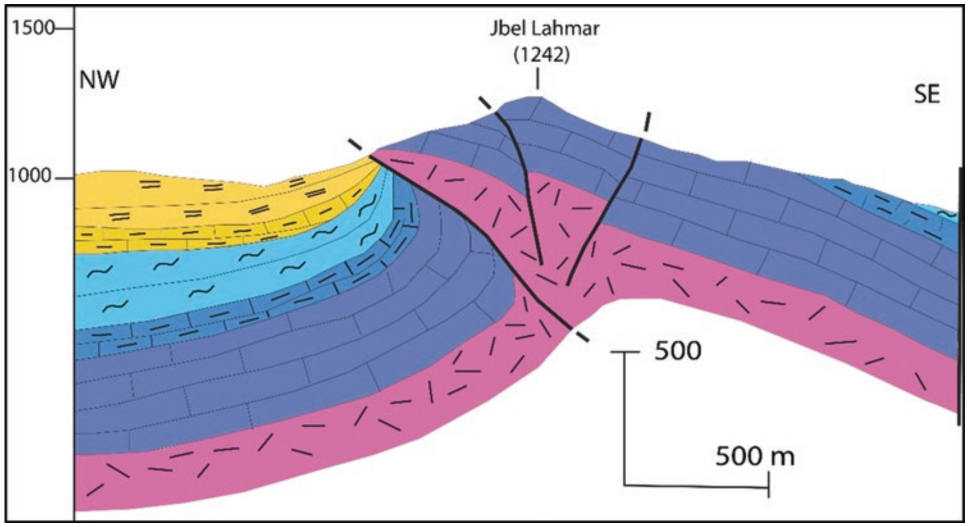

Fig. 9.2 Geological section of Jbel Lahmar. (Baadi 2021)

Fig. 9.3 (**a**) General view of one of the canyons of the Bizi geosite; (**b**) Waters of the Bizi canyons reach 4 m depth in winter; c) Width of canyons not exceeding 8 m

the region as well as the realization of outings accompanied by amateur guides and professionals to highlight the fluvial heritage. It is important that local authorities undertake to review their economic and social priorities for the economic development of the region while preserving this heritage. It is a question of developing this heritage as a raw material

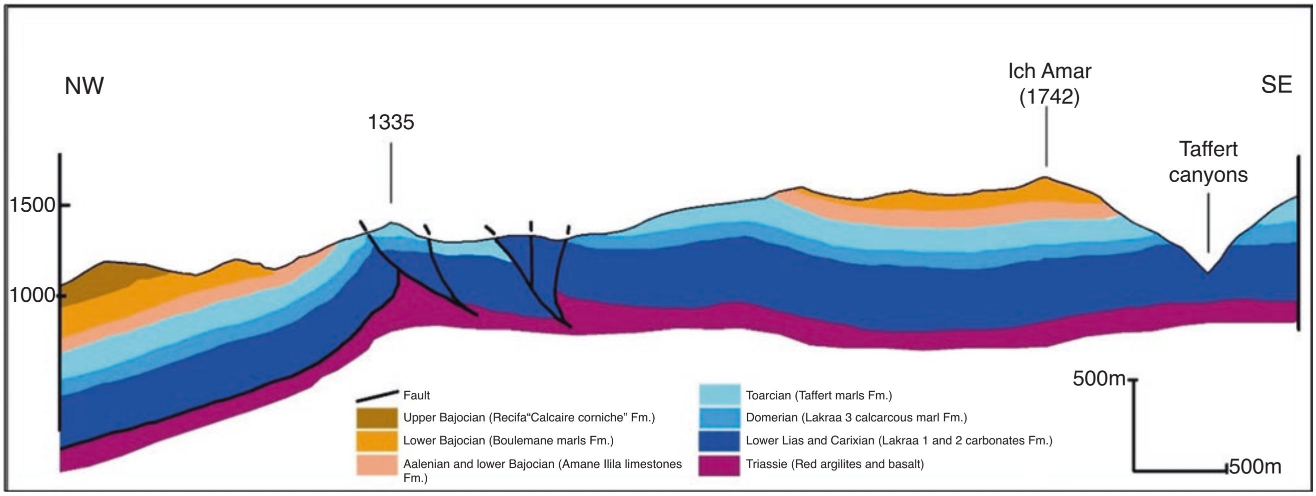

Fig. 9.4 Geological section of the Taffert canyons. (Baadi et al. 2021)

Fig. 9.5 (**a**) Vertiginous walls of the Taffert canyons; (**b**) Taffert canyons digging into the karstified lands of the Lias; (**c**) Waterfall on the walls of the canyons

Fig. 9.6 (**a**) Two sides of the valley; (**b**) Limestone cornices of the meander of Taferdoust; (**c**) Perched douar of Taferdoust

generating economic benefits for the local population in a territory abounding in a unique but unfortunately underprivileged and threatened river heritage.

9.5 Conclusion

The lithological, structural, hydric, karstic and volcanic heritage has marked these landscapes by giving the Middle Atlas chain an innumerable fluvial heritage. The different geological and geomorphological characteristics of this heritage make the Middle Atlas a crossroads of sites that deserves to be recognized and preserved. This set of sites has all the necessary assets to promote the river heritage through sustainable development projects.

The selection of fluvial geosites required good prior scientific knowledge of the geomorphological evolution of the terrain. Quantitative and degree of deterioration assessment serves as an important tool to determine the scientific value of geosites and their state of degradation in order to present the strengths and weaknesses of each geosite.

Among the 23 inventoried geosites, during the quantitative assessment "Ss," 2 out of 23 geosites presented an $Ss \geq 2.5$, 5 had a $1.5 \leq Ss < 2.5$ and the remaining 16 an $Ss < 1.5$. These results indicate that some sites had this rating of $Ss \leq 2.5$ because of their low state of preservation status. The quantitative assessment aims to obtain the best possible separation between the geosites. This separation is also reinforced by the fact that the highest score for each criterion is of order 3. For the assessment of the scientific value, the criterion of state of preservation is among the decisive criteria of the final score of the site, which explains the obtaining of only 2 sites out of 23 which have a high scientific value due to their location in protected territories.

For the next stage, seven geosites were selected for the stage of the degree of deterioration "Sd." Among these seven geosites, no geosite has an $Sd \geq 2.5$, four had a $1.5 \leq Sd < 2.5$ and three had an $Sd < 1.5$. This step showed that no geosite shows a high deterioration despite and the other sites a moderate to low deterioration. Despite these results, it is important that special attention should be paid and a priority for the management of geosites as part of a geoconservation strategy will be recommended.

As for the results of the calculation of their total “Sv” value, this was positive for the seven geosites, which indicates that the scientific value exceeds the value of the degree of deterioration of the geosites and means that the geosites have a significant overall value. However, out of 23, 7 geosites passed to the last stage of usage values, which represents 30.4% of the geosites listed and presented a $1.5 \leq Su < 2.5$.

The results obtained enabled 3 fluvial geosites (geosites of Bizi, Taffert and Taferdoust) to be selected for a detailed descriptive study by their representativeness, their rarity and their geological diversity. Among these geosites, three were studied. Two geosites have a high value of $Ss \geq 2.5$ (Taferdoust ($Ss = 2.52$) and Taffert ($Ss = 2.52$)) and the Bizi geosite ($Ss = 2.04$) which had a value of $1.5 \leq Ss < 2.5$.

During all these results, the first stage of inventory must be updated at a defined periodic frequency, and in this work, the inventory was carried out in 2020 and was updated in 2021, during which we noticed that several geosites lost their scientific value, which led to updated results.

Almost all geosites inventoried and studied have not undergone previous academic studies. Half of these sites are inventoried and assessed for the first time in this work. Some sites do not have a high degradation value due to their remoteness from anthropogenic action as they are difficult to access due to the lack of road infrastructure and the rugged state of the terrain.

All the results obtained lead to the sustainable development of strategies and projects to enhance and promote the fluvial heritage of the Middle Atlas.

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Part V

Karst Heritage

Exo- and Endokarst of the Middle Atlas (Morocco): From Inventory to Promotion

10

Khaoula Baadi and Bernard Lebreton

Abstract

The Middle Atlas presents exo- and endokarstic characteristics of national and even continental rarity by providing valuable information on a multitude of elements forming the karst heritage of the region. Today, awareness of this karstic heritage is a ray of hope for its preservation. The latter announces an interest between the heritage value of the karst and its promotion. This work reports a study of inventory, quantitative assessment and degree of deterioration of karstic geosites for the purpose of a promotion proposal. During the inventory, 136 karstic geosites were inventoried, 32 of which were selected for the quantitative assessment stage with a score of $Ss \geq 1.5$ and the remaining 104 were withdrawn from the selection given their low scientific value. For the stage of the degree of deterioration, these 32 geosites all had a score of $Sd < 2.5$, and no geosite had an $Sd \geq 2.5$. As for the results of the calculation of their total value, this was positive for 23 geosites, the remaining 9 therefore have an $Sv < 0$. Among this multitude of exo- and endokarstic geosites, eight are selected for a more detailed study based on criteria tangible values of representativeness, rarity, geological diversity and state of preservation.

Keywords

Exo- and endokarst · Heritage · Inventory · Quantitative assessment · Degree of deterioration · Promotion · Middle Atlas

K. Baadi (✉)
Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, Fez, Morocco

B. Lebreton
French Speleology Federation, Lyon, France

10.1 Introduction

The Middle Atlas is a favorable environment for the genesis of karstic formations. It is named the "cave capital of Morocco." It constitutes a vast karstic domain which has been the subject of several geoscientific studies (Casteret 1935; Russo 1935; Ek and Mathieu 1964; Tennevin 1978; Martin 1981; Gourari 2001; Harmouche 2004; Salomon 2006; Taous et al. 2009; Akdim et al. 2012; Wassenburg et al. 2012) despite the fact that they remain few in number compared to geological studies covering other areas of expertise. This vast karst domain offers important sources of information on the characteristics and varieties of karst. The latter occupies 30% of the area of the chain.

From 1934, explorations were carried out by Norbert Casteret and then by other French, Spanish, Moroccan or Swiss speleologists. These explore several underground networks in the region, including the Gouffre Friouato network. In 1981, many underground cavities were identified by the Hydraulic Service of the Ministry of Equipment. Today, more than 300 cavities have been listed by several speleological federations and associations but without any official document published.

The endokarst has known more importance compared to the exokarst. It is very developed and is at the origin of very diversified endokarstic forms. All the exo- and endokarstic forms are the refuge of an exceptional biodiversity including several endemic species.

The karst heritage of the Middle Atlas has seen little work (De Waele and Melis 2009; Hili and El Khalki 2017; Mounir et al. 2019; Baadi et al. 2021). Among these previous works, there are those that have relied on scientific and secondary criteria and other methodologies that have not used any methodology. Recently, Baadi et al. (2021) proposed an inventory focused only on the northern part of the Middle Atlas.

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In this chapter, we propose an inventory, a quantitative assessment and to determine the degree of deterioration of the karst heritage. The geosites selected, of exceptional geological diversity and of national or international renown, have a high scientific value and are mostly in a good state of preservation. The promotion of karstic heritage plays a decisive role in the conservation of geosites previously subject to inventory and assessment procedures. It is particularly important in territories corresponding to unique and unified geographical areas where sites of international geological importance are managed with a concept of protection and promotion.

10.2 Karstic Geomorphology

Karst is a complex natural environment that is often difficult to access. Its understanding requires the integration of several multidisciplinary approaches. The development of this karst is dependent on several factors. Most of the karst formations of the Middle Atlas originated in fractured Liassic carbonates of the Lower and Middle Lias. Generally, the outcrops of the dolomitic terrains of the Lower Lias are less karstified than the outcrops of the limestone terrains of the Middle Lias.

Karstic activity in the Middle Atlas began in the Miocene and was very important in the Pliocene, a very humid period when erosion was very intense there (Martin 1981). During the Pleistocene, karstic dynamics were also important following all the phases of uplift and tectonic readjustment of the Middle Atlas (Martin 1981). The juxtaposition, by faults, of permeable Liassic terrains and impermeable Triassic terrains has contributed to the formation of important karstic and fluvio-karstic morphologies.

According to the examination of the topographic plans of the various underground cavities, the sections of the caves show two main directions. These are the NE-SW direction sections, from N40 to N60 direction, and the NW-SE direction sections, N120 to N160 (Baadi et al. 2019).

Tennevin (1978) showed that there was a relationship between the different types of karsts, their altitude (Fig. 10.1) and their climate. He subdivided the exokarst of the Middle Atlas into three levels according to the altitudes: the lower level (located between 500 m and 1000 m), the middle level (located between 1000 m and 2000 m) and finally the upper level (located between 2000 m and 3000 m). Karstification allows, on the one hand, the penetration and storage of a very high proportion of meteoric water by infiltration (35–40% according to Bentayeb and Leclerc (1977)), and on the other hand, the feeding the groundwater network.

All these conditions have offered the Middle Atlas an abundant and varied sampling of exo- and endokarstic forms. The most striking exokarstic forms are the immense lapiaz fields with sinkholes reaching an area of more than 1 km^2, the ouvalas, the ponors and the poljes. While the underground karst morphology “endokarst” is represented by sinkholes, caves, underground galleries, underground lakes, horizontal galleries and/or vertical wells, etc. The endokarst also shelters perennial underground rivers where the flow is carried out by a multitude of elementary channels rather than by large underground galleries.

10.3 Karstic Geosites

10.3.1 Inventory and Quantitative Assessment

The karstic heritage constitutes a fundamental source of information on the various factors which condition karstification: lithological, tectonic, morphostructural, paleoclimatic and botanical. This rich heritage was inventoried based on scientific criteria of the methodology of Baadi et al. (2020). This inventory led to 136 inventoried karstic geosites (Table 10.1). Each of the karstic geosites of these 136 inventoried has an information sheet. Seven out of 136 geosites had an $Ss \geq 2.5$, 25 geosites a $1.5 \leq Ss < 2.5$ and the remaining 104 had an $Ss < 1.5$ (Table 10.2). The latter were withdrawn from the selection due to their low scientific value.

10.3.2 Degree of Deterioration

Thirty-two geosites were therefore selected for the degree of deterioration stage (Table 10.3). Among these 32 geosites, no geosite had an $Sd \geq 2.5$, 11 had an $Sd < 1.5$ and 21 had a $1.5 \leq Sd < 2.5$.

As for the results of the calculation of their total value, this was positive for 23 geosites, and the remaining 9 therefore have an $Sv < 0$.

Among this multitude of geosites, eight are selected for a more detailed study based on scores of values of representativeness, rarity, geological diversity and state of preservation.

10.3.2.1 Ademame

Ademame is located 32 km south of Taza. This geosite has the particularity of presenting a ruiniform relief composed of several lapiesed sinkholes.

The stone dolines of the geosite of Ademame are inscribed in the carbonates of the Lower Lias and affected by several faults. These faults are numerous and their orientation follows the axis of the first anticline. These faults transformed the Lower Liassic carbonate slab into a “swell” of ridges (Fig. 10.2a). Large sinkholes lined up between the different ridges. We also find poljes, like the Louta polje “Poljé Louta” case (Fig. 10.2b). These carbonates, which are 200 m thick

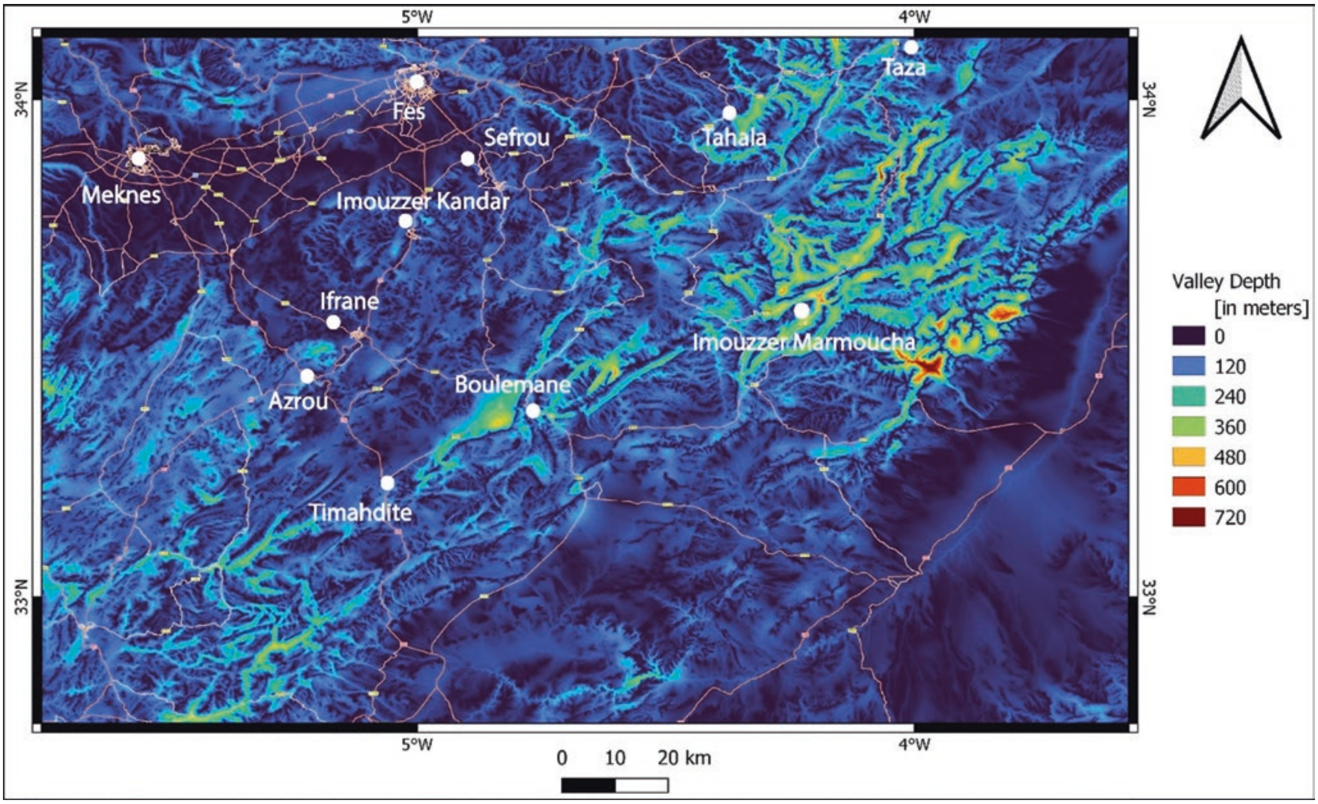

Fig. 10.1 Slope map of the Middle Atlas

and of a whitish-gray color, show massive beds rich in oncholites accompanied by birdeyes and laminites presenting a quadrangular framework which is arranged in a plane conforming to the fissuring and stratification of this rock mass. We are therefore in the presence of a field of lapiesed sinkholes, with vertical walls, which can reach 3 m in depth. These sinkholes form orthogonal labyrinths modeled on joint networks and lacerate karstic pseudo-valleys (Tennevin 1978).

The Ademame lapiaz contains innumerable forms of kamenitza (Fig. 10.2c, d) with a width sometimes exceeding 35 centimeters and a depth of 10 to 40 centimeters. These dimensions give an idea of the duration of the formation of these forms. Cucchi et al. (1989) showed that a land subsidence rate of 0.02–0.03 mm/year means that it takes between 1670 and 2500 years for the formation of a 5 cm deep kamenitza.

Ademame has the largest number of stone dolines in the Middle Atlas. It includes two types of exokarst: sinkholes and lapiaz.

10.3.2.2 Chaâra

Chaâra is located 60 km east of Tahala. This geosite presents the most important karstic complex of the Middle Atlas (Fig. 10.3).

The lapiaz field of the Chaâra geosite is located at the foothills of the first anticlinal ridge of Azrou-Ouassès (Fig. 10.4a). It is located here at more than 1600 m above sea level. It is affected by several reverse faults which put the Toarcian marls in contact with the various formations of the Lower and Middle Liassic and sometimes with the clays and basalts of the Triassic (Fig. 10.3).

The field of lapiaz (Fig. 10.4b), with grooves, is dug in the limestones and dolomitic limestones of the Lower Lias. In this field is a karstic complex which corresponds to sinkholes, pits and losses along the contacts of the faults as well as chiseled towers over 4 km in length. Where Triassic clays outcrop, several fluvio-karstic poljes have formed, such as the Laarouch polje (Fig. 10.4c).

10.3.2.3 Poljé Chiker

Poljé Chiker is located 20 km south of Taza. It is located within the Daya Chiker syncline and at the foot of Jbel Bou Messaoud. This geosite has the advantage of presenting the most remarkable polje of the Middle Atlas chain.

The polje of this geosite is formed in the marly limestones of the Domerian and the marls of the Toarcian and even of the limestones of the Aalenian. It occupies a vast closed flat-bottomed depression that is more than 10 km long and 2 km wide. This depression corresponds to the NE-SW Daya Chiker syncline. This polje is framed by the faulted anti-

Table 10.1 List of inventoried karstic geosites (SIBE "Sites of Biological and Ecological Interest"; TNP "Tazzeka National Park")

Karstic geosites	Identification code	Type of genite	Coordinates			Administrative location	Property	Accessibility	Protected area
			X	*Y*	*Z*				
Ademame	Kar01	Sinkhole	34° 2′57.30″N	4° 6′32.47″W	1498	Taza	Public	Difficult	TNP
Aferrane	Kar02	Sinkhole	33° 1′33.60″N	5°27′39.34″W	1467	Ajdir	Public	Medium	–
Agouni Izguère	Kar03	Polje	33°26′19.91″N	4°54′20.99″W	1685	Imouzzer Kandar	Public	Medium	–
Agrane	Kar04	Polje	34° 0′44.09″N	4° 8′44.36″W	1189	Ademame	Public	Medium	–
Ahoussal	Kar05	Sinkhole	32°57′51.01″N	5°19′1.12″W	1898	Ajdir	Public	Medium	–
Ain El Aouda	Kar06	Cave	34° 5′51.68″N	4° 1′47.65″W	1617	Bab Boudir	Public	Difficult	TNP
Ain Erreha	Kar07	Lapiaz	34° 0′15.91″N	4°12′17.33″W	1036	Ademame	Public	Medium	TNP
Ain Jerjoub	Kar08	Polje	34° 1′49.02″N	4° 6′34.00″W	1326	Ademame	Public	Medium	TNP
Ain Kahla	Kar09	Lapiaz	33°14′8.65″N	5°13′44.13″W	2162	Ain Leuh	Public	Medium	–
Ait Ahmed	Kar10	Lapiaz	33°51′56.68″N	4°12′30.43″W	1053	Tazarine	Public	Difficult	–
Ajdir	Kar11	Sinkhole	32°57′46.70″N	5°26′5.30″W	1623	Ajdir	Public	Medium	–
Al Maarad	Kar12	Lapiaz	33° 0′20.76″N	5°30′3.63″W	1539	Ajdir	Public	Medium	–
Aoumchach I	Kar13	Cave	34° 1′51.35″N	4° 7′50.29″W	1380	Ademame	Public	Difficult	–
Aoumchach II	Kar14	Cave	34° 1′31.43″N	4° 7′12.89″W	1490	Ademame	Public	Difficult	–
Aven Koul	Kar15	Chasm	33°47′38.28″N	4°29′7.08″W	1020	Ribat al Khayr	Public	Medium	–
Azegza	Kar16	Polje	32°59′31.32″N	5°28′17.00″W	1518	Ajdir	Public	Medium	–
Bab Bou Idir	Kar17	Cave	34° 4′55.54″N	4° 7′2.31″W	1400	Taza	Public	Medium	TNP
Bab Tafertest	Kar18	Polje	34° 7′10.42″N	4° 1′6.23″W	1407	Taza	Public	Medium	TNP
Bir Yala	Kar19	Sinkhole	33°44′57.10″N	4° 8′41.51″W	2240	Bou-Iblane	Public	Difficult	–
Bled Nertène	Kar20	Lapiaz	33°17′2.98″N	5°19′11.58″W	1792	Ain Leuh	Public	Medium	–
Bou Hyati	Kar21	Cave	34° 4′46.21″N	4° 7′6.46″W	1441	Taza	Public	Medium	TNP
Bou Imourdassane	Kar22	Lapiaz	33°44′19.88″N	4°49′21.33″W	1421	Annoceur	Public	Medium	–
Bou Lebrrouj	Kar23	Lapiaz	33°41′37.27″N	5°11′35.99″W	1270	El Hajeb	Public	Difficult	–
Bou Mennjel	Kar24	Cave	33°43′41.72″N	5° 8′53.89″W	1152	El Hajeb	Public	Medium	–
Bouslama	Kar25	Cave	34° 5′24.43″N	4° 6′48.19″W	1500	Taza	Public	Difficult	–
Chaâra	Kar26	Lapiaz	33°58′46.31″N	4°13′34.24″W	1253	Kaouane	Public	Difficult	–
El Khars	Kar27	Polje	34° 3′13.73″N	4° 7′43.83″W	1634	Bab Boudir	Public	Difficult	TNP
El Malekef	Kar28	Cave	33°44′28.52″N	4° 8′25.65″W	2140	Bou-Iblane	Public	Difficult	–
El Oulja	Kar29	Lapiaz	34° 2′6.99″N	4°11′52.25″W	1134	Ademame	Public	Difficult	–
El Qalaâ	Kar30	Cliff	33°55′51.19″N	3°59′27.18″W	1434	Meghraoua	Public	Difficult	–

El-Malekef	Kar31	Sinkhole	33°45′29.41″N	4° 7′12.84″W	2140	Bou-Iblane	Public	Difficult	–
Feldi	Kar32	Sinkhole	33°11′10.33″N	4°57′18.10″W	2143	Achlouj	Public	Difficult	–
Ghar Bied	Kar33	Cave	34° 5′46.01″N	4° 1′22.14″W	1600	Taza	Public	Difficult	TNP
Gouffre aux pigeons	Kar34	Chasm	33°43′48.85″N	4°59′57.70″W	1400	Imouzzer Kandar	Public	Medium	–
Gouffre Friouato	Kar35	Chasm	34° 6′16.95″N	4° 4′21.10″W	1450	Taza	Private	Difficult	TNP
Grotte Chaâra	Kar36	Cave	33°57′20.58″N	4°14′47.67″W	2056	Kaouane	Public	Difficult	–
Grotte Chiker	Kar37	Cave	34° 7′17.38″N	4° 2′18.43″W	1342	Taza	Public	Difficult	TNP
Grotte El Kalaa	Kar38	Cave	33°56′18.77″N	4° 0′18.20″W	890	Meghraoua	Public	Difficult	–
Ich Maakel I	Kar39	Cave	34° 0′4.18″N	4° 3′52.74″W	1270	Taza	Public	Difficult	TNP
Ich Maakel II	Kar40	Cave	34° 0′8.85″N	4° 3′55.51″W	1270	Taza	Public	Difficult	TNP
Ich Maakel III	Kar41	Cave	34° 0′14.26″N	4° 4′22.12″W	1270	Taza	Public	Difficult	TNP
Iferaoun	Kar42	Sinkhole	33° 8′43.42″N	5°22′59.85″W	1597	Ain Leuh	Public	Medium	–
Ifrah	Kar43	Polje	33°33′35.08″N	4°55′48.46″W	1627	Imouzzer Kandar	Public	Easy	–
Ifrennta	Kar44	Sinkhole	33° 9′24.52″N	5°21′55.12″W	1660	Ain Leuh	Public	Medium	–
Ifri Ahnachen	Kar45	Cave	34° 0′59.49″N	4° 9′20.50″W	1270	Meghraoua	Public	Difficult	–
Ifri Azeroual	Kar46	Chasm	33°50′37.78″N	4°22′58.34″W	1140	Ribat al Khayr	Public	Difficult	–
Ifri Broud	Kar47	Cave	33°41′42.13″N	4°12′42.40″W	1300	Bou-Iblane	Public	Difficult	–
Ifri Ichac	Kar48	Chasm	33°26′22.75″N	4°20′1.63″W	1789	Imouzzer Marmoucha	Public	Difficult	–
Ifri Jider	Kar49	Chasm	33°42′6.05″N	4° 6′3.81″W	2040	Bou-Iblane	Public	Difficult	–
Ifri Ljahac	Kar50	Cave	33°37′14.06″N	4°15′3.96″W	1760	Talzemt	Public	Difficult	–
Ifri n′Oudey (gouffre du juif)	Kar51	Chasm	33°50′43.47″N	4°24′0.81″W	1120	Ribat al Khayr	Public	Difficult	–
Ifri n′Tioutchilt	Kar52	Cave	33°28′12.14″N	4°13′5.47″W	1950	Imouzzer Marmoucha	Public	Difficult	–
Ifri Ou Berrid	Kar53	Cave	33°15′10.76″N	5°15′31.90″W	1830	Azrou	Public	Easy	–
Ifri Ouska	Kar54	Cave	33°18′6.27″N	5°11′20.22″W	1866	Azrou	Public	Easy	–
Ighrenba	Kar55	Sinkhole	33°11′47.01″N	4°56′2.49″W	2116	Achlouj	Public	Difficult	–
Jbel Aoua	Kar56	Chasm	33°38′50.82″N	5° 2′53.35″W	1730	Imouzzer Kandar	Public	Difficult	–
Kef Admam	Kar57	Cave	34° 1′36.28″N	4° 9′8.30″W	1340	Meghraoua	Public	Difficult	–
Kef Aïn Hallouf	Kar58	Chasm	34° 0′51.29″N	4° 9′52.68″W	1470	Meghraoua	Public	Difficult	–
Kef Anghara	Kar59	Chasm	33°40′25.92″N	4°11′48.57″W	1600	Bou-Iblane	Public	Difficult	–

(continued)

Table 10.1 (continued)

Karstic geosites	Identification code	Type of genite	Coordinates			Administrative location	Property	Accessibility	Protected area
			X	*Y*	*Z*				
Kef Bab Mfraj	Kar60	Cave	34° 5′42.95″N	4° 6′40.10″W	1530	Taza	Public	Difficult	TNP
Kef Bou Hayati	Kar61	Chasm	34° 5′38.44″N	4° 5′54.92″W	1390	Bab Boudir	Public	Difficult	–
Kef Bou Hayati I	Kar62	Cave	34° 5′49.21″N	4° 6′33.58″W	1575	Taza	Public	Difficult	TNP
Kef Bou Hayati II	Kar63	Cave	34° 6′1.96″N	4° 6′13.33″W	1520	Taza	Public	Difficult	TNP
Kef dial R′Kam	Kar64	Loss	33°41′55.28″N	4° 6′29.43″W	2080	Bou-Iblane	Public	Difficult	–
Kef El Ahnach	Kar65	Cave	33°57′20.76″N	4°13′44.61″W	1280	Kaouane	Public	Difficult	–
Kef El Bouk	Kar66	Cave	34° 3′34.61″N	4° 7′50.64″W	1750	Taza	Public	Difficult	TNP
Kef El Fiss	Kar67	Cave	34° 4′6.84″N	3°59′58.80″W	1230	Taza	Public	Difficult	TNP
Kef El Hmam	Kar68	Chasm	33°47′50.37″N	4°24′38.89″W	1110	Taza	Public	Difficult	TNP
Kef el Jnoun	Kar69	Chasm	34° 1′27.90″N	4° 8′59.14″W	1230	Meghraoua	Public	Difficult	–
Kef El Ma	Kar70	Cave	34° 5′23.92″N	4° 6′31.57″W	1420	Taza	Public	Difficult	TNP
Kef El Mohand	Kar71	Chasm	33°57′26.73″N	4°13′49.36″W	1300	Kaouane	Public	Difficult	–
Kef El Sao	Kar72	Cave	34° 7′49.93″N	4° 2′41.51″W	1510	Taza	Public	Difficult	TNP
Kef El Seroual	Kar73	Chasm	33°58′53.93″N	4°13′8.28″W	1245	Kaouane	Public	Difficult	–
Kef Hazar	Kar74	Cave	34° 5′53.95″N	4° 2′45.38″W	1440	Taza	Public	Difficult	TNP
Kef Idra	Kar75	Cave	33°59′27.57″N	4° 8′37.40″W	1115	Meghraoua	Public	Difficult	–
Kef Izoura	Kar76	Cave	34° 5′38.44″N	4° 5′54.92″W	1377	Taza	Public	Difficult	TNP
Kef Kaouane	Kar77	Chasm	33°57′39.77″N	4°14′51.10″W	1120	Kaouane	Public	Difficult	–
Kef Karia	Kar78	Cave	34° 8′35.63″N	4° 0′31.23″W	1000	Taza	Public	Difficult	TNP
Kef Maakel El Tahtani	Kar79	Chasm	34° 0′29.61″N	4° 4′26.82″W	1220	Tamtroucht	Public	Difficult	–
Kef Meghous	Kar80	Cave	33°58′0.68″N	4°10′22.59″W	1205	Taza	Public	Difficult	TNP
Kef Targat	Kar81	Cave	34° 1′24.91″N	4° 8′22.29″W	1540	Taza	Public	Medium	TNP
Kef Toumat	Kar82	Chasm	33°50′48.61″N	4°23′34.99″W	1105	Ribat al Khayr	Public	Difficult	–
Kef Zaarour	Kar83	Chasm	33°50′45.20″N	4°23′26.77″W	1400	Taza	Public	Medium	TNP
Kef-El-Mers-Ahmed	Kar84	Cave	34° 4′57.82″N	4° 2′43.26″W	1550	Taza	Public	Difficult	TNP
Kef-Nahal-Tikhoubaï	Kar85	Chasm	34° 0′16.82″N	4° 2′50.81″W	1050	Taza	Public	Difficult	TNP
Kissarite	Kar86	Lapiaz	33°12′58.18″N	5°21′13.41″W	1710	Ain Leuh	Public	Medium	–
Kssouatène	Kar87	Sinkhole	33° 7′40.72″N	5°23′6.35″W	1600	Ain Leuh	Public	Medium	–
Louta	Kar88	Polje	34° 1′36.13″N	4° 6′36.35″W	1309	Al Anssar	Public	Medium	–
Meshoul	Kar89	Lapiaz	34° 3′17.82″N	4° 5′53.09″W	1584	Ademame	Public	Difficult	–

Meshoul I	Kar90	Sinkhole	34° 3′37.08″N	4° 6′26.77″W	1567	Ademame	Public	Difficult	–
Mimejad	Kar91	Sinkhole	32°59′16.20″N	5°15′58.30″W	2050	Ajdir	Public	Medium	–
Mirssa	Kar92	Sinkhole	32°57′8.82″N	5°17′29.48″W	1933	Ajdir	Public	Medium	–
Missartène	Kar93	Sinkhole	32°59′46.88″N	5°26′52.00″W	1557	Ajdir	Public	Medium	–
Moutferaoun	Kar94	Sinkhole	33°38′48.20″N	4°48′35.25″W	1376	Annoceur	Public	Medium	–
Ouaousseguerna	Kar95	Sinkhole	33° 9′22.69″N	5°25′47.56″W	1576	Ain Leuh	Public	Medium	–
Ouiouane	Kar96	Polje	33° 7′37.50″N	5°20′44.30″W	1612	Ain Leuh	Public	Easy	–
Ouled-Ayach	Kar97	Chasm	34° 2′46.72″N	4° 2′14.58″W	1280	Taza	Public	Difficult	–
Ounane	Kar98	Sinkhole	33° 9′4.84″N	5°24′29.60″W	1572	Ain Leuh	Public	Medium	–
Ouoouchène	Kar99	Polje	33°24′30.82″N	4°54′42.40″W	1656	Almis Guigou	Public	Medium	–
Poljé Ain El Aouda	Kar100	Polje	34° 6′10.32″N	4° 1′58.69″W	1469	Taza	Public	Medium	–
Poljé Beni Mkoud	Kar101	Polje	33°52′57.73″N	4°18′6.77″W	1347	Kaouane	Public	Difficult	–
Poljé Chaâra	Kar102	Polje	33°58′46.31″N	4°13′34.24″W	1232	Kaouane	Public	Difficult	–
Poljé Chiker	Kar103	Polje	34° 6′52.56″N	4° 2′36.62″W	1350	Bab Boudir	Public	Easy	TNP
Poljé El Ghar	Kar104	Polje	33°54′9.40″N	4°16′44.81″W	1276	Kaouane	Public	Difficult	–
Poljé Kaouane	Kar105	Polje	33°57′4.94″N	4°16′5.45″W	1289	Kaouane	Public	Difficult	–
Poljé Laarouch	Kar106	Polje	33°55′58.87″N	4°15′51.60″W	1286	Kaouane	Public	Medium	–
Poljé Madegh	Kar107	Polje	33°56′50.92″N	4°13′52.93″W	1311	Kaouane	Public	Medium	–
Ras El Oued (Oued el bared)	Kar108	Cave	33°51′14.36″N	4° 0′10.43″W	962	Taza	Public	Difficult	SIBE
Sidi Amar	Kar109	Lapiaz	33°43′22.22″N	4°15′40.94″W	1460	Ribat al Khayr	Public	Difficult	–
Sidi Maanar	Kar110	Chasm	33°43′54.18″N	5° 1′24.04″W	1250	Imouzzer Kandar	Public	Medium	–
Sidi Majbar	Kar111	Cave	34° 8′41.03″N	4° 1′26.17″W	1240	Taza	Public	Difficult	TNP
Taanzoult	Kar112	Ponor	33° 4′10.82″N	5° 1′1.71″W	2101	Timahdite	Public	Easy	–
Taboughout	Kar113	Sinkhole	32°56′39.36″N	5°29′2.03″W	1507	Ajdir	Public	Medium	–
Taboughout Nord	Kar114	Sinkhole	32°57′27.05″N	5°29′40.61″W	1549	Ajdir	Public	Medium	–
Taffert Est	Kar115	Sinkhole	33°40′19.91″N	4° 9′0.88″W	1929	Bou-Iblane	Public	Difficult	–
Taffert Nord	Kar116	Sinkhole	33°40′37.91″N	4° 9′25.65″W	1954	Bou-Iblane	Public	Difficult	–
Taffert Nord-Est	Kar117	Sinkhole	33°40′31.67″N	4° 8′17.48″W	2059	Bou-Iblane	Public	Easy	–
Taffert Ouest	Kar118	Sinkhole	33°40′34.15″N	4° 9′56.38″W	1967	Bou-Iblane	Public	Difficult	–
Tahfourt	Kar119	Lapiaz	33°42′44.87″N	4°10′24.48″W	1848	Ribat al Khayr	Public	Difficult	–

(continued)

Table 10.1 (continued)

Karstic geosites	Identification code	Type of genite	Coordinates			Administrative location	Property	Accessibility	Protected area
			X	*Y*	*Z*				
Talghremte	Kar120	Sinkhole	32°57′54.40″N	5°15′52.12″W	2005	Ajdir	Public	Medium	–
Talou Ou Taachat	Kar121	Lapiaz	33°44′18.28″N	4°14′21.99″W	1400	Ribat al Khayr	Public	Difficult	–
Tidrine	Kar122	Lapiaz	33°29′42.27″N	5° 3′55.29″W	1758	Ifrane	Public	Easy	–
Tifratine	Kar123	Cave	33°41′40.78″N	5°22′48.08″W	930El	Hajeb	Public	Difficult	–
Tigouyal	Kar124	Sinkhole	32°58′9.55″N	5°22′27.46″W	1634	Ajdir	Public	Medium	–
Timezouine	Kar125	Sinkhole	34° 2′57.83″N	4° 6′6.76″W	1545	Taza	Public	Difficult	–
Timezouine	Kar126	Lapiaz	34° 2′35.43″N	4° 6′32.67″W	1523	Ademame	Public	Difficult	–
Tirardine	Kar127	Lapiaz	33°26′59.66″N	4°21′50.79″W	1445	Imouzzer Marmoucha	Public	Difficult	–
Tisfoula	Kar128	Lapiaz	33°14′40.86″N	5°20′51.93″W	1705	Aïn Leuh	Public	Easy	–
Tit Azourane	Kar129	Polje	34° 6′1.93″N	4° 1′13.46″W	1441	Taza	Public	Medium	–
Tizaraght	Kar130	Sinkhole	32°57′42.00″N	5°28′17.89″W	1581	Ajdir	Public	Medium	–
Tizaraght Est	Kar131	Sinkhole	32°57′22.33″N	5°27′22.90″W	1606	Ajdir	Public	Medium	–
Tizerghine	Kar132	Sinkhole	32°58′0.19″N	5°23′52.54″W	1637	Ajdir	Public	Medium	–
Tlet fam	Kar133	Lapiaz	34° 2′18.82″N	4° 5′28.65″W	1569	Al Anssar	Public	Difficult	–
Toughlamte	Kar134	Lapiaz	34° 7′47.29″N	4° 2′46.98″W	1517	Taza	Public	Difficult	–
Trou Arhelouet	Kar135	Chasm	33°40′21.79″N	4°11′37.54″W	1650	Bou-Iblane	Public	Medium	–
Trou de Panthère	Kar136	Chasm	33°17′7.52″N	5°13′25.72″W	1800	Azrou	Public	Medium	–

Table 10.2 Quantitative assessment (Ss) of karstic geosites

Geosites	Critera of quantitative assessment(Ss)					Total of pointing	Final scoring matrix (Ss)					Total of Ss	Result (Ss)
	Representativeness	Rarity	Geological diversity	State of preservation	Documentation		Representativeness * 24%	Rarity * 18%	Geological diversity * 20%	State of preservation * 24%	Documentation * 14%		
Ademame	3	2	3	1	3	12	0.72	0.36	0.6	0.24	0.42	2.34	Medium
Aferrane	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Agouni Izguère	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Agrane	1	1	1	2	2	7	0.24	0.18	0.2	0.48	0.28	1.38	Low
Ahoussal	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Ain El Aouda	2	1	2	1	2	8	0.48	0.18	0.4	0.24	0.28	1.58	Medium
Ain Erreha	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Ain Jerjoub	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Ain Kahla	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ait Ahmed	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Ajdir	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Al Maarad	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Aoumchach I	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Aoumchach II	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Aven Koul	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Azegza	2	1	1	2	2	8	0.48	0.18	0.2	0.48	0.28	1.62	Medium
Bab Bou Idir	2	1	2	2	2	9	0.48	0.18	0.4	0.48	0.28	1.82	Medium
Bab Tafertest	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Bir Yala	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Bled Nertène	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Bou Hyati	2	1	2	1	2	8	0.48	0.18	0.4	0.24	0.28	1.58	Medium
Bou Imourdassane	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Bou Lebrrouj	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Bou Mennjel	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Bouslama	2	2	2	2	3	11	0.48	0.36	0.4	0.48	0.42	2.14	Medium
Chaâra	3	2	3	2	3	13	0.72	0.36	0.6	0.48	0.42	2.58	High
El Khars	1	1	1	2	2	7	0.24	0.18	0.2	0.48	0.28	1.38	Low
El Malekef	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
El Oulja	2	1	2	1	2	8	0.48	0.18	0.4	0.24	0.28	1.58	Medium
El Qalaâ	3	2	2	1	1	9	0.72	0.36	0.4	0.24	0.14	1.86	Medium
El-Malekef	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Feldi	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Gouffre Friouato	3	2	3	2	3	13	0.72	0.36	0.6	0.48	0.42	2.58	High
Ghar Bied	1	1	1	2	2	7	0.24	0.18	0.2	0.48	0.28	1.38	Low

(continued)

Table 10.2 (continued)

Geosites	Critera of quantitative assessment(Ss)					Total of pointing	Final scoring matrix (Ss)					Total of Ss	Result (Ss)
	Representativeness	Rarity	Geological diversity	State of preservation	Documentation		Representativeness * 24%	Rarity * 18%	Geological diversity * 20%	State of preservation * 24%	Documentation * 14%		
Gouffre aux pigeons	2	1	2	2	2	9	0.48	0.18	0.4	0.48	0.28	1.82	Medium
Grotte Chaâra	3	3	2	2	3	13	0.72	0.54	0.4	0.48	0.42	2.56	High
Grotte Chiker	3	3	2	2	3	13	0.72	0.54	0.4	0.48	0.42	2.56	High
Grotte El Kalaa	2	1	2	1	1	7	0.48	0.18	0.4	0.24	0.14	1.44	Low
Ich Maakel I	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Ich Maakel II	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Ich Maakel III	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Iferaoun	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Ifrah	2	2	2	2	2	10	0.48	0.36	0.4	0.48	0.28	2	Medium
Ifrennta	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Ifri Ahnachen	1	1	1	2	2	7	0.24	0.18	0.2	0.48	0.28	1.38	Low
Ifri Azeroual	1	1	1	2	2	7	0.24	0.18	0.2	0.48	0.28	1.38	Low
Ifri Broud	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Ifri Ichac	1	1	1	2	2	7	0.24	0.18	0.2	0.48	0.28	1.38	Low
Ifri Jider	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Ifri Ljahac	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Ifri n'Oudey (gouffre du juif)	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Ifri n'Tioutchilt	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Ifri Ou Berrid	2	1	1	1	3	8	0.48	0.18	0.2	0.24	0.42	1.52	Medium
Ifri Ouska	2	1	1	1	3	8	0.48	0.18	0.2	0.24	0.42	1.52	Medium
Ighrenba	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Jbel Aoua	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Kef Admam	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Kef Aïn Hallouf	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Kef Anghara	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Kef Bab Mfraj	1	1	1	2	2	7	0.24	0.18	0.2	0.48	0.28	1.38	Low
Kef Bou Hayati	1	1	1	2	2	7	0.24	0.18	0.2	0.48	0.28	1.38	Low
Kef Bou Hayati I	1	1	1	2	2	7	0.24	0.18	0.2	0.48	0.28	1.38	Low
Kef Bou Hayati II	1	1	1	2	2	7	0.24	0.18	0.2	0.48	0.28	1.38	Low
Kef dial R'Kam	1	1	1	2	2	7	0.24	0.18	0.2	0.48	0.28	1.38	Low
Kef El Ahnach	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Kef El Bouk	1	1	1	2	2	7	0.24	0.18	0.2	0.48	0.28	1.38	Low
Kef El Fiss	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Kef El Hmam	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Kef el Jnoun	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low

Kef El Ma	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Kef El Mohand	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Kef El Sao	2	2	2	2	2	10	0.48	0.36	0.4	0.48	0.28	2	Medium
Kef El Seroual	1	1	1	2	2	7	0.24	0.18	0.2	0.48	0.28	1.38	Low
Kef Hazar	1	1	1	2	2	7	0.24	0.18	0.2	0.48	0.28	1.38	Low
Kef Idra	1	1	1	2	2	7	0.24	0.18	0.2	0.48	0.28	1.38	Low
Kef Izoura	2	2	2	2	2	10	0.48	0.36	0.4	0.48	0.28	2	Medium
Kef Kaouane	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Kef Karia	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Kef Maakel El Tahtani	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Kef Meghous	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Kef Targat	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Kef Toumat	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Kef Zaarour	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Kef-El-Mers-Ahmed	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Kef-Nahal-Tikhoubaï	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Kissarite	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Kssouatène	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Louta	2	1	2	1	2	8	0.48	0.18	0.4	0.24	0.28	1.58	Medium
Meshoul	2	1	2	1	1	7	0.48	0.18	0.4	0.24	0.14	1.44	Low
Meshoul I	2	1	2	2	1	8	0.48	0.18	0.4	0.48	0.14	1.68	Medium
Mimejad	1	1	1	2	2	7	0.24	0.18	0.2	0.48	0.28	1.38	Low
Mirssa	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Missartène	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Moutferaoun	2	1	2	1	2	8	0.48	0.18	0.4	0.24	0.28	1.58	Medium
Ouaousseguerna	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Ouiouane	2	1	2	1	2	8	0.48	0.18	0.4	0.24	0.28	1.58	Medium
Ouled-Ayach	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Ounane	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Ouoouchène	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Poljé Ain El Aouda	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Poljé Beni Mkoud	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Poljé Chaâra	2	1	2	1	2	8	0.48	0.18	0.4	0.24	0.28	1.58	Medium
Poljé Chiker	3	3	3	2	3	14	0.72	0.54	0.6	0.48	0.42	2.76	High
Poljé El Ghar	2	1	2	1	1	7	0.48	0.18	0.4	0.24	0.14	1.44	Low
Poljé Kaouane	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Poljé Laarouch	2	2	2	1	2	9	0.48	0.36	0.4	0.24	0.28	1.76	Medium

(continued)

Table 10.2 (continued)

Geosites	Critera of quantitative assessment(Ss)					Total of pointing	Final scoring matrix (Ss)					Total of Ss	Result (Ss)
	Representativeness	Rarity	Geological diversity	State of preservation	Documentation		Representativeness * 24%	Rarity * 18%	Geological diversity * 20%	State of preservation * 24%	Documentation * 14%		
Poljé Madegh	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Ras El Oued (Oued el bared)	3	3	3	2	3	14	0.72	0.54	0.6	0.48	0.42	2.76	High
Sidi Amar	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Sidi Maanar	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Sidi Majbar	2	2	2	2	2	10	0.48	0.36	0.4	0.48	0.28	2	Medium
Taanzoult	2	2	2	2	2	10	0.48	0.36	0.4	0.48	0.28	2	Medium
Taboughout	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Taboughout Nord	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Taffert Est	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Taffert Nord	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Taffert Nord-Est	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Taffert Ouest	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Tahfourt	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Talghremte	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Talou Ou Taachat	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Tidrine	2	2	2	1	2	9	0.48	0.36	0.4	0.24	0.28	1.76	Medium
Tifratine	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Tigouyal	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Timezouine	2	1	1	1	1	6	0.48	0.18	0.2	0.24	0.14	1.24	Low
Timezouine	2	1	1	1	1	6	0.48	0.18	0.2	0.24	0.14	1.24	Low
Tirardine	2	1	1	1	2	7	0.48	0.18	0.2	0.24	0.28	1.38	Low
Tisfoula	3	3	3	1	3	13	0.72	0.54	0.6	0.24	0.42	2.52	High
Tit Azourane	1	1	1	1	2	6	0.24	0.18	0.2	0.24	0.28	1.14	Low
Tizaraght	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Tizaraght Est	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Tizerghine	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Tlet fam	1	1	1	2	1	6	0.24	0.18	0.2	0.48	0.14	1.24	Low
Toughlamte	1	1	1	1	1	5	0.24	0.18	0.2	0.24	0.14	1	Low
Trou Arhelouet	2	1	2	1	2	8	0.48	0.18	0.4	0.24	0.28	1.58	Medium
Trou de Panthère	2	1	2	1	2	8	0.48	0.18	0.4	0.24	0.28	1.58	Medium

Table 10.3 Degree of deterioration (Sd) of karstic geosites

	Critera of degree of deterioration (Sd)						Final scoring matrix (Sd)						
Geosites	Vulnerability	Fragility	Accessibility	Demography	Number of visitors	Total of pointing	Vulnerability * 19%	Fragility * 19%	Accessibility * 25%	Demography * 20%	Number of visitors * 17%	Total of Sd	Result (Sd)
Ademame	1	1	1	1	1	5	0.19	0.19	0.25	0.2	0.17	1	Low
Ain El Aouda	2	2	1	1	1	7	0.38	0.38	0.25	0.2	0.17	1.38	Low
Azegza	3	2	1	1	1	8	0.57	0.38	0.25	0.2	0.17	1.57	Medium
Bab Bou Idir	2	2	2	2	1	9	0.38	0.38	0.5	0.4	0.17	1.83	Medium
Bou Hyati	2	2	2	1	1	8	0.38	0.38	0.5	0.2	0.17	1.63	Medium
Bouslama	3	3	1	2	2	11	0.57	0.57	0.25	0.4	0.34	2.13	Medium
Chaâra	2	2	2	2	2	10	0.38	0.38	0.5	0.4	0.34	2	Medium
El Oulja	1	2	2	1	1	7	0.19	0.38	0.5	0.2	0.17	1.44	Low
El Qalaâ	2	2	1	1	1	7	0.38	0.38	0.25	0.2	0.17	1.38	Low
Gouffre Friouato	3	3	3	2	1	12	0.57	0.57	0.75	0.4	0.17	2.46	Medium
Gouffre aux pigeons	2	2	2	1	1	8	0.38	0.38	0.5	0.2	0.17	1.63	Medium
Grotte Chaâra	3	3	2	2	1	11	0.57	0.57	0.5	0.4	0.17	2.21	Medium
Grotte Chiker	3	3	3	2	1	12	0.57	0.57	0.75	0.4	0.17	2.46	Medium
Ifrah	2	2	3	2	1	10	0.38	0.38	0.75	0.4	0.17	2.08	Medium
Ifri Ou Berrid	2	2	3	1	2	10	0.38	0.38	0.75	0.2	0.34	2.05	Medium
Ifri Ouska	1	1	2	1	1	6	0.19	0.19	0.5	0.2	0.17	1.25	Low
Kef El Sao	2	2	1	1	1	7	0.38	0.38	0.25	0.2	0.17	1.38	Low
Kef Izoura	2	2	3	2	2	11	0.38	0.38	0.75	0.4	0.34	2.25	Medium
Louta	2	2	2	1	1	8	0.38	0.38	0.5	0.2	0.17	1.63	Medium
Mîshoul I	2	2	1	1	1	7	0.38	0.38	0.25	0.2	0.17	1.38	Low
Mmtferaoun	1	2	1	1	1	6	0.19	0.38	0.25	0.2	0.17	1.19	Low
Ouiouane	2	3	3	2	2	12	0.38	0.57	0.75	0.4	0.34	2.44	Medium
Poljé Chaâra	2	2	1	2	1	8	0.38	0.38	0.25	0.4	0.17	1.58	Medium
Poljé Chiker	2	3	3	2	1	11	0.38	0.57	0.75	0.4	0.17	2.27	Medium
Poljé Laarouch	2	2	1	1	1	7	0.38	0.38	0.25	0.2	0.17	1.38	Low
Ras El Oued (Oued el bared)	3	3	1	1	1	9	0.57	0.57	0.25	0.2	0.17	1.76	Medium
Sidi Mjbar	2	2	1	2	1	8	0.38	0.38	0.25	0.4	0.17	1.58	Medium
Taanzoult	2	2	3	1	1	9	0.38	0.38	0.75	0.2	0.17	1.88	Medium
Tidrine	2	2	2	2	1	9	0.38	0.38	0.5	0.4	0.17	1.83	Medium
Tisfoula	3	3	3	1	2	12	0.57	0.57	0.75	0.2	0.34	2.43	Medium
Trou Arhelouet	1	2	2	1	1	7	0.19	0.38	0.5	0.2	0.17	1.44	Low
Trou de Panthère	1	2	1	1	1	6	0.19	0.38	0.25	0.2	0.17	1.19	Low

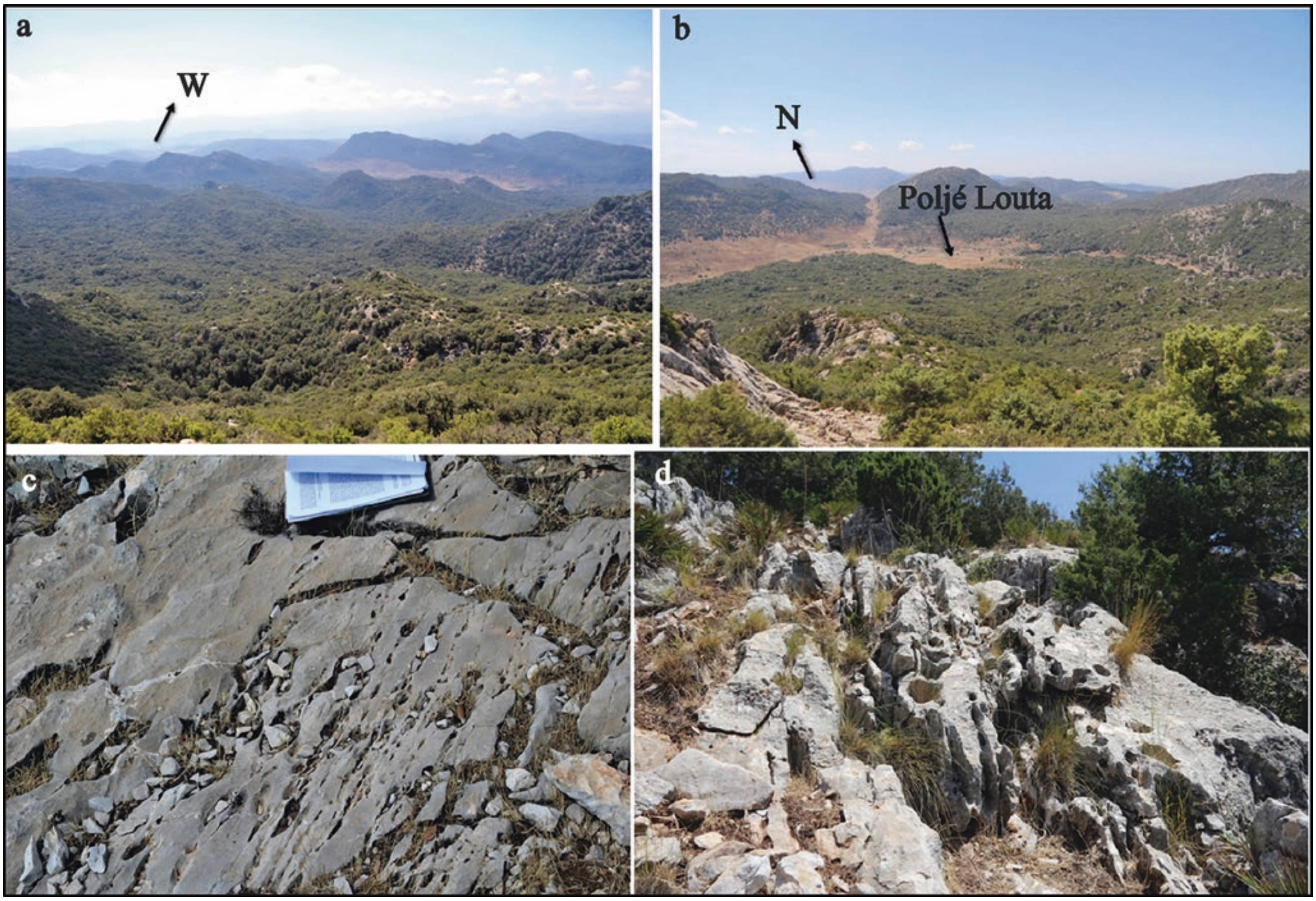

Fig. 10.2 (**a**) Stoned dolines of Ademame; (**b**) Poljé Louta between the stoned sinkholes; (**c**) and (**d**) Forms of kamenitza

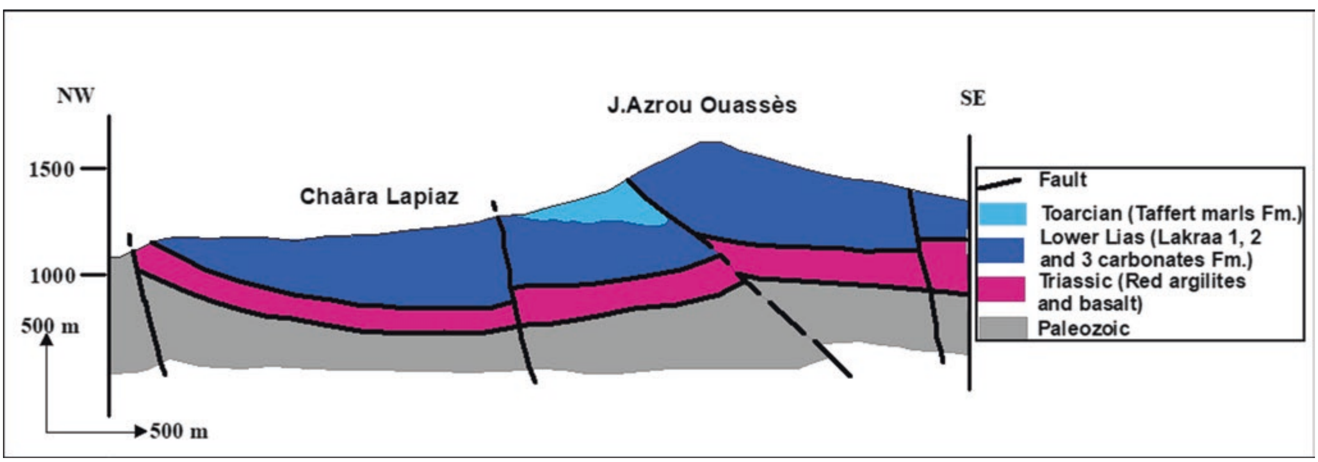

Fig. 10.3 Geological section of the Chaâra geosite (Baadi et al. 2021)

clines of Jbels Bou Messaoud (Fig. 10.5a) and Mers Hammad.

The Poljé Chiker presents a karstic drainage by two "ponors" orifices (Fig. 10.5b). The flat bottom of the polje is due to the dissolution of the walls and the bottom of the depression by the flooding sheet. In winter, runoff loss converges at the bottom of the polje (Fig. 10.5c). The latter regularly turns into a temporary lake. Several streams cross the entire Daya and are lost in the funnels and sinkholes and also at the level of the Chiker cave. The losses of this polje feed an underground river and a deep karst reservoir dug in the Lias. They are the source of water inflows from the large

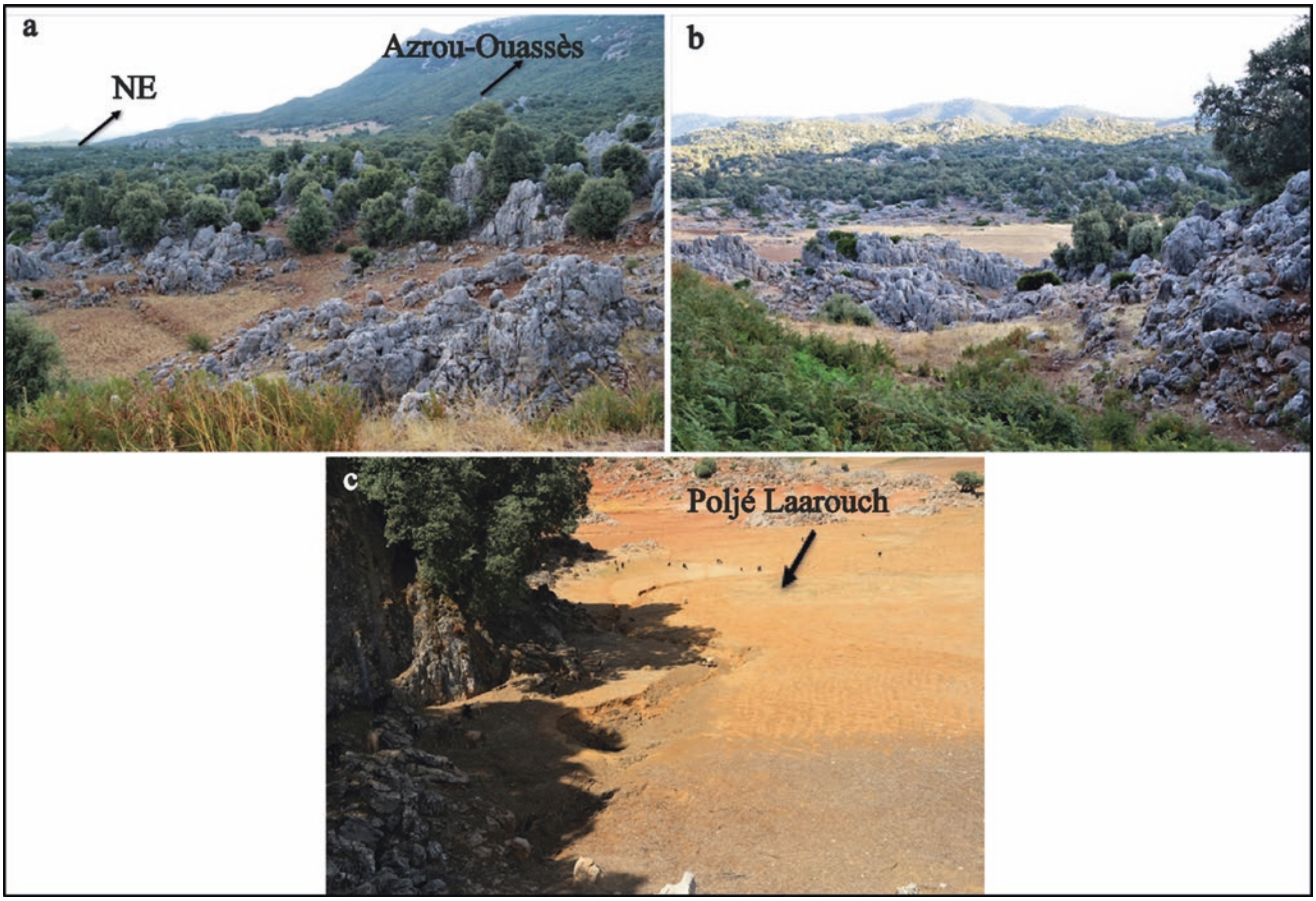

Fig. 10.4 (**a**) Chaâra lapiaz field at the foot of the first Azrou-Ouasses ridge; (**b**) Chaâra lapiaz field; (**c**) Poljé Laarouch

source of Ras El Ma (Taous et al. 2009) (see geosite of Ras El Ma).

10.3.2.4 Tisfoula

Tisfoula is located 29.3 km southwest of Azrou. This geosite has the particularity of representing the most important ruiniform landscape in the form of “mushrooms” of the Middle Atlas chain.

The ruiniform landscape of the Tisfoula geosite (Fig. 10.6a) is inscribed in dolomitic limestone from the Lower Lias. This landscape is characterized by forms of “rocky mushrooms” (Fig. 10.6b), pinnacles and towers several meters high, cut by rectilinear hollows and trenches. This is the convergence of the processes of karstification (summit slab with lapiaz and basins) and gelifraction (mushroom stem). At Tisfoula, the dolomitic limestones are “mushroom” shaped and have been differentially eroded and dissolved along vertical fractures isolating adjacent rock towers up to 4 m in height. At the top of many of these towers, phytokarst phenomena have led to the development of solution tanks or kamenitza.

The ruiniform landscapes of the Tisfoula geosite present the best example of a more advanced stage in the evolution of the karstic landform in the Middle Atlas.

10.3.2.5 Grotte Chaâra

Grotte Chaâra is located 40 km northeast of Ribat al Khayr. This geosite holds the famous cave of Chaâra which is known by its long underground river.

The Grotte Chaâra geosite is a cave with two entrances: the first is that of Ifri Azagarla, the second is that of Kef Sfargal. It is dug in carbonate formations of the Lower Lias. The direction of this cave (Fig. 10.7), mainly related to directional faults, is the same as that of the Middle Atlas chain (NE-SW). Its development (Fig. 10.8) is 7650 m long. Rainwater that infiltrates through cracks and losses has led to

Fig. 10.5 (**a**) Location of Poljé Chiker at the foot of Jbel Bou Messaoud; (**b**) Ponor of the Daya Chiker; (**c**) Runoff water converging on the Poljé Chiker

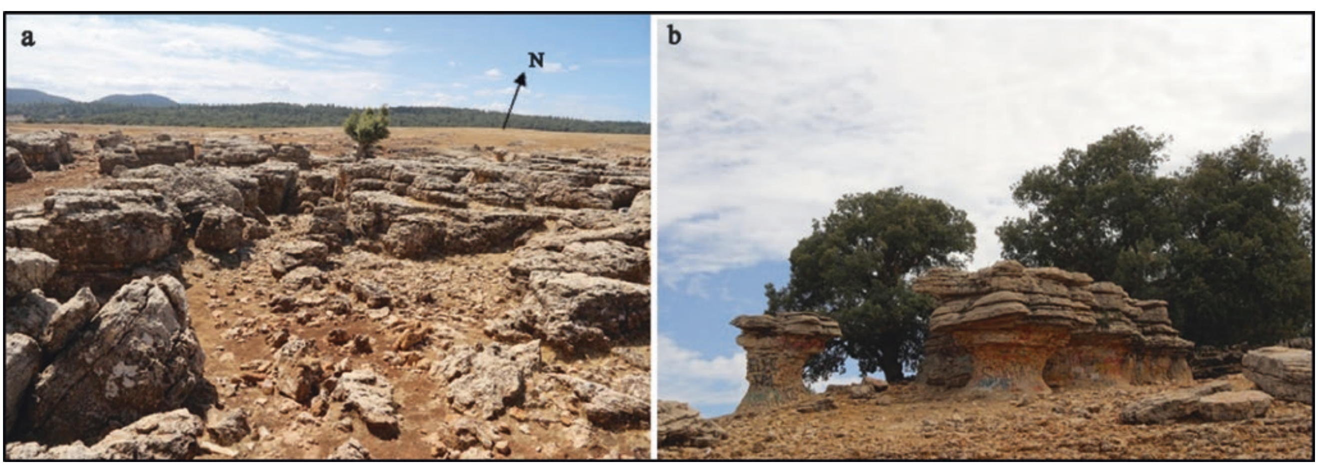

Fig. 10.6 (**a**) Ruiniform landscape of the Tisfoula geosite; (**b**) Stoned mushroom-shaped dolomites

the formation of several permanent underground lakes that flow into the underground river. The cave is famous for its remarkable stalagmitic flows (Fig. 10.9a) and for the variety of its speleothems (Fig. 10.9b, c).

This cave is the second largest cave in Morocco after that of Win Timdouine in Tizgi n'Chorfa (Souss-Massa). It is considered one of the most beautiful cavities in Morocco. By its length, it is also the fourth longest cave in Africa. This cave is also known for its speleothems which constitute a real "database" and a real "natural recording tool" of environmental and paleoclimatic data (Wassenburg et al. 2012). It also has the largest number of underground lakes and its vast galleries stretch over more than 500 m.

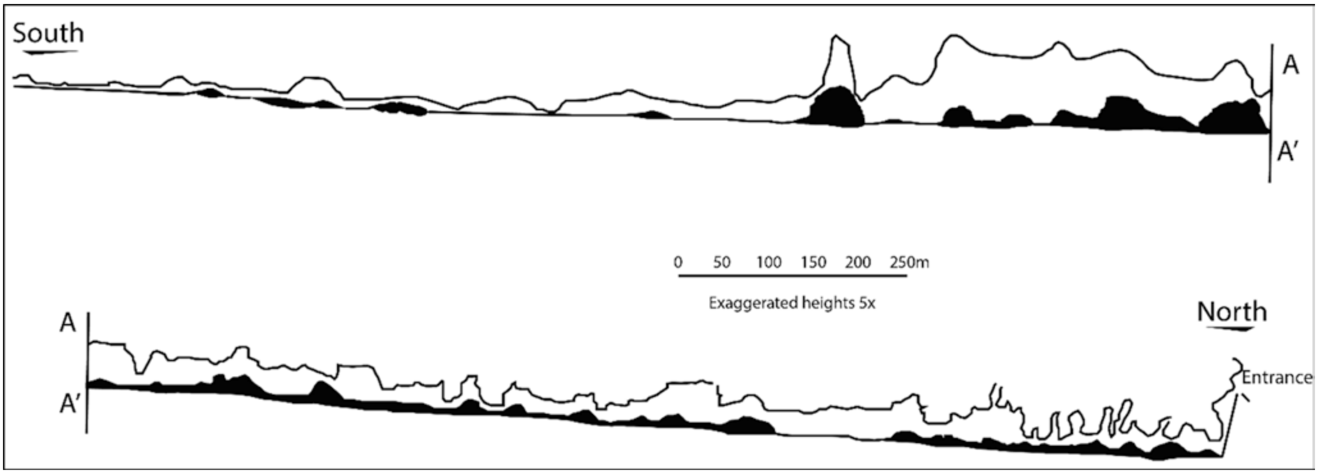

Fig. 10.7 Longitudinal section of the Grotte Chaâra (Ek and Mathieu 1964)

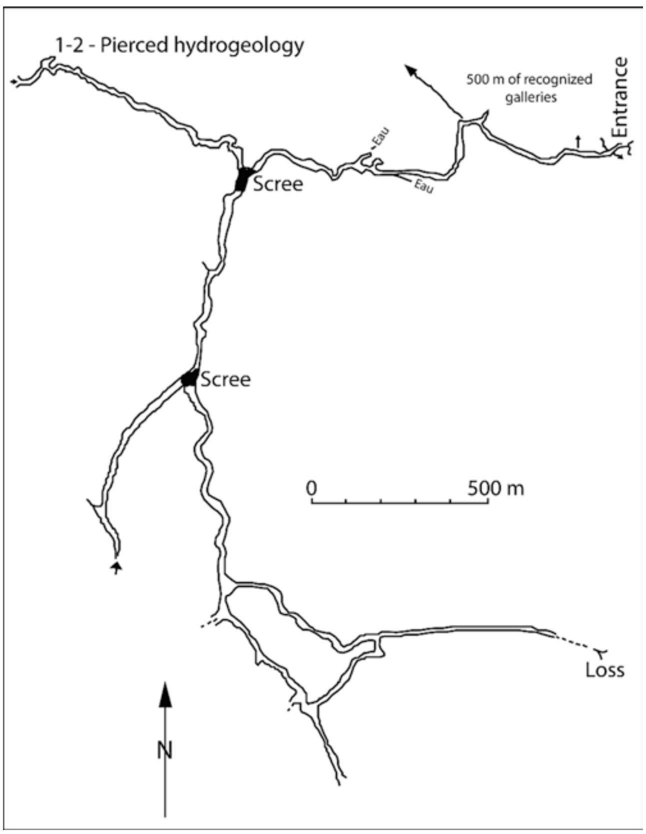

Fig. 10.8 General plan of the Chaâra Cave (Ministère de l'Équipement du Maroc-Direction de l'Hydraulique 1981)

The Grotte Chaâra geosite is a geosite of international interest which deserves to be registered on the World Heritage List.

10.3.2.6 Grotte Chiker

Grotte Chiker is located 20 km south of Taza. It lies under the often flooded Daya Chiker. This geosite represents the fourth cavity of the country by its length.

The Grotte Chiker collects all the waters from the Daya Chiker. It opens at the bottom of a rocky cove on the bank, NW of the temporary lake of Chiker, between the SE flank of the faulted anticline which forms the Jbel Bou-Messaoud and the NW edge of the syncline which forms the Chiker depression. The entrance has been fitted out and allows you to descend, at low water level, into the first gallery (Fig. 10.10a). The lake works by penstock during rainy periods. When the lake is dry, we easily recognize on the Daya plain very visible traces of the hydrographic network which converge toward the orifice of the cave (loss).

The Grotte Chiker is dug in the dolomitic limestones of the Lower Lias and the Middle Lias. It consists of a succession of shafts and galleries, stalactites, stalagmites (Fig. 10.10b), walls and concretionary floors (Fig. 10.10c). We also encounter draperies (Fig. 10.10d), fistulous (Fig. 10.10e) and gours (Fig. 10.10f, g). The waters of the Daya have deeply eroded the rock of the conduits over nearly 70 m in height. At a depth of 140 m and over a length of 3865 m, the cavity develops subhorizontally under the Daya and parallel to the general direction of NMAF (NE-SW). This network of faults continues to the NE until the resurgence of Ras El Ma located below. It develops approximately in the direction of the Gouffre Friouato.

The cave is fed by the waters of the Daya Chiker for at least half of the year. The geosite of the Grotte Chiker is as vast as the most famous cavities of Morocco. It is the cave with the largest number of wells, siphons and underground

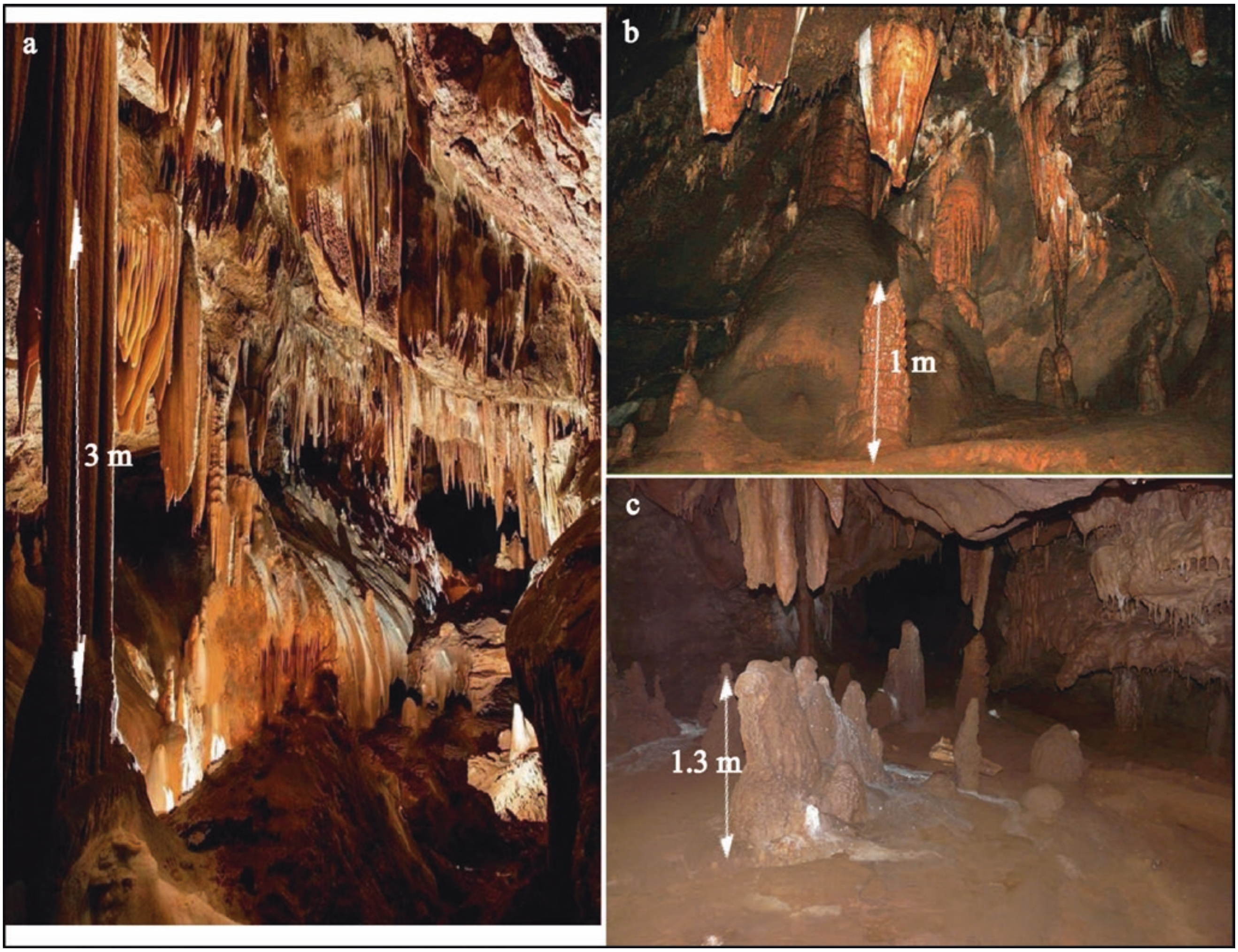

Fig. 10.9 (**a**) Stalagmite flows; (**b**) and (**c**) Speleothems of the Grotte Chaâra geosite

waterfalls. These waterfalls fall through cracks, faults and chimneys which are the result of multiple burials that occur on the crevassed and pierced surface of natural wells of Jbel Bou-Messaoud. The beginning of the intense karstic activity that characterizes the history of the Chiker goes back at least to the time of the 1450 m flattenings (Ek and Mathieu 1964).

10.3.2.7 Gouffre Friouato

Gouffre Friouato is located 25 km south of Taza. This geosite corresponds to the only underground cavity equipped for tourists.

The Gouffre Friouato has a circular entrance 30 m in diameter (Fig. 10.12a). It has a depth of 150 m and its length reaches 3500 m. It opens on the side of Jbel Bou Messaoud and 56 m from its opening is a huge scree which constitutes the bottom of the first shaft (Fig. 10.11). The chasm is marked by several underground lakes. The waters that infiltrate the cracks in the limestone reach the galleries of the abyss and feed these underground lakes.

Along the Gouffre Friouato, the underground galleries follow two directions: an NE-SW direction and an SE-NW direction. The Gouffre Friouato is characterized by its many rooms sometimes dominated by huge scree. The "Lixi" room, with concretions of more than 6 m in height, draperies exceeding 2 m in height (Fig. 10.12b) and its numerous speleothems (Fig. 10.12c) is one of them.

The Gouffre Friouato is part of the karstic system "Daya Chiker-Gouffre Friouato-spring of Ras El Ma." The underground network of the Gouffre Friouato joins that of the cave Chiker in the NE direction.

10.3.2.8 Ras El Oued

Ras El Oued is located 30 km southeast of Meghraoua. This geosite has the particularity of presenting an emergence which springs at the level of the cave of Ras El Oued and which bears the name of Aïn El Bared.

The waters of the Ras El Oued geosite emerge in a system of underground galleries shaped in a carbonate layer of the

Fig. 10.10 (**a**) Loss of the Daya Chiker waters giving access to the Grotte Chiker; (**b**) Gours, stalagmites and stalactites; (**c**) Walls and concretionary floors of the Grotte Chiker; (**d**) draperies; (**e**) Fistulous; (**f**) Gours seen from above; (**g**) Gours seen in profile(Credit photo (g): Houcine El Mansouri)

Lower Lias. This emergence is in a porch giving access to the cave of Ras El Oued (Fig. 10.13a), with an opening 20 m high and 10 m wide. Near the entrance, there are stepped gours characteristic of this cave (Fig. 10.13b). The latter (Fig. 10.14) is traversed by a permanent and siphoning underground river emerging from the terminal siphon with a flow rate of 5 m^3/s at low water and 10 m^3/s in winter to supply the spring.

The waters leaving the cave (Fig. 10.13c) are the result of the waters infiltrating the Liassic carbonate terrains on the SE flank of the second anticline as well as in the part of the Bou-Iblane sector (Obda et al. 2009). The structure of the Liassic terrains, whose dip is substantially oriented toward the NE, means that the drainage of groundwater is from the SW to the NE. After emerging at the source of Ras El Oued, the water flows NE along Oued Meloulou which is one of the main tributaries of Oued Moulouya.

Since 2006, this resurgence has been classified as a SIBE site because of the biodiversity that surrounds it and the presence of *Salmo trutta fario* (Brown Trout).

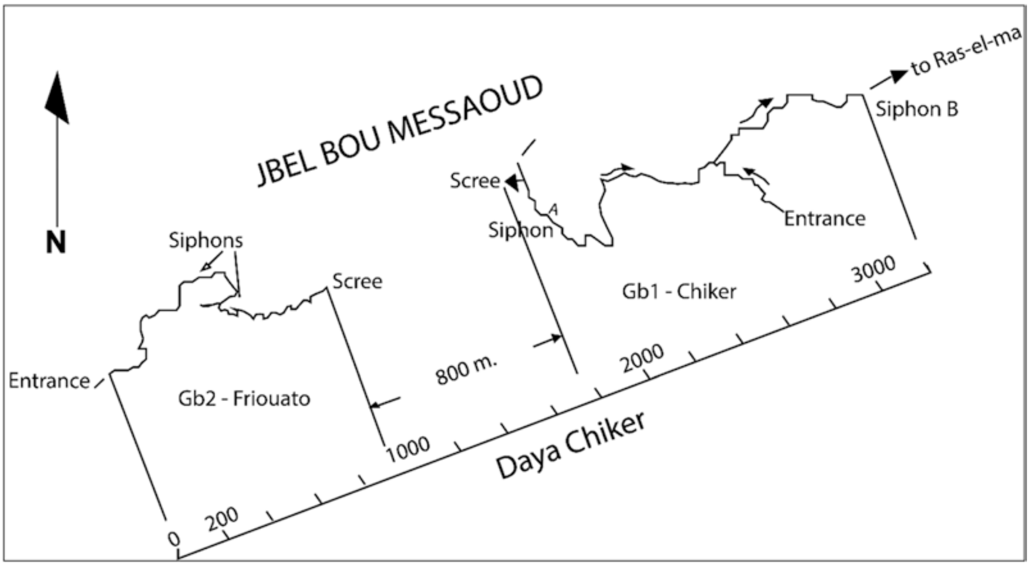

Fig. 10.11 Underground network of the Gouffre Friouato-Grotte Chiker (Ministère de l'Équipement du Maroc, Direction de l'Hydraulique 1981)

Fig. 10.12 (**a**) Entrance to the Gouffre Friouato (credit photo: L'Oriental Marocain); (**b**) Drapery; (**c**) Different speleothems of the Gouffre Friouato geosite

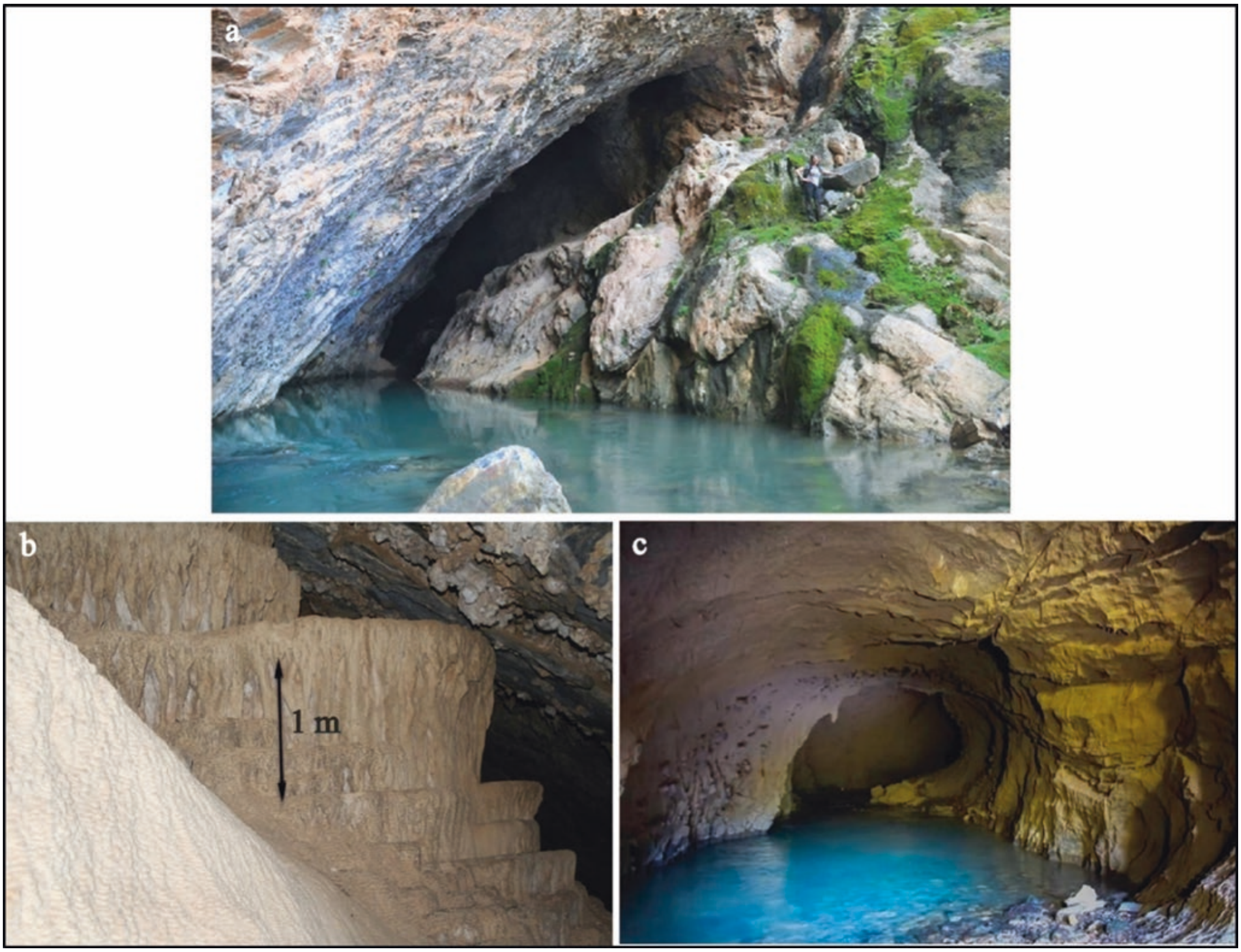

Fig. 10.13 (**a**) General view of the Ras El Oued geosite within the carbonate terrains; (**b**) Succession of gours; (**c**) Entrance to the Ras El Oued cave

10.4 Karstic Heritage Promotion Initiatives

The karst reconstructs a good part of the geological history of the Middle Atlas by studying the arrangement of several disciplines. The promotion of karst heritage is a crucial task to reveal its scientific value to the public, and particularly relevant in all preservation and conservation activities. The involvement of the community to promote this heritage is a necessity and its promotion can constitute a bridge for sustainable economic development between scientific knowledge and the general public through several initiatives to raise awareness of the heritage value.

In the Middle Atlas, and for a century, several initiatives have been carried out by speleological associations and federations developing research and training activities on exokarst and endokarst. Among these initiatives, a scientific training, under the name "For a contribution to the knowledge and protection of the underground heritage" (Fig. 10.15a), organized by the Moroccan National Federation of Speleology (FNMS) and the French Federation of Speleology (FFS) took place in Taza in 2018. Several disciplines, related to the underground domain, were approached: biology, geology, karstology and topography. Fourteen Moroccan participants presenting different Moroccan scientific associations had access to this different knowledge (Fig. 10.15b). This initiative is a precursor to the CaveMAB Network program (https://cavemab.com/) which launched an awareness campaign to promote the understanding, exploration and protection of the biological and cultural diversity of cave and karst environments through sustainable actions (Fig. 10.15c, d). CaveMAB is a network of biosphere reserves around the world that cherishes natural and cultural phenomena related to caves. This multidisciplinary network will respond to the similar challenges we all face, whether social, educational, cultural or scientific, in protecting the biodiversity of unique cave and karst environments under the Man and the Biosphere Programme. The objective is to deepen education on caves

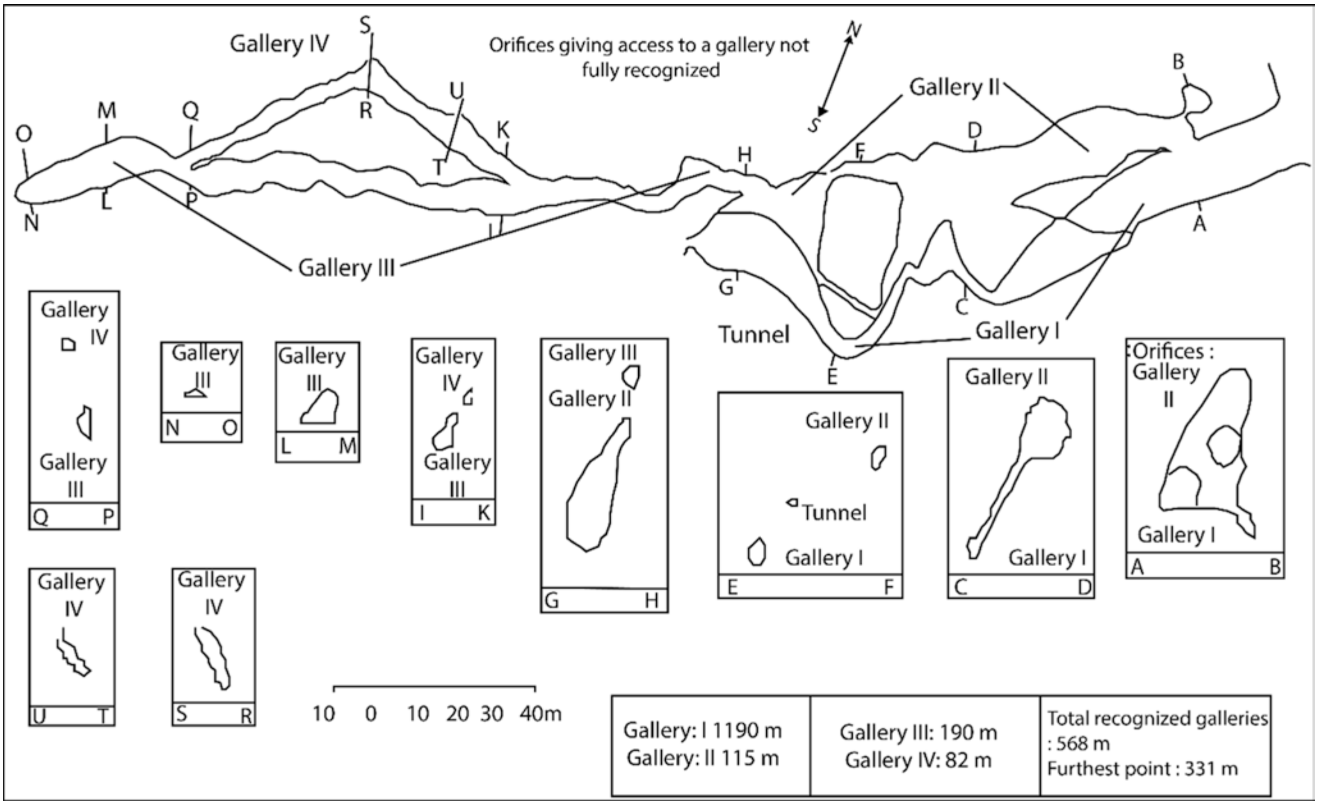

Fig. 10.14 Topographic map of the Ras El Oued cave (Strinati 1953)

and karst, strengthen community participation and sustainable development. The 2018 scientific internship, in Taza, is therefore to be renewed.

10.5 Conclusion

The study of the carbonated karstic terrains of the Middle Atlas revealed a spectacular exo- and endokarstic richness including 136 karstic geosites. Thirty-two reached the stage of the degree of deterioration, which represents 23.5% of all geosites inventoried. During this work, eight exo- and endokarstic geosites were studied. These geosites were chosen according to both the importance of their karstic, superficial and underground development, their extent, their genesis, their morphology and their geological diversity establishing their representativeness and their particularity of being unique in the Middle Atlas, in Morocco and even in Africa.

Among these eight geosites, seven geosites had a high scientific value of $Ss \geq 2.5$ (Poljé Chiker ($Ss = 2.76$), Ras El Oued ($Ss = 2.76$), Chaâra ($Ss = 2.58$), Gouffre Friouato ($Ss = 2.58$), Grotte Chaâra ($Ss = 2.56$), Grotte Chiker ($Ss = 2.56$) and Tisfoula ($Ss = 2.52$)). The only remaining geosite had an average scientific value of $1.5 \leq Ss < 2.5$ (Ademame ($Ss = 2.34$)). For the degree of deterioration, no site had a high deterioration score due to the presence of a good part of the karstic geosites located in the Tazzeka National Park (TNP) with a certain degree of preservation.

Despite this, some geosites give way to natural and anthropogenic degradation manifested through livestock and agriculture that have developed in the poljes as well as some quarries altering the karst landscapes. The practice of unregulated caving can cause the physical degradation of the walls of underground cavities (engravings and paintings of visitors), the degradation of underground fauna, little known and often endemic, and the disturbance of bats during periods of hibernation and whelping. The underground environment attracts not only speleologists but also “looters.” It is victim of the collectors of stalactites and stalagmites which are the first affected elements. The mineral trade is in vogue and the “crystals” of caves are the first victims. Repeated and unregulated visits to these environments can also cause groundwater pollution.

To preserve this karst heritage and make it known to the general public, several federations and associations are involved in promoting links between the karst and all other aspects of the natural and cultural heritage of the Middle Atlas. These initiatives are an effective way to guarantee the sustainability of the use and promotion of karst in the Middle Atlas.

Fig. 10.15 (**a**) Poster of Taza's scientific training; (**b**) Participatory team at the Taza scientific training; (**c**) and (**d**) Field trips to raise awareness of the value of underground karst heritage

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11 Geomorphological Study of the Endo-Karst of the Middle Atlas as a Geological Heritage to Be Preserved, Case of the Chaara Cave, Province of Taza

Hicham Benani, Ayoub Nehili, Lalla Amina Ouzzaouit, and Larbi Boudad

Abstract

The caves, since the dawn of history, represented for Man a shelter and a refuge. Their mystery continues to amaze us with what they preserve: rock engravings, parietal paintings, fossils, etc. In the region of Taza, renowned for the diversity of the reliefs, and for the large number of caves discovered, there is an exceptional attractive cave: the Chaara cave, explored for the first time by speleologists in 1962, also known under the name Ifri Azougagh in Berber meaning the red cave. It has been the subject of several expeditions, notably those of Cerberus Speleological Society, the French Association for the Exploration of Gouffres and Canyons, the Speleological Group of Orsay and the Speleological Research and Study Group of Taza between 1981 and 1998. This cave is an active underground river, containing several galleries spread over two floors. The Chaara cave has a great scientific and heritage value and contains first-rate occurrences for the development of geosciences. Its geomorphology, speleothems and characteristic speleometry of water activity over thousands of years make it an exceptional heritage, adding to this the recent discovery of a Teleosauridae crocodylomorph from the Lias less than 500 m. Main entrance enriches the geomorphosites that will have to be protected and enhanced as cave heritage.

H. Benani (✉) · L. A. Ouzzaouit · L. Boudad
Mohammed V University, Faculty of Sciences, Rabat, Morocco
e-mail: hicham.benani@um5r.ac.ma

A. Nehili
Sultan Moulay Slimane University, Faculty of Letters and Human Sciences, Beni Mellal, Morocco

Keywords

Geomorphology · Endo-Karst · Speleothem · Topography · Photogrammetry

11.1 Introduction

The Taza region is considered the captain of caves and caving of Morocco in view of its wealth of Karstic sites. The endokarstic and exokarstic geomorphosites, some of which are listed and mapped, are numerous and diversified, and in this article, we will look at the Endokarst of the Chaara cave characterized by its beauty and splendor. It is considered one of the richest karstic sites of the Middle Atlas as it stands out for its caving, speleothems and rich geomorphological and paleontological heritage (Mounir et al. 2019).

The Chaara cave is part of the rural town of Smià belonging to the province of Taza, circle of Tahla, in the region of Taza-Al Hoceïma-Taounate, covers an area of 257 km^2 and consists of 27 douars (Fig. 11.1). It is limited to the north by the rural commune of Bouchfaa and Matmata, to the south by the rural commune of Zrarda, to the east by the rural communes of Bab Boudir, Maghraoua and Tazarine, and to the west by the urban commune of Tahla and the rural commune of Ait Seghrouchene.

The rural municipality of Smia has a particular natural landscape: Forests, mountains characterized by biological and ecological diversity, in particular its proximity to the Bab Louta dam, but mainly caves such as Kaouane, Rouadi, Lhnech, Afejjaj, Sferjel, Tabhirt and all particularly the Chaara cave, which makes it an area of tourist attraction par excellence.

Indeed, the Karstic landscape around the Chaara cave is developed and diversified, and the phenomenon of Karstification is important there.

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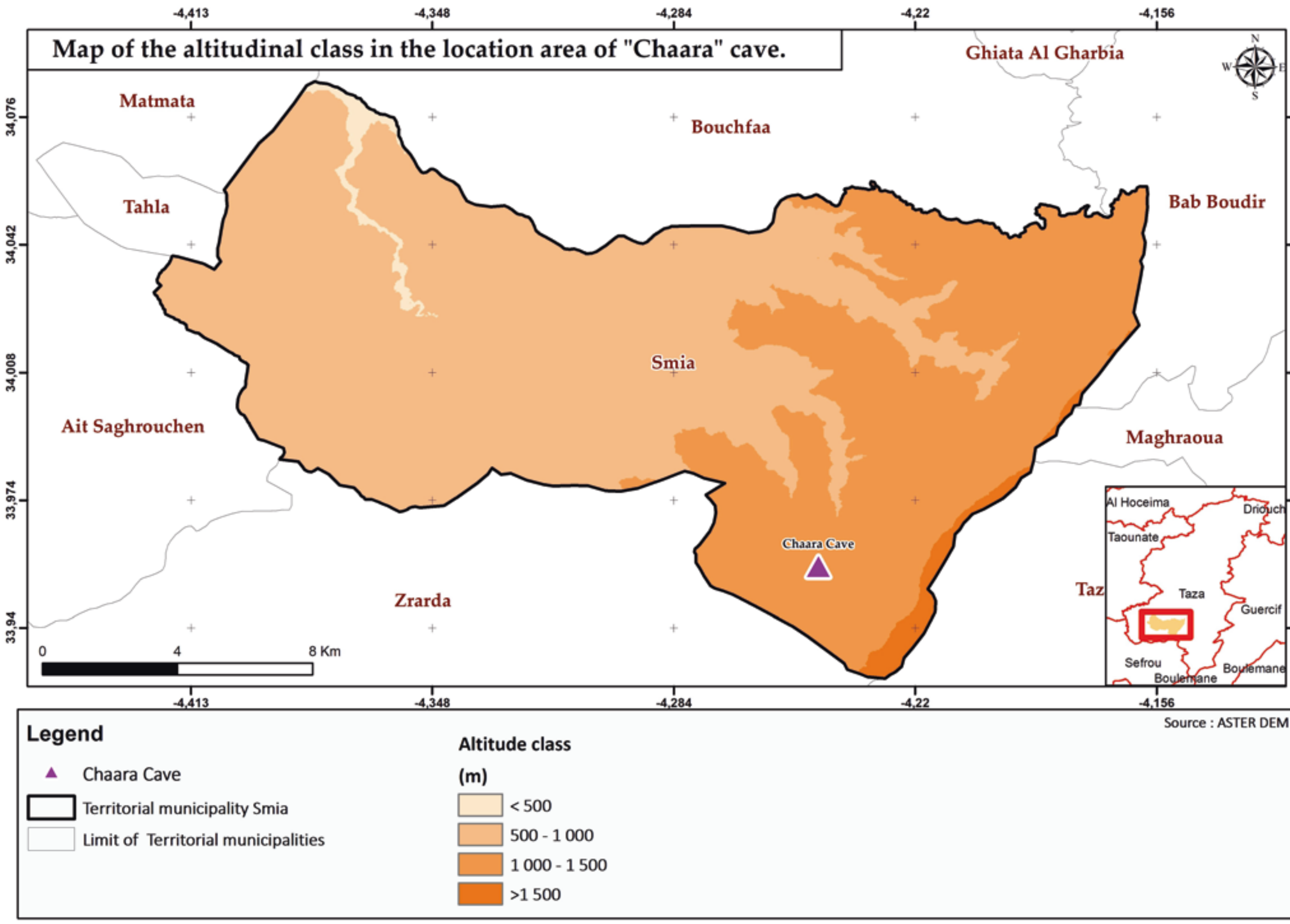

Fig. 11.1 Maps of location and delimitation of the Chaara basin

This article will discuss the geological framework, the speleometry via the topography of the main axis of the cave by DistoX method, the speleothems which characterize the geomorphology of the karst of the Chaara cave, the contribution of photogrammetry for the enhancement of the heritage cave paleontology (Bussa et al. 1997; Reinhart 2017; Chatelon 2014; Grussenmeyer 2016; Baadi et al. 2021; Benani et al. 2022).

11.2 Location of the Study Area

Chaara cave is geographically located at point 33.95676, −4.24582.

The Chaara karst is prisoner of the surrounding mountains, and it is flanked by a belt of depression. The limestone slab of Chaara is folded and violently faulted.

11.2.1 The Karstic Basin of the Chaara Cave

The digitalization of the contours of the topographic map made it possible to obtain the digital model of the karstic basin of Chaara, and the cave is at an altitude of 1300 m (Fig. 11.2).

The Chaara basin is characterized by a variety of geological structures between normal faults and reverse faults. Between the base and these limestones, a buffer of clayey marls from the Permo-Trias has favored brittle tectonics and thrusts, all of which is often accompanied by Diapirism. The lithological study provides information on the nature of the limestone. Indeed, the porous and cracked limestone allows the coexistence of karstic circulations, and the tectonics facilitates the understanding of the development of the karst by the widening under the action of water. The karstic zone studied is located in the folded Middle Atlas, characterized by deferent geological times: Quaternary.

11.3 Geological Setting

The study area is part of the eastern extension of the central Middle Atlas and there are two areas represented mainly by Mesozoic terrains separated by the Hercynian Massif of Tazekka of Paleozoic age:

- Middle Atlas Causse or “tabular Middle Atlas”; less extensive than the folded Middle Atlas, with a predominance of carbonate deposits which result in flat plateaus

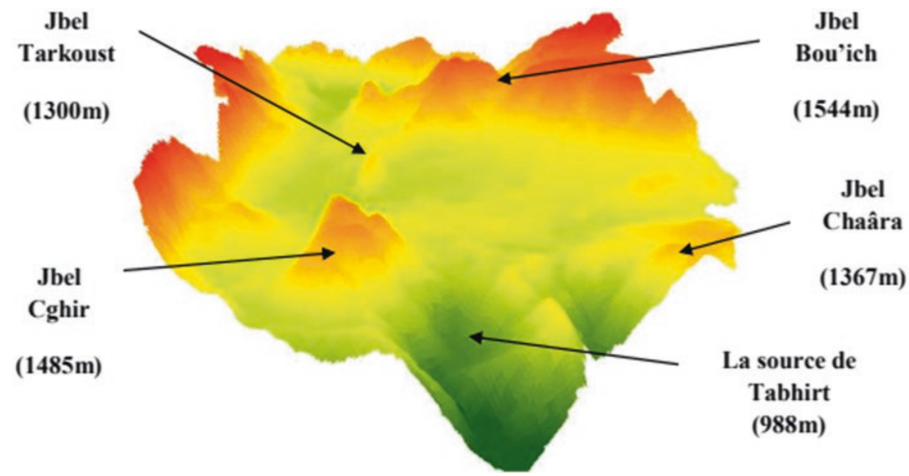

Fig. 11.2 3D digital terrain model of Chaara cave watershed

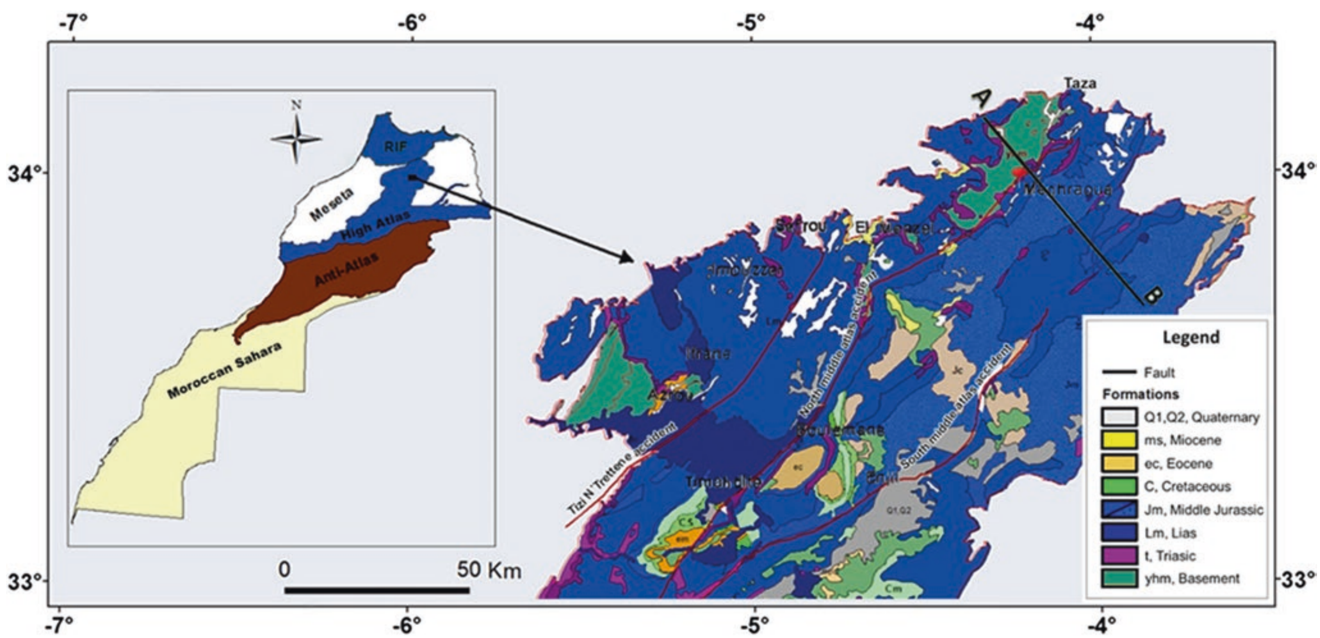

Fig. 11.3 Simplified geological map of the study area (in Mounir et al. 2019)

shaped by karstic erosion. The Causse shows two main units which are the Causse de Tahla and the Causse de Oued Zra-El Menzel.

- Middle Atlas proper or "folded Middle Atlas" with an altitude between 800 and 1200 m, exceeds 3000 m on the eastern links of the folded domain (Charrière 1990; Charroud 1990; Frizon de Lamotte et al. 2004, 2008; Sabaoui 1998). The stratigraphic series of the study area begins with a Paleozoic basement surmounted in angular unconformity by a folded and structured Mesozoic cover during the Alpine orogeny (Fig. 11.3).

11.3.1 Paleozoic

Represented by the Massif de Tazekka formed by Paleozoic metamorphic rocks consisting of schists, pelites and quartzitic sandstones from the Cambro-Ordivian to the Middle Devonian (Hoepffner 1987). This series is topped by a volcano-clastite complex associated with andesitic lavas and rhyolitic tuffs of the Upper Visean-Namurian which rests in angular unconformity on the olive-green shales of Tazekka.

11.3.2 Trias

The Triassic series begins with a detrital level composed of sandstone and microconglomerates rich in pebbles of the acid volcano-sedimentary complex, and which rests in angular unconformity on the Paleozoic basement. It generally presents the association of three terms: detrital and clay-salt at the base, basaltic in the middle part and clay-salt at the top. The tholeiitic basalts are of a lower Liassic age and can reach 300 m NE of Tazzeka (Fig. 11.3).

11.3.3 Lower and Middle Lias

The Chaara sector presents an intense karstification clearly visible on the ground and the whole of the lower Lias series is represented essentially by generalized carbonate platform deposits on the scale of the entire western Tethys (De Graciansky et al. 1979) and which are reflected in this zone by massive formations with dolomitic and dolomitic limestone facies, of which several localities show constructed limestones of Sinemurian to Lower Carixian age (Sabaoui 1998). The middle Lias is characterized by a limestone sedimentation rich in Ammonites (Figs. 11.3 and 11.4).

11.3.4 Upper Lias and Dogger

The Upper Lias and Dogger terrains outcrop widely in the synclinal depressions of the folded Middle Atlas (Sabaoui 1998). Marly sedimentation, which began in the Domerian, asserts itself and establishes a mudflat regime that will continue until the lower Aalenian-Bajocian (Fig. 11.3).

11.3.5 Quaternary

The Quaternary deposits of the Chaâra region are mainly represented by fluvial deposits, terra rossa from the decalcification of the Middle Lias, travertines and lacustrine limestones.

The sedimentary cover of the Middle Atlas, which extends from the Tazekka massif to the high summit of Bou Iblane toward the South East, forms a succession of anticlinal ridges running NE-SW, separated by large synclinal depressions (Zloul, Tazarine, Meghraoua) corresponding to zones of accumulations of sedimentary deposits with marl and marl-limestone dominance of the Toarcian and the Dogger. These series rest on a Permo-Triassic series formed essentially of saliferous argillites with basalt. It is indeed an impermeable substratum of the entire Jurassic series (Martin 1981; El Arabi 1987; Taous et al. 2009).

The Chaara cave is located just at the level of the first anticline ridge. The latter is affected by a North Middle Atlas accident beam, marking the transition from the Middle Atlas Causse to the folded Middle Atlas (Fig. 11.3). It is a continuous anticline structure with two main virgations at the crossing of transverse faults (NW-SE) of Sidi Brahim and Oued Zra.

These anticlinal ridges are formed by massive limestone from the lower Lias, and constitute the most karstified stage. The Middle Lias, formed by stratified limestones, is found on the reverse of the ridges. Between the base and these limestones, a buffer of clay marl from the Permo-Trias favored the formation of the Grotte Chaara in the carbonate formations of the Lower Lias (Tennevin 1978; Sabaoui 1998; Baadi et al. 2021).

On the tectonic level, this eastern part of the Middle Atlas has undergone the same evolution as that of the subtabular part of the chain (Martin 1981). From the Lower Pliocene, it underwent compressive tectonics, coupled with the Riffian thrust, which induced generalized uplift. This uplift is responsible for a shift toward the North, and the reactivation of certain structural lines (Charrière 1990; Piqué 1994). The NE-SW, NW-SE and N-S accidents remained active later, as evidenced by the deformation of the Pliocene and Villafranchian terrains (Charrière 1990; Sabaoui 1998). Tectonics strongly influenced the development of karstification. These networks of fractures, created by these tectonic movements, were used by surface and underground water flows, which favors the development of an intense karstogenesis whose direction and development is the same as that of the faults (NE-SW and NW-SE). The direction of this cavity, mainly linked to faults, is the same as that of the Middle Atlas chain (NE-SW) (Sabaoui 1998; Taous et al. 2009).

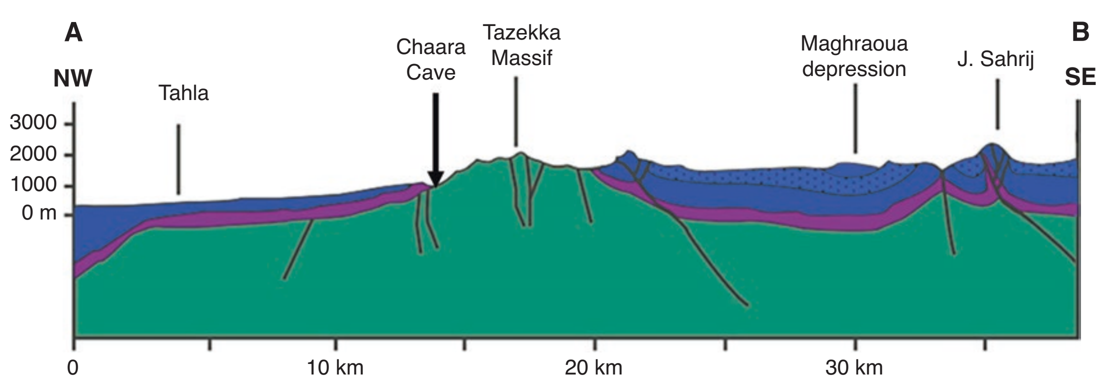

Fig. 11.4 E-W geological section at the level of the north-eastern Middle Atlas study area (Sabaoui 1998, simplified)

11.4 Presentation of the Chaara Cave

The Chaara cave can be considered as a slide hidden by a forest of holm oaks in the primary conduit leads to a huge gallery announcing the start of an easy progression through the different rooms that make up the main axis of the cave over several hundreds of meters, in the very bed of the Chaara river.

The Chaara River is permanent and active throughout the four seasons. The total of its development is 7650 m, and it is classified as the second longest cave of Morocco.

We note that the Chaara cave has two entrances: the first is called (Ifri Azougagh), a name of Berber origin and means the red color of the ground, the second entrance to the cave is called (Kehf Sferjel), it is on the eastern side of the cave and constitutes a narrow, nonaccessible entrance, a photogrammetry of this entrance shows the narrowness and the difficulty of accessing the cave through this entrance (Fig. 11.5) (Benani et al. 2022).

The Sferjel entrance is 2.23 m wide and 0.6 m high, and the access becomes narrower and more rugged over the first 5 m.

11.5 Speleometry and Topography of the Chaara Cave

The spatial representation is a fundamental element in the study of the Endokarst, It helps to determine the spatial relationships between the objects and geological elements, and the stratigraphic contexts in which they are located, this allows to complete the scientific interpretation of an observed geological object or phenomenon (Redovniković et al. 2014; Benani et al. 2022).

Although the techniques of spatial representation and topography in accessible open environments have been well established for a long time with equipment in caves and caverns, the representation of these environments in a scientific and methodological way has only been developed since the end of the nineteenth century.

However, the representation of these extreme and difficult environments in view of the complex geomorphology of the Endokarstic environment does not leave a large choice of material. Thus, the DistoX, by its small compact size (55 × 31 × 122 mm) and a weight of 150 g, is the surveying instrument most used by the speleological community on a global scale, and the system is based on a modification of the Leica X310 portable electronic laser rangefinder by installing a motherboard integrating a module for measuring slope and orientation relative to north as well as a Bluetooth chip allowing data to be sent directly to an electronic topography notebook already installed on PDA or smartphone. This device It was developed to map cave systems to replace the traditional method of manual measurements and paper sketches, which is time-consuming and labor-intensive.

The Chaara cave has been surveyed since its first speleological exploration in 1962. A first representation was made by the caving club of the "Maison des jeunes et de la Culture d'Aix En Provence."

In 1998, "Associations Franciliennes d'Exploration des Gouffres et des Canyons" published a detailed synthesis of the topography of the cave, in order to have precise and usable data we decided to resume the topography and the exploration of this underground river.

In our situation, the use of the DistoX allowed us to redo 2.7 km of topography from the entrance to the chandelier room, passing by the recently discovered crocodylomorph Teleosauridae fossil (Heeb 2014; Trimmis 2018; Benani et al. 2022).

The topography using the DistoX allowed us to have detailed information on the orientation, the depth, the development of the cave up to the Luster room as well as the position of the mandible. From the data of the topography we locate the fossil at point XY: 33°57′20.22″N 4°14′58.09″W, we also know that the discovery is at 455.07 m and at a depth of −8 m by contribution l entrance to the cave (Fig. 11.6). These results will be completed during a new mission: to finish the topography of the cave in its entirety and to carry out a survey in more detail in the fossil room.

11.6 Chaara Cave Exploration

The main course of the Chaara river is lost in its own bed. From the normal extension of the cave, toward the resurgence (Baadi et al. 2021). The Chaara gallery continues over a width of 7–8 m which allows easy progression without major constraints, the stream flows over pebbles and sand. A first gallery goes WNW about 1500 m from the entrance, on a very narrow rolling mill. Between 1000 and 1500 m from the entrance, there are huge scree, the vault is very high (20–30 m) (Fig. 11.7).

At the large screen, 2000 m from the entrance, two galleries start. One in SSW ends in a siphon at 700 m and the other, after a few bifurcations and low arches, continues for 1700 m from the large scree; which gives us 3700 m in length from the entrance.

On the upper floor of the cave, there is a development of about 600 m with dry galleries. The total length of the network with the ramifications is estimated at 7650 m. The dry gallery shows the richness of endokarstic forms, particularly concretions and crystallizations (Fig. 11.8).

The underground flows of the Chaara cave allow the formation of lakes when these flows are interrupted by overflow in

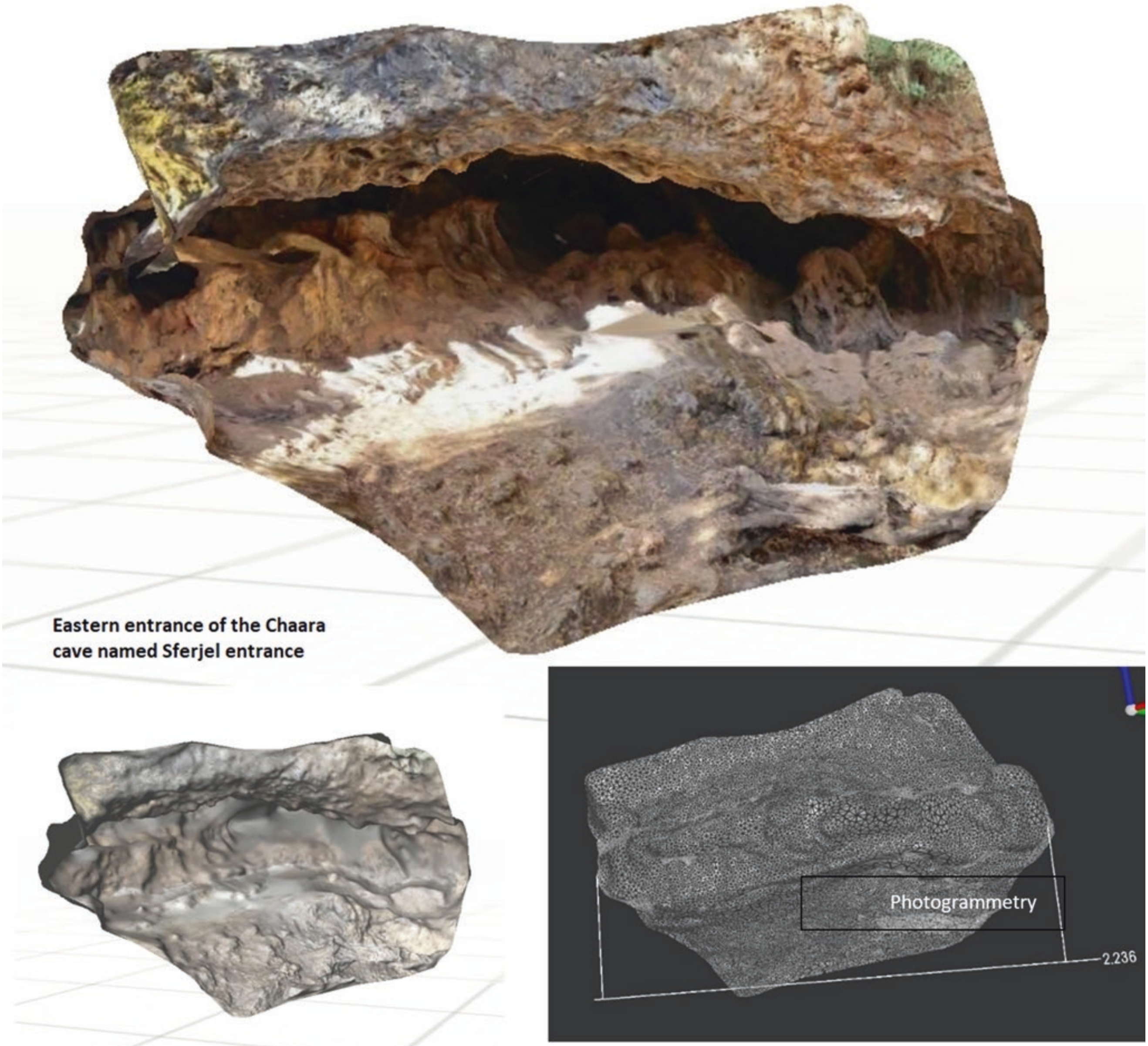

Fig. 11.5 Photogrammetry of the East entrance of the Chaara cave named Sferjel entrance

an impermeable basin or a depression. The latter are formed when these flows are interrupted by overflow into an impermeable basin or depression.

11.6.1 The Underground Rooms of the Chaara Cave

These are large underground empty spaces that form large rooms. The Chaara cave is characterized by the presence of large rooms adorned by concreting and depositing calcite (Fig. 11.9).

From the entrance, these rooms present many speleothems of stalactites, stalagmites and draperies that adorn the rooms, and some rooms are distinguished by whitish deposits of calcite like the cemetery room.

11.6.2 The Speleothems of the Chaara Cave

Speleothems are the subject of growing interest from climatologists because of their strong potential as paleoclimatic archives, most often studied for their isotopic records of oxygen and carbon, and they are also vectors of important

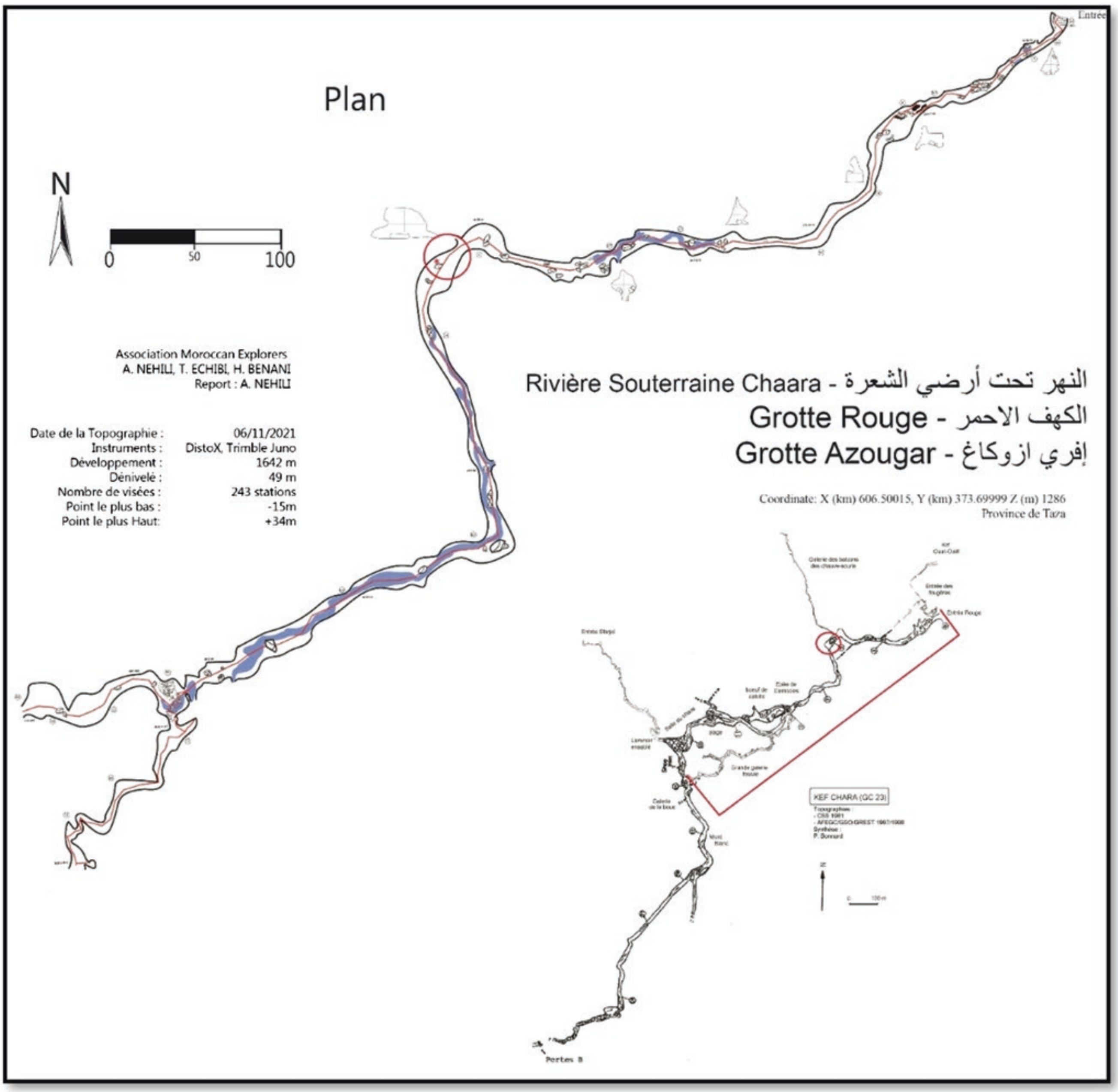

Fig. 11.6 Topography of the main axis of the Chaara cave by DistoX rangefinder

paleoenvironmental information at different scales and resolutions.

These are secondary chemical deposits linked to the degassing of percolation water in the cavity. They are therefore essentially of inorganic origin (although in some cases a microbial contribution is suspected.

Speleothems present a very wide variety of shapes, their mass being essentially made up of calcium carbonate and most often calcite (90% of endokarstic concretions).

These speleothems generally consist of calcium carbonate (calcite, aragonite) calcium sulfate (gypsum) transported in solution in the percolation waters. The speed of concretions depends on several elements (Pomel and Maire 1997; Couchoud 2008; Frisia et al. 2022; Sánchez et al. 2022):

- Amount of (CO_2) in the solution
- Water and air temperature
- Physico-chemical nature of the soil
- Composition of the atmosphere
- Hygrometry
- Other…

Fig. 11.7 The active gallery of the main course of the Chaara cave with an active concretion (Márton 2020)

The speleothems of the Chaara cave can be considered as endokarstic sedimentary accumulations of chemical origin; they are represented by stalagmites, stalactites, columns, tubes, gours, draperies, chandeliers and other types of various shapes depending on the shape and the calcite precipitation process (Figs. 11.10, 11.11, and 11.12).

Water saturated with calcium bicarbonate (CaCO3) enters the cave through cracks in the rock and deposits its calcium bicarbonate through the degassing of carbon dioxide and the precipitation of calcium bicarbonate, which dries and crystallizes into calcite, but also by evaporation and deposit of calcite which crystallizes naturally, gradually forming a concretion, Among the most spectacular speleothems in the cave we can cite (Fairchild et al. 2006; Léger 2022).

11.6.3 Chaara Cave Chandelier

11.6.4 The Columns of the Chaara Cave

If the height between the ceiling and the ground is quite low, or during a long period of karstic evolution, it is possible that the stalactite and the stalagmite meet on the same axis to form a column.

Fig. 11.8 One of the dry galleries of the Chaara cave which is located on the upper floor

Fig. 11.9 Concretion and deposit of calcite in the cemetery hall at the Chaara cave

Fig. 11.10 Concretion and deposit of calcite in drapery case of the chandelier of the Chaara cave

11.6.5 Chaara Cave Draperies

The very frequent drip flow shapes the stalactite on the ceiling, vertically, and the stalagmite is born and grows on the floor of the galleries and rooms (Fig. 11.13).

11.6.6 The Stalactites of the Chaara Cave

When a drop of water seeps from the ceiling through the cracks in the wall, the degassing that occurs leads to a deposit of calcium carbonate. A small tube will thus form, lengthen and grow as water arrives in the open air. If the central channel is blocked, the water will run off along the stalactite and will continue its elaboration, and the stalactite can thus reach imposing dimensions. Particular conditions can give stalactites more irregular shapes, sometimes with more or less horizontal growths (Figs. 11.14 and 11.15) (Poulain et al. 2014).

Stalactites make it possible to trace the climatic evolution of a region, in the same way as the taking of ice cores or, on a lesser scale, tree rings by dendrochronology.

11.6.7 Stalagmites of the Chaara Cave

When a drop of water falls from the ceiling from the end of a stalactite, it still contains calcium carbonate in solution, on

Fig. 11.11 Concretion and formation of columns following the junction of a stalactite and a stalagmite

Fig. 11.12 Junction between stalactite and stalagmite in action to form a column

Fig. 11.13 Stalactites and Drapery of the Chaara Cave with

its arrival on the ground, it produces splashes which deposit fine mineral particles on its side.

At the point of impact, it creates a kind of base which by progressive increase of its summit will give a stalagmite. If the height of the fall of the water is significant and if the flow is sufficient, the splashes make it possible to erect special structures. The size of the stalagmites is related to the flow of water and the height of the fall (Figs. 11.16 and 11.17).

11.6.8 Calcite Crystals in the Shape of Sharp Teeth

Another variety of calcite development especially in dry gours where oversaturation favors the crystallization of calcite to generate crystals of all kinds and sizes: "wands," "coroles," "chalices" and more rarely "teeth of pig," "rhombohedrons" and "hollow triangles." Some, in clusters, form "hedgehog cushions" (Fig. 11.18).

11.6.9 The Gours of the Chaara Cave

At times there is the appearance of small calcite dams with horizontal crests, which are in the diversion zones, between two bodies of water. The genesis of the gours in these places is explained by the fact that the water circulates there in weak slice with eddies causing its aeration and facilitates the precipitation of calcium carbonate in excess (Fig. 11.19).

Fig. 11.14 Stalactites and Drapery of the Chaara cave from the upper floor room of the cave

Fig. 11.15 Stalactites of the dry gallery of the upper floor of the Chaara cave

Fig. 11.16 Chaara Cave stalagmite

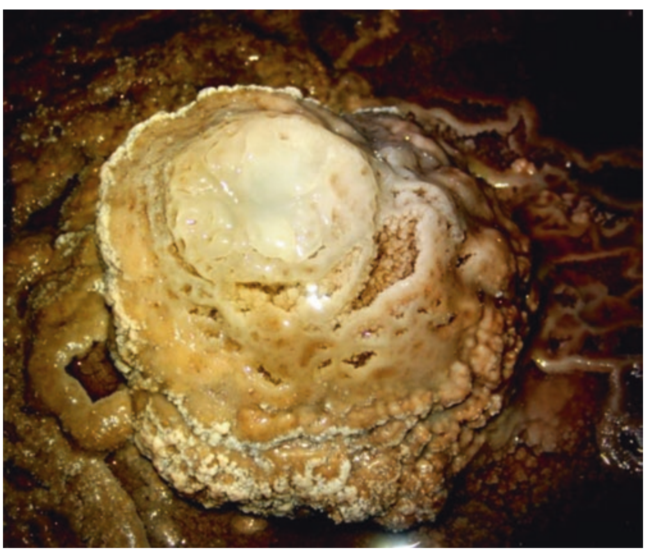

Fig. 11.17 Birth of a stalagmite by percolation of water rich in calcite

11.7 Photogrammetry of Crocodylomorph Teleosauridae from Chaara Cave

3D modeling techniques are used in many fields such as forensic science, petrochemicals, mining, structural monitoring, automotive, defense, archeology and heritage conservation. There are mainly two methods of 3D modeling,

Fig. 11.18 Details of calcite crystals in the shape of sharp teeth (Carol & Forti, 1997)

lasergrammetry and photogrammetry (Fig. 11.20) (Adrian et al. 2008; Jaillet 2019; Benani et al. 2022).

Photogrammetry makes it possible to represent objects in three dimensions from digital or silver images. It relies on the vision of an object from two different points of view to reconstruct an exact 3D copy of reality. The implementation of this method requires the production of shots and a support canvas. This method is a good alternative to using the laser scanner because of its low investment cost and its ease of use. In addition, it allows the production of 3D models of very good quality, close to the models obtained by lasergrammetry.

In our context, we have priced 32 photos to build a 3D image of the mandible of the crocodylomorph Teleosauridae from Chaara cave.

11.8 Conclusion

The Endokarstic environment is well known for its morphological richness, the numerous underground rooms in the cave present concretions of surprising beauty. The screes also give morphology in Endokarstic landscapes and are the result of cave collapse.

Chaara Cave is characterized by the nonactive and dry upper floor gallery and an active gallery in the main course of the underground river. The Chaara sector presents an active karst, all the current physical conditions of the land are favorable to the evolution of karstification.

Fig. 11.19 Example of Chaara Cave gours

Fig. 11.20 Photogrammetry of the mandible from Chaara cave belonging to a Telesaurdea crocodylomorph from the Lower Liassic

The geological analysis of the context shows the abundance of limestone soils, and cracks favorable to increased water infiltration at depth. Chaara climate data analysis has always experienced significant rainfall, benefiting from the altitudinal factor.

The abundance and richness of the forest massifs on the slopes testify to the age of the continuous and abundant plant cover necessary for karstogenesis.

The geomorphological approach adopted for the study of the Chaara karst allowed us to define and map the different endokarstic forms. It also made it possible to recognize the Vaucluse springs allowing the drainage of deep water.

According to what has just been described, the cave of Chaara contains first order occurrences for the development of geosciences. Indeed, this cave conceals many geological, paleontological and geomorphological assets. The discovery of the “Teleosauridae” specimen reported in this article is further evidence of this scientific relevance. However, it is evident that the site is undergoing rapid damage due to unregulated tourist activities, as well as recorded vandalism of the cave.

All the actors currently involved in the exploration and safeguarding of the Chaara cave agree on the absolute urgency of implementing policies for the protection and enhancement of this site. They are strongly convinced of the great development opportunities that this cave can generate in terms of sustainable social and economic growth.

Several actions are to be taken to protect this natural heritage through the creation of a geomuseum in the region to inform visitors and encourage them to discover the cave where the specimen was found.

Produce and install indicative and interpretative signs. Carry out an environmental impact study on the site and regulate its access. On the other hand, we strongly recommend assessing the geodiversity of Chaara Cave and determining its geoheritage values. A recently developed geoheritage inventory and assessment methodology (Arrad et al. 2018, 2019) could be of great interest in order to link the cave as a primary geosite with the main relevant occurrences within the cave and the latter as secondary geosite.

The recommended initiatives are fundamental to prevent irreversible damage to the potential Chaara Cave geosite. They will also make it possible to set priorities for protection and conservation as well as to establish a framework for the sustainable development of the cave.

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12 Biodiversity endokarstic of the Middle Atlas (Morocco): An Underground Richness to Inventory

Bernard Lebreton

Abstract

The endokarst heritage of the Middle Atlas is of high geological and geomorphological value, and biodiversity is one of its main elements. Not well known and still insufficiently taken into account, it is also very rich and varied. An inventory of aquatic and terrestrial species currently recorded allows to reveal the richness and variety of this heritage increasingly affected by environmental changes and various human impacts.

Keywords

Endokarst · Heritage · Inventory · Aquatic and terrestrial species · Middle Atlas

12.1 Introduction

The Middle Atlas has a vast karstic domain occupying 30% of its area (Fig. 12.1). The snow and rainfall, very important, allow this mountainous region to give it the role of "water tower" from which are born the great rivers of the country. To date, there are more than 370 karst phenomena in the Middle Atlas. Of high geological and geomorphological value, they shelter an important biodiversity. After a history of the different investigations carried out in the Middle Atlas, the particularities and a presentation of this biodiversity, completed by a list of the recorded species, reveal all the richness. The environmental changes and human impacts that affect more and more this underground life are also stated.

B. Lebreton (✉)
French Speleology Federation, Lyon, France

12.2 Historical Summary

Norbert Casteret explored the region of Taza in 1934 and discovered a multitude of chasms and caves (Casteret 1935). The first observations on endokarst biodiversity were made in the Chiker cave where the first troglobitic beetles of Morocco, *Trechus (Antoinella) groubei* Antoine 1936 and *Apteranillus rotroui* (Scheerpeltz 1936) were discovered; the myriapod *Lithobius chikerensis* Verhoeff 1936 and the first cavernicolous Campodeidea of North Africa, *Tachycampa lepineyi* (Silvestri 1936). Members of the Speleological Society of Morocco, from 1948, collected fauna in the underground cavities of the region of Taza (Friouato chasm, Oulad Ayach chasm, Kef el Rhar cave). Swiss scientific missions (Strinati 1953a) and Spanish teams of the Associación Catalana de Bioespeleologia (BIOSP) explore and sample the caves of the Middle Atlas. An assessment of the known endokarst biodiversity of the Middle Atlas is given in 2001 (Boutin et al. 2001). The Association Friouato pour la Protection de l'Environnement, la Spéléologie et le Tourisme de Montagne (AFSTM), in collaboration with the Fédération Nationale Marocaine de Spéléologie (FNMS) and the Scientific Commission of the Fédération Française de Spéléologie (FFS-CoSci), organizes, in 2018, a scientific course under the theme "Caving at the crossroads of sport, science and protection of the underground environment" (Fédération Française de Spéléologie-Scientific Commission 2018). The Natural History Museum of Marrakech (MHNM), Cadi Ayyad University, with the collaboration of AFSTM and the company Eléana SASu are organizing, in 2019, a caving and scientific expedition in the Middle Atlas. A new speleological and scientific expedition is organized, in 2020, by the Museum of Natural History of Marrakech (MHNM) and the Center for Underground Biology Studies of the Federal University of Lavras.

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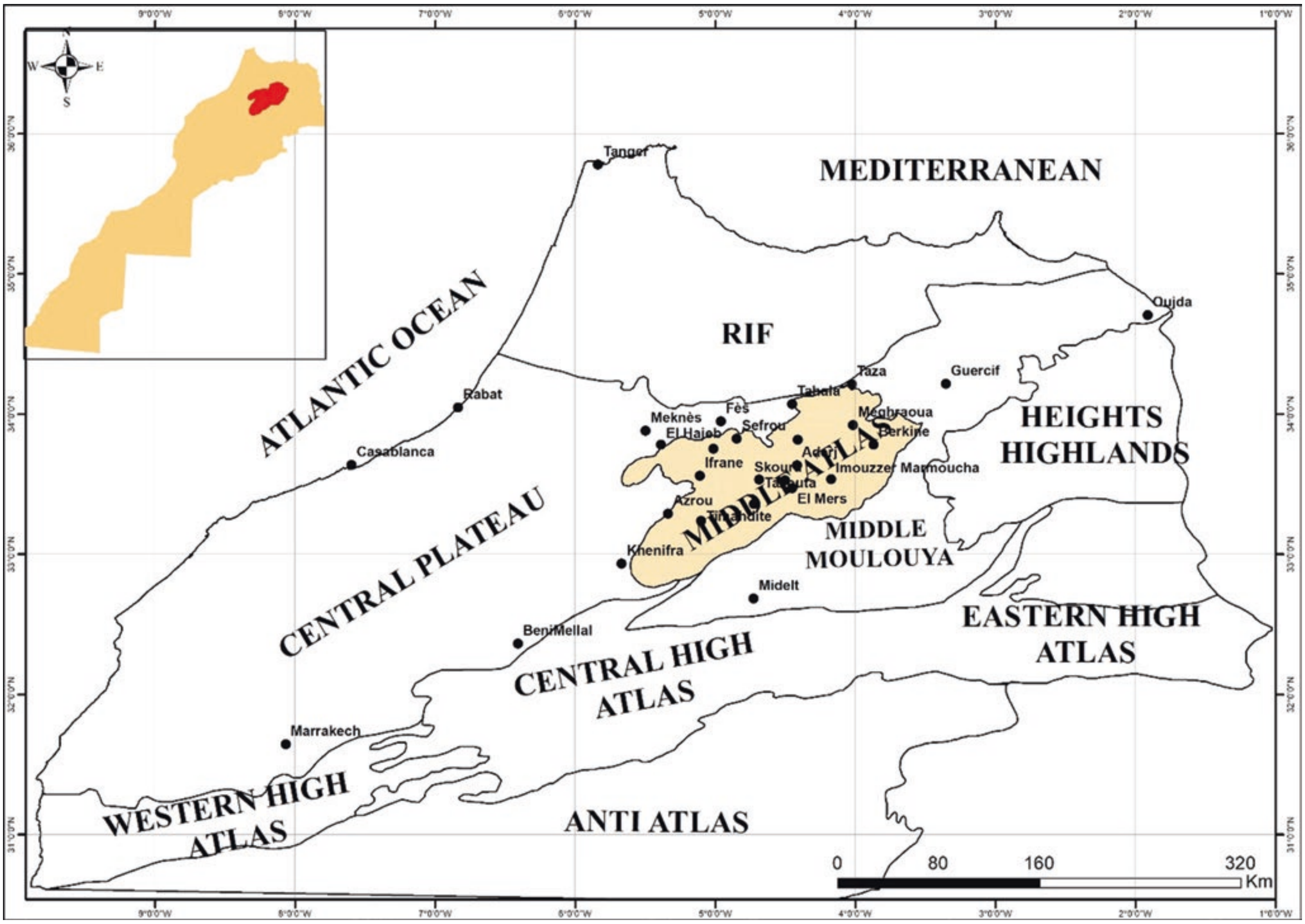

Fig. 12.1 Localization of the Middle Atlas

12.3 Endokarst Biodiversity

We often imagine the underground environment as an obscure and lifeless world, without suspecting for a moment that it conceals a multitude of living organisms, sometimes highly specialized and very sensitive to environmental disturbances. Biospeology or biospeleology is the science that studies the endokarst biodiversity. It is a relatively young science born during the nineteenth century which takes its rise in the twentieth century. The works and the discovery of new species in the karst are linked today showing that this biodiversity is very varied, very rich and that it is an integral part of the underground heritage. It was Emil Racoviță (1868–1947), a Romanian biologist, zoologist, oceanographer and speleologist who laid the foundations of this science in 1907 (Racoviță 1907).

The scientific community classifies the endokarst biodiversity according to the degree of adaptation or dependence on the environment in which the living beings of the subterranean domain live into several ecological groups. There are species that live and reproduce only in the underground domain (stygobiont for aquatic species and troglobiont for terrestrial species). There are some species from outside that come to spend only part of their existence underground, like bats for example (stygophile and troglophile). There are the species foreign to the underground environment, arrived there more or less by accident (stygoxene and trogloxene).

The interest of the scientists is rather focused on the stygobiont or troglobiont species because they have been able to develop remarkable faculties of adaptation like: the reduction or the disappearance of their eyes (anophthalmia); the development of their organs of the senses (antennas); the elongation of their legs; the discoloration of their integuments (depigmentation); the reduction or the disappearance of their wings (apterism); the slowing down of their life cycle; their very weak fecundity. However, not all stygobiont/troglobiont have all these characteristics.

Subterranean ecosystems are characterized by a reduced food supply, as they contain only very small quantities of organic matter carried to these depths by water, air or other animals. It is precisely these characteristics that make the endokarst environment a unique biotope for many organisms and of great value to scientists. Their food comes essentially from: water infiltrations in the faults and cracks of the earth's crust (organic matter); from the loss of external watercourses (organic debris); from the external elements fallen in the chasms (organic debris and various corpses); from the droppings (guano) of bats and other small mammals; from bacteria; from the living beings themselves.

12.3.1 Aquatic Endokarst Fauna (Stygofauna) of the Middle Atlas

The stygofauna include all the fauna living in underground aquatic environments (underground rivers, groundwater, underflow of rivers, springs, wells …). The animals of the stygofauna are classified into three groups according to their life cycle: stygoxene, stygophile and stygobiont. In the Middle Atlas, groundwater is a reservoir of biodiversity, populated by a wide variety of organisms, often small and endemic. Most of the known forms of groundwater, which can also occur in caves, have been found in pore waters, wells or springs (Boutin et al. 2001). Many Crustaceans from continental groundwater belong to groups absent in fresh surface waters and have a marine origin. Often considered as chronostratigraphic markers, they allow to date ancient geological events, such as a transgression-regression cycle, and to determine the location of paleo-recoveries. They are therefore used for various paleogeographic reconstructions. Underground "ancient" forms, which have remained morphologically "primitive," also allow to complete the paleontological data. The stygofauna of the Middle Atlas are represented by the following species:

Arthropoda: Insecta: Coleoptera: *Agabus politus* (Reiche 1861); *Elmis atlantis* (Alluaud 1922); *Oulimnius fuscipes* (Reiche 1879). **Arthropoda: Malacostraca: Amphipoda:** *Gammarus gauthieri* (Karaman 1935) [stygoxene]; *Gammarus marmouchensis* (Fadil and Dakki 2006); *Gammarus rifatlensis* (Fadil and Dakki 2006) (Fig. 12.2a); *Pseudoniphargus maroccanus* (Boutin and Coineau 1988) [stygobiont] (Fig. 12.2b). **Arthropoda: Malacostraca: Bathynellacea:** *Paraiberobathynella maghrebensis* (Boutin and Coineau 1978) [stygobiont]. **Arthropoda: Malacostraca: Isopoda:** *Microcharon alamiae* (Boulanouar et al. 1998) [stygobiont] *Thyphlocirolana fontis* (Gurney 1908) [stygobiont]. **Arthropoda: Maxillopoda: Copepoda:** *Acanthocyclops robustus* (Sars 1863) *Paracyclops fimbriatus* (Fischer 1853). **Arthropoda: Ostracoda:** *Darwinulla* sp.; *Stenocypris* sp. **Mollusca:** *Bulinus* sp.; *Gyraulus* sp.; *Heideella andreae* (Backhyus and Boeters 1974); *Heideella knidiri* (Ghamizi 1998); *Heideella makhfamensis* (Bodon et al. 1999); *Horatia aghbalensis* (Damme and Ghamizi 2010); *Hydrobia maroccana* (Pallary 1921); *Ifrania zerroukansis* (Glöer et al. 2020); *Iglica seyadi* (Backhyus and Boeters 1974); *Islamia karawiyiensis* (Mabrouki et al. 2021); *Islamia tifertensis* (Glöer et al. 2020); *Limnaea* sp.; *Melanopsis* sp.; *Physella acuta* (Draparnaud 1805); *Pisidium* sp. (Fig. 12.2c); *Pikasia smenensis* (Taybi et al. 2021); *Planorbis planorbis* (Linnaeus 1758); *Pseudamnicola tafoughaltensis* (Taybi et al. 2022); *Radix labiata* (Rossmässler 1835); *Rifiya yakoubii* (Ghamizi 2020); *Valvata* sp.

Triclada: *Acromyadenium maroccanum* (de Beauchamp 1931).

12.3.2 Terrestrial Endokarst Fauna (Troglofauna) of the Middle Atlas

All fauna living in underground terrestrial environments (sinkholes, caves, Mesovoid Shallow Substratum, etc.) is classified in the troglofauna. The organisms of the troglofauna are classified in three groups according to their life cycle: trogloxene, troglophile and troglobiont. The troglofauna of the Middle Atlas is represented by the following species.

Arthropoda: Arachnida: Acari: *Aphelacarus acarinus* (Berlese 1910); *Chamobates hauseri* (Mahunka 1980); *Euryparasitus emarginatus* (Koch 1839) [trogloxene]; *Linopodes motatorius* (Linnaeus 1758) [trogloxene see troglophile]; *Parasitus loricatus* (Wankel 1861) [troglophile-guanophile]; *Ramusella paillei* (Mahunka 1980); *Trombicula strinatii* (Cooreman 1951) [troglophile see troglobiont] (Fig. 12.3a, b).

Arthropoda Arachnida: Araneae: *Diplocephalus inanis* (Tanasevitch 2014); *Holocnemus caudatus* (Dufour 1820) [troglophile]; *Leptyphantes aelleni* (Denis 1957) [trogloxene see troglophile]; *Lepthyphantes imazigheni* (Barrientos et al. 2020); *Lepthyphantes leknizii* (Barrientos et al. 2020); *Lepthyphantes longipedis* (Tanasevitch 2014); *Lepthyphantes maurusius* (Brignoli 1978); *Lepthyphantes pieltaini* (Machado 1940); *Lepthyphantes sasi* (Barrientos et al. 2020); *Lepthyphantes taza* (Tanasevitch 2014); *Megalepthyphantes brignolii* (Tanasevitch 2014); *Meta bourneti* (Simon 1922) [troglophile]; *Palliduphantes cadiziensis* (Wunderlich 1980); *Pholcus opilionoides* (Schrank 1781); *Scotoneta barbara* (Simon 1910) [troglophile]; *Tegenaria* sp.; *Tegenaria pagana* (Koch 1841); *Tenuiphantes tenuis* (Blackwall 1852) (Fig. 12.3c, d).

Arthropoda: Arachnida: Pseudoscorpiones: *Chthonius* sp.; *Ephippiochthonius atlantis* (Mahnert 1980) [troglophile]; *Ephippiochthonius longesetosus* (Mahnert 1976) [troglophile-endemic]; *Ephippiochthonius maroccanus* (Mahnert 1980) [troglophile].

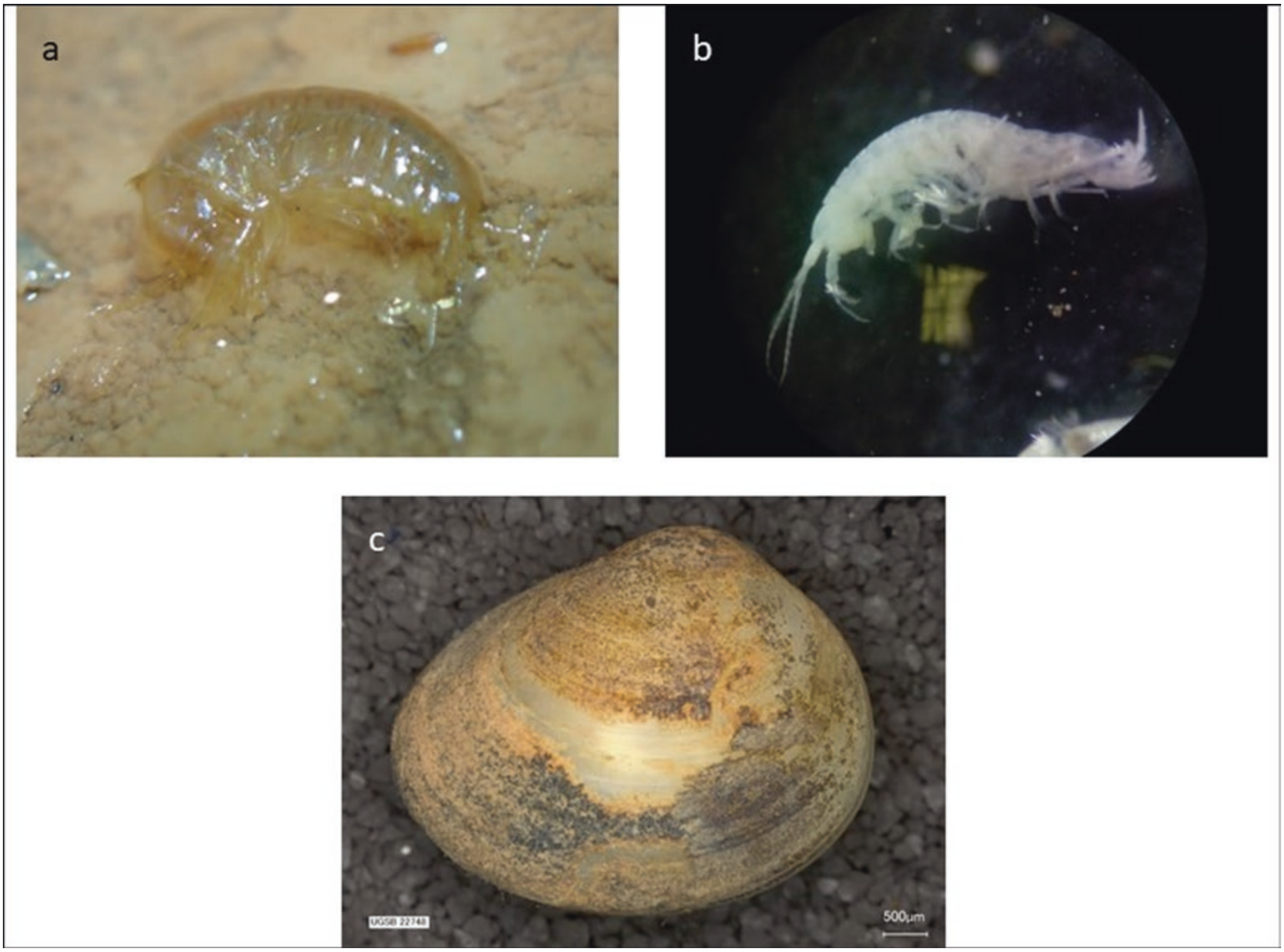

Fig. 12.2 (**a**) Amphipoda; (**b**) Amphipoda; (**c**) Mollusca

Arthropoda: Entognatha: Collembola: *Acherontiella xenylliformis* (Gisin 1952) [troglobiont-guanophile]; *Bilobella aurantiaca* (Caroli 1910); *Ceratophysella denticulata* (Bagmall 1941); *Cryptopygus hipunctatus* (Axelson 1903); *Cyphoderus assimilis* (Borner 1906); *Desoria olivacea* (Tullberg 1871); *Deuteraphorura ghidinii* (Denis 1938) [trogloxene see troglophile]; *Folsomia quadrioculata* (Tullberg 1871); *Friesea decipiens* (Steiner 1958); *Furculanurida duodecimoculata* Thibaud and Massoud 1980; *Heteromurus nitidus* (Templeton 1835) [troglophile]; *Hypogastrura manubrialis* (Tullberg 1869); *Hypogastrura (Franzura) synacantha* (Cassagnau and Deharveng 1976); *Lepidocyrtus lanuginosus* (Gmelin 1788); *Megalothorax mininus* (Willem 1900); *Mesaphorura critica* (Ellis 1976); *Mesogastrura boneti* (Tarsia 1941) [guanobiont]; *Neelus murinus* (Folsom 1896; *Onychiuroides granulosus* (Stach 1930); *Orchesella cincta* (Linnaeus 1758); *Parisotoma notabilis* (Schäffer 1896); *Protanura deharvengi* (Thibaud and Massoud 1980); *Pseudosinella strinatii* (Gisin 1951) [troglobiont]; *Sphaeridia pumilis* (Krausbauer 1898); *Typhlogastrura atlantea* (Gisin 1951) [troglobiont] (Fig. 12.4a).

Arthropoda: Entognatha: Diplura:
Tachycampa lepineyi (Silvestri 1936) [troglobiont] (Fig. 12.4b).

Arthropoda: Insecta: Coleoptera:
Aloconota sulcifrons (Stephens 1832); *Anthobium longicorne* (Fauvel 1886); *Antoinella groubei salibai* (Antoine 1953) [troglobiont]; *Apteranillus rotroui* (Scheerpeltz 1936) [troglobiont-endemic]; *Atheta subcavicola* (Brisout de Barneville 1863); *Atheta trinotata* (Kraatz 1856); *Catops* sp.; *Catops fuscus fuscoides* (Reitter 1909); *Laemostenus aelleni* (Antoine 1952) [troglophile-guanophile-endemic]; *Laemostenus villardi* (Antoine 1948) [troglobiont-endemic]; *Laemostenus (Pristonychus) algerinus* (Gory 1833); *Laemostenus (Sphodroides) attlanticus atlanticus* (Escalera 1913); *Leptobium gracile* (Gravenhorst 1802); *Lobrathium comasi* (Hernando 2012); *Nebria rubicunda maroccana* (Antoine 1925); *Ocalea rivularis* (Miller 1852); *Ocydromus maroccanus* (Antoine 1923); *Oxypoda* sp.; *Penetretus temporalis* (Bedel 1909); *Pleurophorus caesus* (Panzer 1796); *Quedius (Raphirus) ustus* (Fauvel 1878); *Scaurus tingita-*

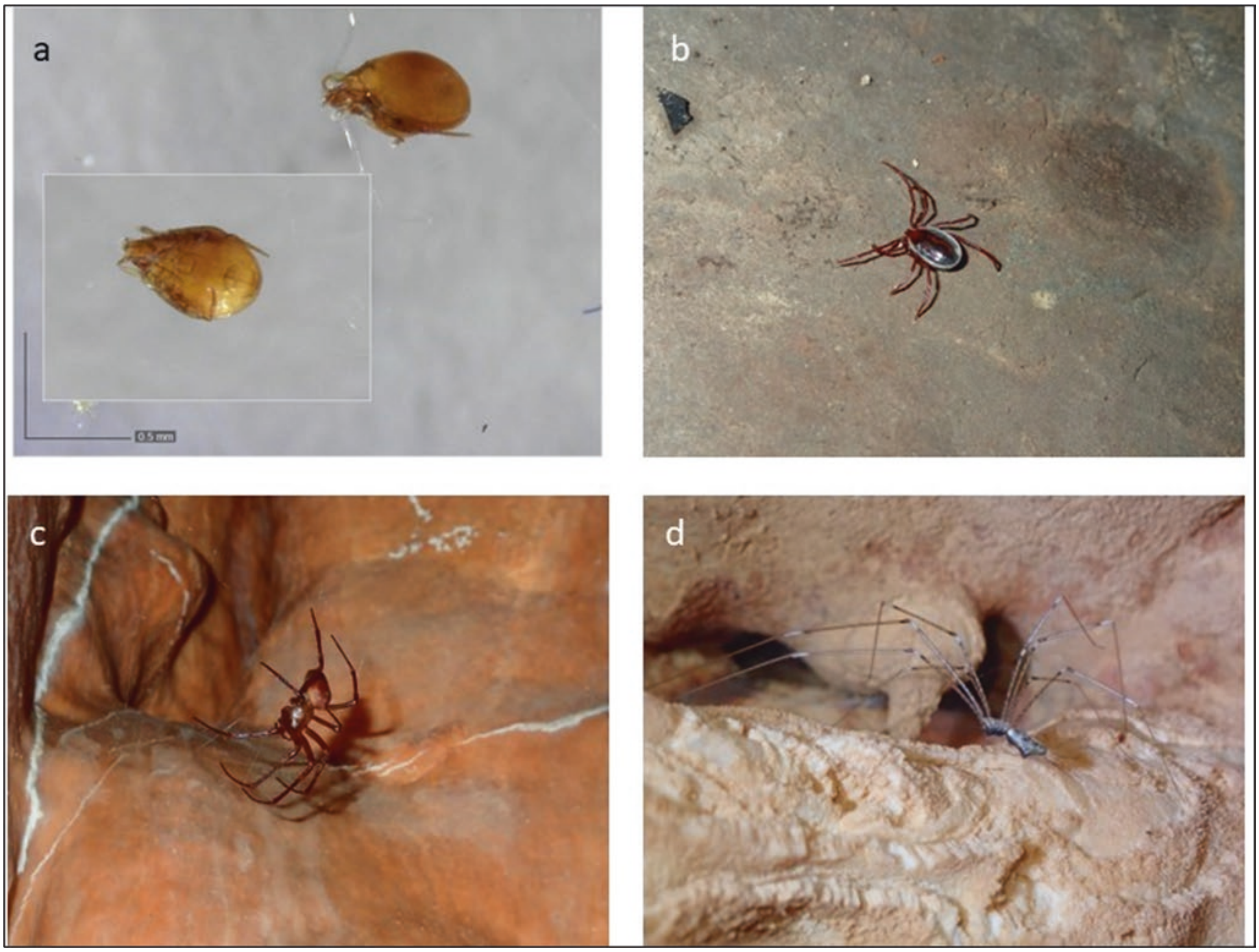

Fig. 12.3 (**a**) Acari; (**b**) Acari bat parasitic; (**c**) Araneae; (**d**) Araneae

nus tingitanus (Peyerimhoff 1948); *Scaurus tristis* (Olivier 1795); *Sepedophilus cavicola* (Scriba 1870) [troglophile-guanophile]; *Sepedophilus cavicola africanus* (Jeannel and Jarrige 1949); *Speonemadus maroccanus* (Jeannel 1936) [troglophile]; *Speonemadus subcostatus* (Reiche 1864) [troglophile]; *Trechus (Antoinella) espanyoli* (Mateu and Escolà 2006); *Trechus (Antoinella) fadriquei* (Mateu and Escolà 2006); *Trechus (Antoinella) gigoni* (Casale 1982) [troglobiont]; *Trechus (Antoinella) groubei* (Antoine 1936) [troglobiont]; *Trechus (Antoinella) iblanensis* (Mateu and Escolà 2006); *Trechus (Antoinella) lallemantii* (Fairmaire 1859); *Trechus (Irinea) aurouxi* (Mateu and Comas 2006) (Fig. 12.4c, d).

Arthropoda: Insecta: Diptera:

Nycteribia pedicularia (Latreille 1803); *Nycteribia schmidlii* (Schiner 1853); *Nycteribia vexata* (Westwood 1835); *Penicillidia dufourii* (Westwood 1835); *Penicillidia conspicua* (Speiser 1901); *Phthiridium biarticulatum* (Hermann 1804) (Fig. 12.5a).

Arthropoda: Insecta: Orthoptera:

Gryllomorpha sp. (Fig. 12.5b).

Arthropoda: Insecta: Psocoptera:

Prionoglaris stygia (Enderlein 1909); *Psyllipsocus ramburi troglodytes* (Badonnel 1943) (Fig. 12.5c).

Arthropoda: Malacostraca: Isopoda:

Eluma caelata (Miers 1878) [troglophile]; *Trichoniscus halophilus* (Vandel 1951) [troglophile] (Fig. 12.5d).

Arthropoda: Myriapoda: Chilopoda:

Cryptops (Trigonocryptops) numidicus aelleni (Manfredi 1956) [troglobiont, endemic]; *Lithobius chikerensis* (Verhoeff 1936) [troglobiont]; *Litbobius crassipes* (Koch 1862) [trogloxene] (Fig. 12.6a).

Arthropoda: Myriapoda: Diplopoda:

Afropachyiulus lepineyi (Verhoeff 1936) [troglophile]; *Ceratosphys maroccana* (Mauriès 1985) [troglophile]; *Jeekelosoma viginti* (Enghoff and Reboleira 2019); *Origmatogona strinatii* (Manfredi 1956) [troglobiont-endemic] (Fig. 12.6b).

Chordata: Amphibia: Urodela:

Fig. 12.4 (**a**) Collembola; (**b**) Diplura; (**c**) Coleoptera; (**d**) Coleoptera

Salamandra algira atlantica (Hernandez and Escoriza 2019) (Fig. 12.6c).

Chordata: Mammalia: Chiroptera:

Miniopterus schreibersii (Kuhl 1819); *Myotis punicus* (Tomes 1857); *Rhinolophus ferrumequinum* (Schreber 1774); *Rhinolophus hipposideros* (Bechstein 1800) (Fig. 12.6d).

Mollusca:

Aegopinella sp. 1; *Aegopinella* sp. 2; *Aegopinella psaralorena* (Pallary 1900); *Helicella* sp.; *Otala (Otala) lactea* (Müller 1774); *Rumina decollata* (Linnaeus 1758).

12.3.3 Plants and Endokarst Bacteria of the Middle Atlas

The endokarst is divided into three zones: the entrance zone, the penumbra zone and the dark zone. The entrance zone receives a lot of light, which favors the presence of some flowering plants and lichens. The penumbra zone still receives a certain amount of light sufficient for ferns (Fig. 12.7a) and mosses (Fig. 12.7b). The dark zone, on the other hand, receives no natural light, and only a few organisms, such as algae and fungi (Fig. 12.7c), and some bacteria can be found there (Fig. 12.7d). In the caves that have been developed for the public, algae, ferns and mosses grow around the electric lights and are called lampenflora.

12.4 Environmental Changes and Human Impacts

Endokarst biodiversity is currently threatened by the effects of climate change and human activities, including overexploitation of aquifers, destruction of subterranean habitats, pollution and land degradation.

12.4.1 Environmental Changes

The Middle Atlas is experiencing alarming and increasingly frequent droughts, resulting in decreasing amounts of avail-

Fig. 12.5 (**a**) Diptera; (**b**) Gryllomorpha; (**c**) Psocoptera; (**d**) Isopoda

able water. The effects of climate change are reflected in irregular rainfall and temperature, which will increasingly impact endokarst biodiversity (Mammola et al. 2020).

12.4.2 Human Impacts

Other threats to endokarst biodiversity in the Middle Atlas include surface and groundwater pumping and dams, microplastic contamination (Balestra and Bellopede 2022), chemical (Fig. 12.8a) and physical (Fig. 12.8b) discharges. Caving tourism can also impact endokarst communities. The influx of visitors increases the ambient temperature, altering the humidity and composition of the air. Garbage left on site can cause toxic molds to grow. Noise and light emissions directly disturb the biodiversity of the endokarst, as is the case for bats. Indeed, most of the bat colonies, described in the fifties, have disappeared under the effect of increasingly frequent disturbances for simple visits or the use of caves as shelters, or even a destruction by the exploitation of materials or to satisfy an increasing urbanization (Aulagnier et al. 2015). The use of bats in witchcraft (Basset 1920) and more broadly to the negative image they convey, is also a vector of disturbances.

12.5 Perspectives

To date, more than 370 karst phenomena have been inventoried. The karst phenomena (sinkholes, caves, springs or resurgences) sampled for endokarst biodiversity are: Kef el Bouk, Friouato, Oulad Ayach chasms as well as Chiker, Ras el Ma, Sidi Mejbeur, Aïn el Aoudat, Ras el Oued caves, and Aïn Vitel, Arhbalou Aberchane, Aïn Maarouf, Aïn Maâza, Amane Imelallen and Zerrouka springs. Out of 370 karst phenomena identified, only 14 have been sampled. The knowledge is still far from covering the whole endokarst biodiversity of the Middle Atlas. In this context, studies and awareness campaigns will have to be developed before some species join the national list of endangered species (Aulagnier et al. 2015).

Fig. 12.6 (**a**) Chilopoda; (**b**) Diplopoda; (**c**) *Salamandra algira atlantica* (Hernandez and Escoriza 2019); (**d**) Chiroptera

12.6 Conclusion

The Middle Atlas, water tower of Morocco par excellence, is the richest North African mountain in wetlands, including natural lakes, rivers, wells and springs. The endokarst provides essential natural contributions to the populations, including the supply of drinking water. There is no doubt that in the twenty-first century, the earth will experience abrupt climate changes. Inevitably, these changes will affect the distribution of the various species that inhabit the Middle Atlas endokarst. Underground ecosystems are fragile habitats that are home to highly specialized animals. The intervention of man, even minimal, affects the biodiversity in an irreversible way. The current authorities seem to be more concerned about this problem than in the past. Let us hope that they can reconcile human requirements with the preservation of this rich environment that is the endokarst. The endokarst heritage of the Middle Atlas has not yet delivered all its secrets.

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Fig. 12.7 (**a**) Pteridophyta; (**b**) Bryophyta; (**c**) Fungi; (**d**) Bacteria

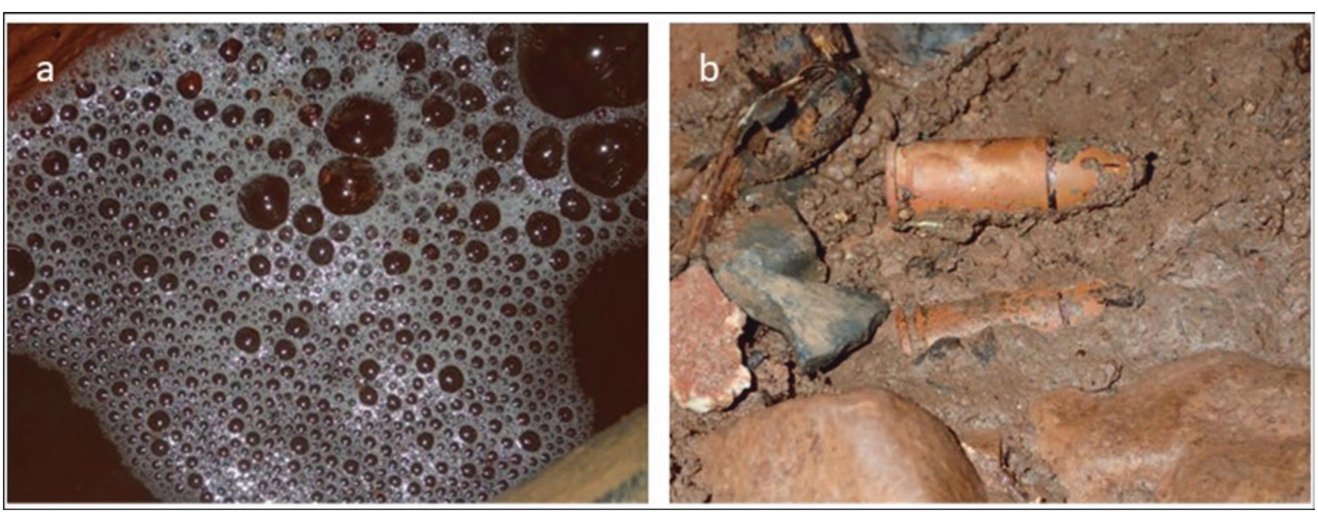

Fig. 12.8 (**a**) Chemical pollution; (**b**) Abandoned military ammunition

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Part VI

Volcanic Heritage

13 Volcanic Landscape of the Middle Atlas: A Representative Heritage of Moroccan Geological History

Khaoula Baadi and Károly Németh

Abstract

During the Miocene-Quaternary, an important volcanic activity occurred in the Middle Atlas which generated innumerable volcanoes of varied origin including Strombolian to Hawaiian style explosive eruption dominated volcanoes of scoria and spatter cones to phreatomagmatic types creating maars and tuff rings, or their mixed varieties. The volcanic geoheritage has been synchronous with the direction of the structures in the region of which most volcanoes and their preserved eruptive products are aligned along the direction of the Hercynian faults. Thus, these volcanic units and their lava flows cover the karstic carbonate surface of the Lower and Middle Lias, which determine the landscape of the ranges. In the present work, we explored the volcanic heritage of the chain by following the main types of volcanoes identified by subdividing the volcanic landscapes into three types: (i) Strombolian style landscape (Bou-Teguerrouine, El Koudiate, Jbel Hébri, Taiissout), (ii) phreatomagmatic style landscape (Lechmine Ait el Haj, Bou-Ibalrhatène, Lechmine n'Ikettane) and (iii) mixed eruption style landscape (Lechmine Izgar, Ouest Hébri, Tahbrite, Timahdite). Subsequently, we provided more detailed spatial data based on satellite imagery and high-resolution terrain analysis specifically developed over the central part of the Middle Atlas volcanic field, where volcanic geodiversity is high, and all types of typical volcanoes located.

K. Baadi (✉)
Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, Fez, Morocco

K. Németh
Volcanic Risk Solutions, Massey University, Palmerston North, New Zealand

Institute of Earth Physics and Space Science, Sopron, Hungary

Saudi Geological Survey, Jeddah, Kingdom of Saudi Arabia

Instituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy

Keywords

Volcanic geoheritage · Volcanic landscape · Geodiversity · Middle Atlas

13.1 Introduction

In the last two decades, several specialists and world organizations showed an increasing interest in the issues of the volcanic landscape and its relevance to geoheritage value (Németh et al. 2017; Sheth et al. 2017; Zangmo et al. 2017; Doniz-Paez et al. 2020). Volcanic landscapes are among the most easily recognizable and readily identifiable natural areas with an additional valuable element that they enjoy elevated level of interest from the public (Erfurt-Cooper 2014; Erfurt 2018). Volcanoes and volcanic landscape can easily form the basis of "stories" that can be utilized to knowledge transfer about how volcanoes work, form, and what benefits we can gain living together with them and what hazard they pose to the human societies. Volcanoes are the key elements that demonstrate the fundamental geological and geomorphological processes to understand the functioning and dynamism of the Earth by connecting the interior and the surface of the Earth. Volcanoes also function as the source of primary rocks forming through magma generation and crystallization. Volcanic rocks are among the starting point of the rock cycle; hence, they carry fundamental geoheritage values to follow the cooling history of Earth providing earth materials to enter to the rock cycle.

In Morocco, the alpine heritage has marked Moroccan geological history. This heritage has led to give a remarkable natural diversity to the country, which manifests itself through several geomorphological and geological processes. Among these volcanic processes and their results are outstanding especially within the geological context of NW Africa. Throughout the country, the Middle Atlas chain hosts the largest and youngest volcanic field in the country and offers a wide

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range of volcanic edifices and products covering approximately 1000 km^2. Eighty percent of these volcanoes are concentrated in the Causses of Azrou, El Hajeb, Ifrane and Timahdite, covering a wide elongated band in the NNW-SSE direction (Martin 1981). Causses in general refer to limestone plateaus like those defined from the type locality within the Massif Central in France. This volcanism has been attributed to the Middle-Quaternary Miocene period as defined by various radiometric dating techniques (Bellon 1976; Harmand and Cantagrel 1984; Harmand and Moukadiri 1986; Berrahma 1995; Rachdi 1995; El Azzouzi et al. 1999).

The volcanic landscapes of the Middle Atlas hold different types of volcanoes such as scoria cones (Fig. 13.1a), maars, tuff rings and more complex volcanic edifices of amalgamated or compound monogenetic volcanoes, multiple scoria and spatter cones, lava blister-caves (Fig. 13.1b), ‘a’ā, pāhoehoe, and block lava flows (Fig. 13.2a). Various lava surface textures are apparent such as lava tunnels, tumuli, and hornitos. Pyroclastic eruptive products are dominated by scoria successions and minor phreatomagmatic tuffs and lapilli tuffs. Unique volcanic products such as pozzolan (very fine grained noncemented siliceous ash) (Fig. 13.2b), phreatomagmatic lapilli tuff and certain volcano-karstic structures made the volcanic geoheritage elements complete. All these volcanic features and structures make these landscapes unique and arguable important to conserve within geoconservation initiatives.

In this chapter, the work will be devoted to reveal the different types of volcanic landscapes encountered in the Middle Atlas by presenting their state of preservation.

13.2 Landform Elements

In this chapter, we provide a narrative summary of the current knowledge of the volcanic geoheritage of the study area. To do this first we use available Sentinel satellite images (https://www.sentinel-hub.com/) to demonstrate the geological context of the volcanism in the region. We utilize the ALOS-PALSAR (https://asf.alaska.edu/data-sets/sar-data-sets/alos-palsar/) 12.5 m resolution digital elevation data to provide digital elevation models (DEM) and associated contour maps within the QGIS environment (https://qgis.org/en/site/). This data was analyzed within SAGA software (https://saga-gis.sourceforge.io/en/index.html) operated within QGIS to create basic terrain analysis models and geomorphon (Jasiewicz and Stepinski 2013) overviews to demonstrate the region morphodiversity that underpins the geoheritage elements of the studied area.

The region where the Plateau Azrou-Timahdite volcanic field is located is a fault bounded but flat landscape where lava flows filling the morphological lows in relatively thin form (Fig. 13.3). The ALOS-PALSAR-based digital elevation model provided the base to generate slope angle map using QGIS (Fig. 13.4). The slope angle map reveals that the lava covered regions representing the flattest region of the landscape following the trend where basement rocks crop out outside of the volcanic field (Figs. 13.3 and 13.4).

The geological map was compared with available Sentinel imagery for the whole field. The Sentinel Geology 8 11 12 band-generated imagery is sensitive for geological features (their spectral radiance); hence, they can be useful to identify key geological elements and rock types. On this map, the field shows distinctly those regions where older rocks crop out and those areas form exposed limestone dominated plateaus and lava fields that occupied the local valleys and depressions within the limestone country (Fig. 13.5). Similar trend can be recognized within the Sentinel Geology 12 8 2 band image where in addition the permeable scoria cones show up with bright green colors differ from the dark brown young lava flows and more rugged light brown thinner and probably older lava flows (Fig. 13.6). In this image, the

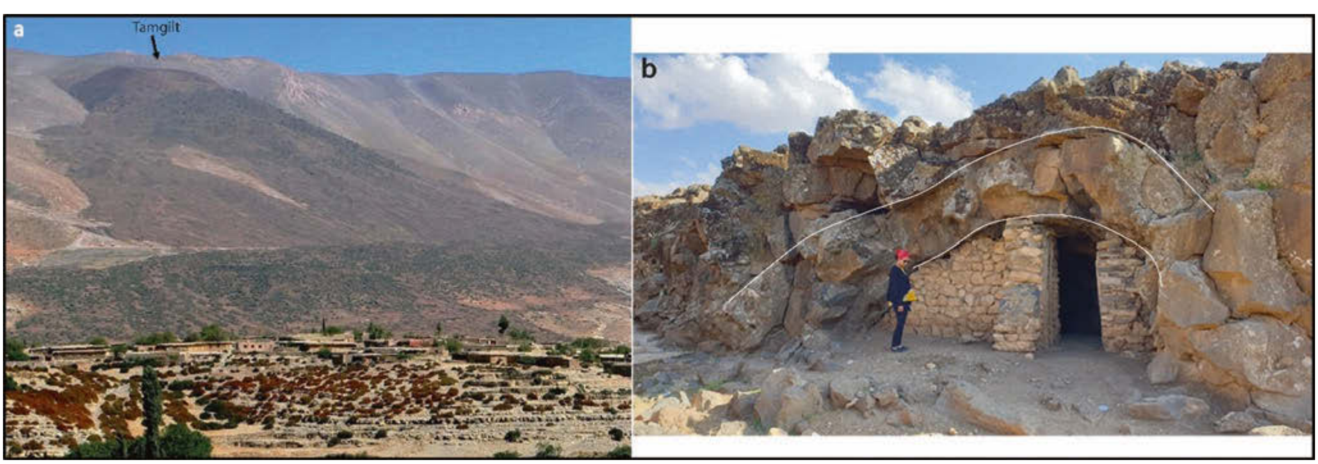

Fig. 13.1 (**a**) Tamgilt scoria cone on the SE flank of the Bou-Iblane basement ridge; (**b**) Lava blister cave structure at the base of the Aghbalou Aberchane lava flow

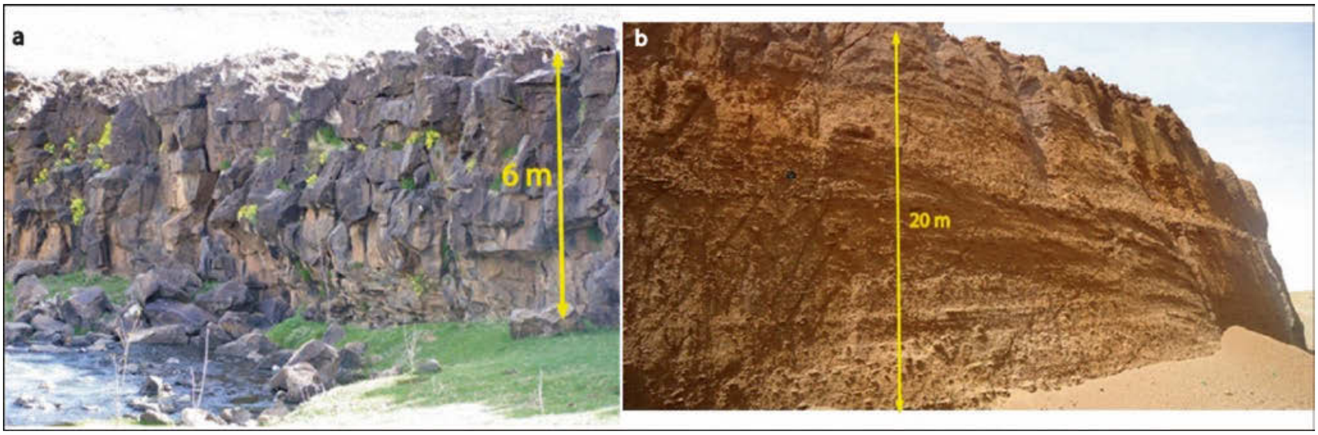

Fig. 13.2 (**a**) Cross section of a stack of pāhoehoe lava flow at Aghbalou Aberchane; (**b**) Levels of red pozzolan (fine-grained red volcanic ash) at the Ouest Hébri quarry

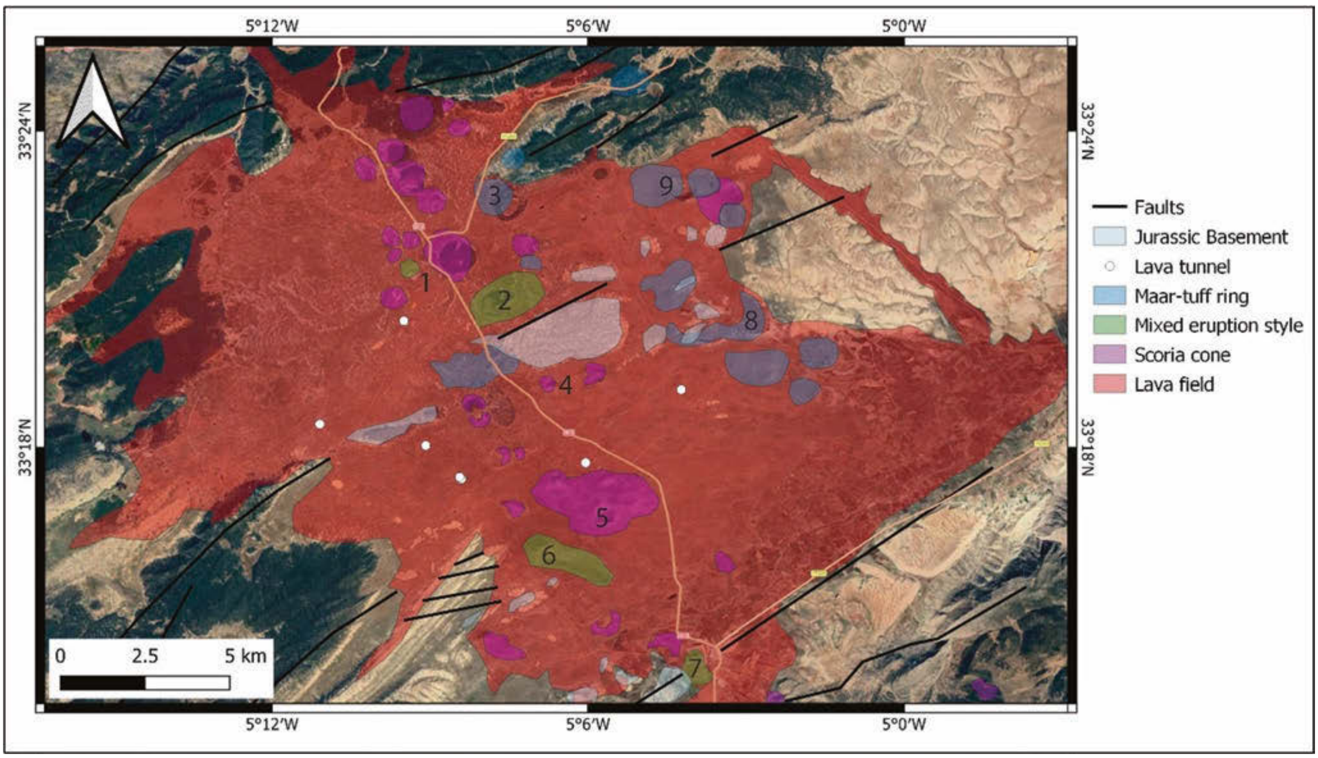

Fig. 13.3 Geological map overlaid a Google Earth Pro satellite image. Note the light creamy color Jurassic limestone basement in the NE side of the region and the way they crop out beneath the thin lava fields. Numbers refer to locations mentioned in the text: (1) Cone-maar Hebri (note that Ouest Hébri [33°21′37.69″N; 5°8′29.99″W] is a scoria cone just west of the maar); (2) Tahabrit; (3) Lechmine N'Kettane; (4) Ta'issaouite; (5) Bou-Teguerrouine; (6) Lechmine Izgar; (7) V. Timahdite; (8) Bou-Ibalrhatène, (9) Lechmine Ait el Haj. Please note that El Koudiate (33°31′10.67″N; 5°9′50.90″W) is not shown on the map as it falls about 10 km to the north of the map view

valley-controlled lava flow lobes clearly visible within the basement bright light-colored limestone plateaus.

Using QGIS GRASS-GIS plugin (https://grass.osgeo.org/) geomorphons, or common geomorphological features were calculated on a basis of 30 m outer search limit. The generated map identified the 10 most common geomorphological features. On this map, the field shows distinctly the valley and ridge pattern of the region graphically demonstrating the SW-NE-trending morphostructural elements within the volcanic field evolved. Moreover, the geomorphon map illustrates well the location of the scoria cones and maar craters as local peaks or depressions (Fig. 13.7).

The morphodiversity of the region is apparent and the satellite imagery suggestive for the link between the various

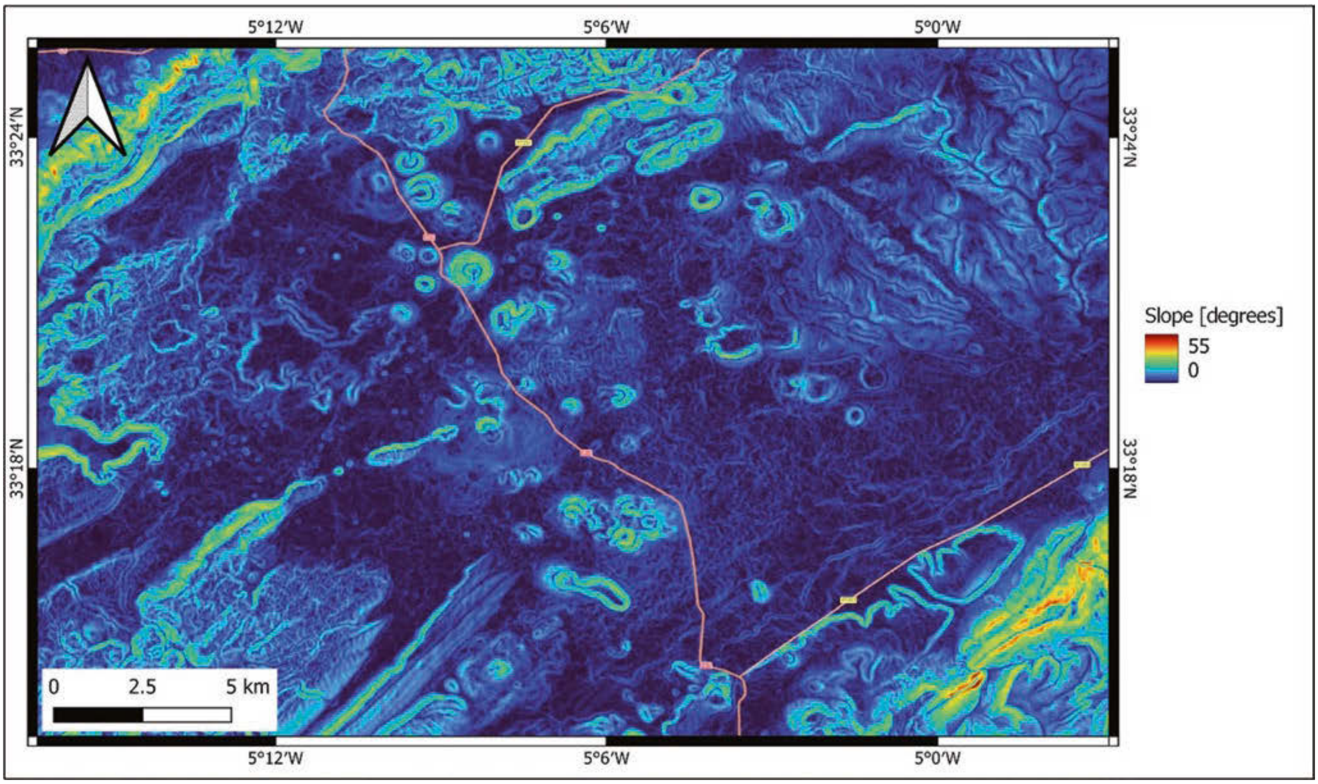

Fig. 13.4 Slope map generated from ALOS-PALSAR 12.5 m resolution elevation data, Note the flat nature of the central part of the field upon circular patterns mark scoria cones and maar craters. The field is also captured within a fault-bounded ridge system in the north and south

volcano types, the underlying lithology, and the hydrogeology of the region. The hydrogeology can be examined very well on a map generated within the QGIS environment using SAGA software to generate wetness map that based on the region morphology. This map is not a direct measurement of the current state of water saturation of the region, instead a theoretical base how surface water movement and accumulation would take place if water available. On this map, it is clearly visible that those areas where theoretical channel networks modeled hosting phreatomagmatic volcanoes such as maar craters while in those areas where drainage is underdeveloped, more dry volcanoes identified (Fig. 13.8). This causal link between the region potential surface water availability and the volcano types is an important element of the region volcanic geoheritage as it demonstrates well the link between the external controlling parameters responsible to generated strikingly different eruptions styles within the short life of these monogenetic volcanoes.

13.3 Diversity of Volcanic Landscapes

During the Plio-Quaternary, the volcanism of the Middle Atlas, of an alkaline nature, was contemporaneous with the sinistral compressive tectonics of the NE-SW oriented strike-slip fault system of the Middle Atlas chain. This shortening is consistent with the transtensional tectonics, which allowed the expression of the Quaternary alkaline volcanism of the Middle Atlas (Harmand and Moukadiri 1986). Most volcanoes and their eruptive products preserved are aligned along the direction of these strike-slip faults. Their spatial distribution as well as the rise of their feeding magmas were formed following rejuvenation of older structural elements due to the reactivation of late Hercynian faults (Harmand and Moukadiri 1986; Hernandez et al. 1987). All these volcanic units and their lava flows cover the Lower and Middle Lias (Jurassic) karstic carbonate surface of the chain (Fig. 13.3) and seem to be concentrated in the central part of the mountain range at the Azrou-Timahdite Plateau.

Miocene-Quaternary volcanism significantly impacted the Middle Atlas landscape. This volcanic terrain is represented by well-preserved, commonly youthfully appeared scoria (cinder) cones, maars, and complex volcanic edifices. Although the Middle Atlas is home to more than 87 identified and geoheritage inventoried volcanoes (Baadi et al. 2021), but lava flows cover about 7% of its area. These flows have followed and filled the major valleys of the region by traveling very long distances. For example, the Tamarakoit volcano emitted one of the longest lava flows in the region that followed the Oued Oum Er-Rbia Valley for about

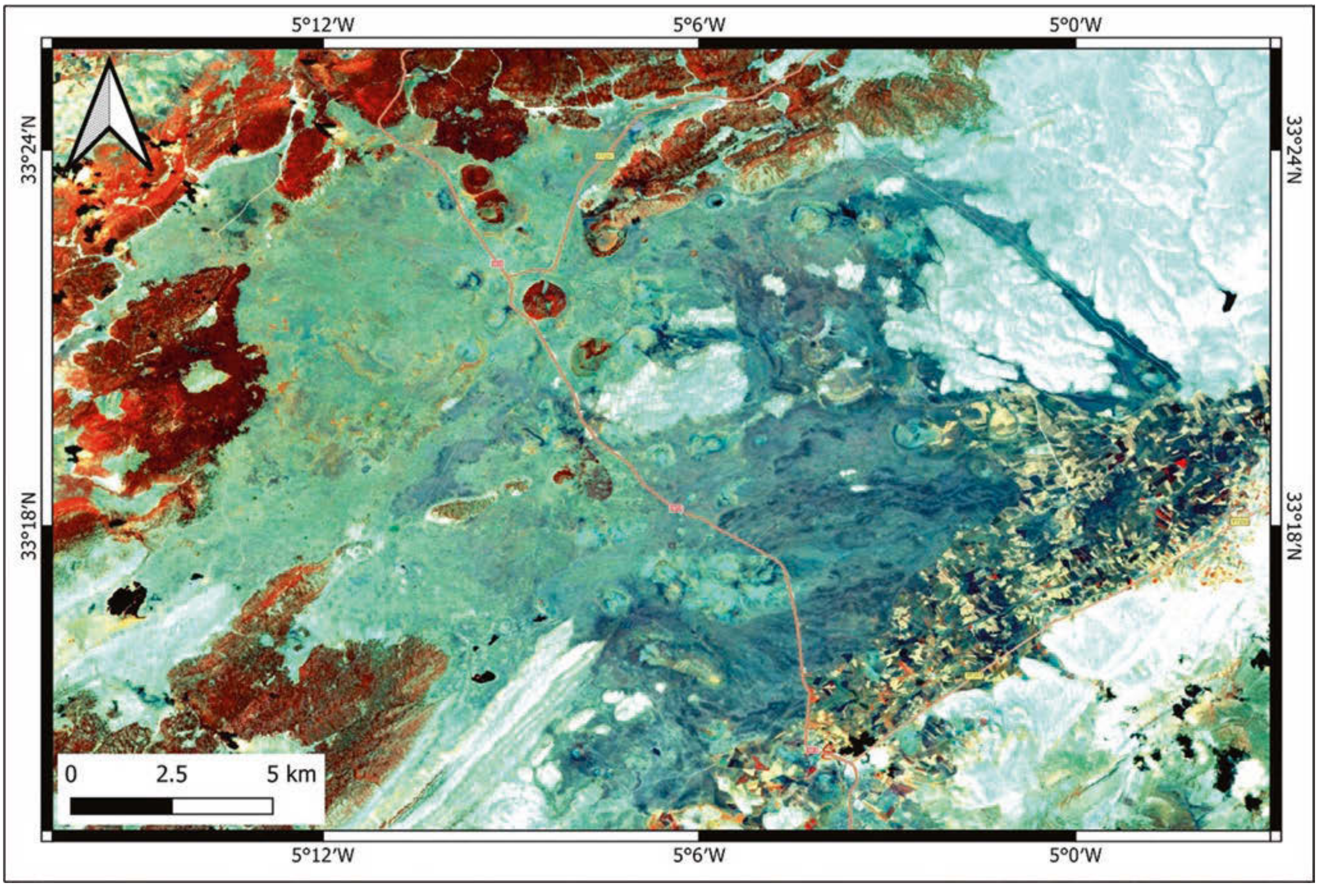

Fig. 13.5 Sentinel Geology 8 11 12 band satellite image clearly showing the surface texture of the lava flow fields. Note the darker lava fields in the south indicating a potentially younger age and thicker appearance. Bright white regions mark Jurassic limestone basement

100 km. Other good example for long basalt lava flows is that reached the South Rifain Corridor, initiated from the Bab Azhar volcano.

According to their respective abundances, the various morphostructural characteristics, the volcanoes of the Middle Atlas consist of volcanoes of Strombolian-style eruption dominated scoria cones, Hawaiian-style lava fountains and explosive magma-water interaction generated phreatomagmatic volcanoes such as maars and tuff rings. The eruption style is controlled by the nature of the interaction between the ascending alkaline and undersaturated magma and type of external water source and its recharging nature (Amine et al. 2019).

In the following sections, we explore the volcanic geoheritage of the field following the main identified volcano types. Beside the direct field regional and outcrop scale observations we provide some hand specimens and microscopic scale evidence to demonstrate the eruption styles identified. We also provide more detailed spatial data based on satellite imagery and high-resolution terrain analysis specifically developed on the central part of the field, where the volcanic geodiversity is high, and all the typical volcano types located.

On a hillshade model generated from the PALOS-ALSAR, digital elevation data shows well the scoria cones and maar craters in the central part of the field where a variety of volcanic landforms are the greatest in the field (Fig. 13.9). The cross sections across the central part of the volcanic field perfectly reveal the trend to have scoria cones in the higher elevation (e.g., less water access) while maar volcanoes or complex phreatomagmatic to magmatic mixed type volcanoes located in the local low areas where shallow ground water tables influenced the eruption style of the rising magma (Fig. 13.10). The general trend of the morphology as a gently easterly dipping landscape is clearly visible on the ALOS-PALSAR data-derived DEM (Fig. 13.11) and the generated slope angle maps (Fig. 13.12).

We also applied a landform categorization method to see the morphodiversity of the central part of the volcanic field applying geomorphon calculations within the QGIS platform GRASS GIS plug in. We obtained two maps with 50 (Fig. 13.13) versus 400-m (Fig. 13.14) calculation radius. The 50-m calculation radius map captured the fine details of the geomorphological elements of the region showing clearly the individual volcanic elements and even beyond them the

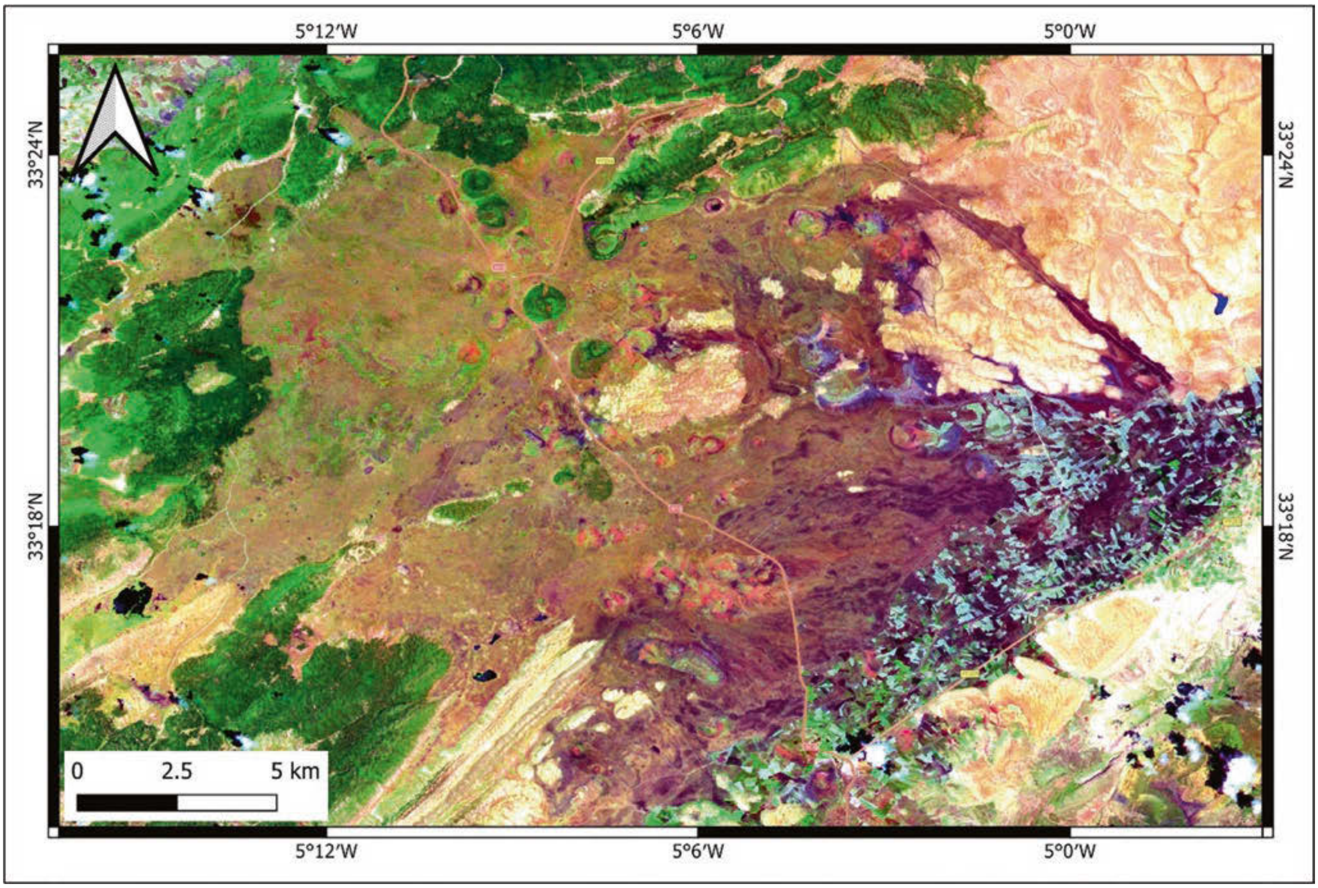

Fig. 13.6 Sentinel Geology 12 8 2 band satellite image shows similar patterns as on Fig. 13.5; however in these images, the scoria cones are more apparent green circular features

fine geomorphological variations. The 400 m calculation radius map provided a more general overview of the common landforms showing the distinct features scoria cones and maar volcanoes provide.

13.3.1 Strombolian-Style Scoria Cone Landscapes

Sixty-six percent of the volcanoes occupying the Middle Atlas landscape are generated by a dominant eruptive activity of explosive Strombolian-style scoria cone-forming events. They are recognized by their slightly higher height from other surrounding landscapes (Figs. 13.9, 13.10 and 13.11). The dynamics of Strombolian style eruptions generate edifice building scoria (cinder) and fluidal bomb (e.g., spindle bombs) dominated scoria cones and distal scoriaceous ash plains. Due to the older age of the volcanoes, such as plains are poorly preserved, but there are regions where such distal successions are preserved. In the next sections, we provide some detailed record of the most significant landforms of scoria cones we consider as geosites.

13.3.1.1 Bou-Teguerrouine [33°16′43.83″N;5°5′41.04″W]

Bou-Teguerrouine corresponds to a complex geomorphological unit composed of a landscape of eight contiguous cones, 200 m high and 4500 m wide. These cones have different sizes and result from simultaneous and juxtaposed eruptions of various but still magmatic style of magma fragmentation. Three of them are larger than the others and reach an altitude of 2006 m, for relative relief of about 200 m (Fig. 13.15a). This steep-sided volcanic complex has clustered craters at its top. The lava emitted by this volcano flows through breakout boccas through its crater wall forming perfect emission points recognizable in the sides of the cone. The solidified lava in the fissures forms levees which act as "ribs" which greatly strengthen the cone.

This volcanic landscape, unique on a national scale as Morocco has limited number of young volcanic landforms, is composed of pyroclastic successions of alternation of scoriaceous ash, lapilli, bombs and some fluidal lava fragments (Fig. 13.15b). In general, pyroclastic rocks are more abundant and associated lava flows at least in proximal to medial setting in reference to the vent position. The mostly

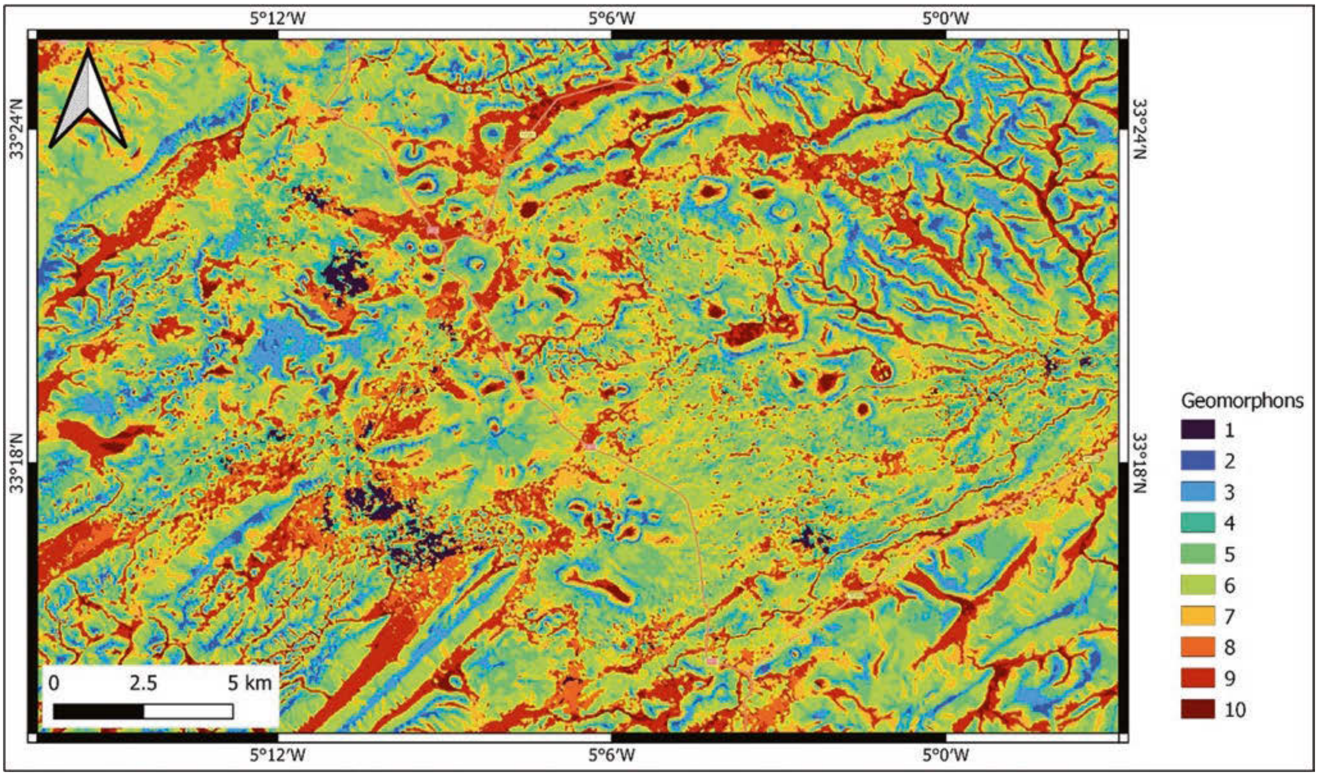

Fig. 13.7 Geomorphon map of the study area based on geomorphon calculations within QGIS GRASS-GIS plugin. The map shows the relatively low morphodiversity of the central part of the filed; however, these increases along the bounding structural elements and at the small monogenetic volcanoes. 1 – flat, 2 – summit, 3 – ridge, 4 – shoulder, 5 – spur, 6 – slope, 7 – hollow, 8 – foot slope, 9 – valley, 10 – depression

pahoehoe surface textured lavas are of basanitic in composition (El Azzouzi et al. 1999), have a vesicular appearance in cross sectional view and a smooth surface. This landscape is artificially opened due to the presence of a quarry revealing countless fine-grained, dark-colored pyroclastic deposits typical for the distal part of a scoria cone (Fig. 13.15b).

13.3.1.2 El Koudiate [33°31′10.67″N;5°9′50.90″W]

El Koudiate corresponds to a typical vast Strombolian style cone landscape (Fig. 13.16a). Its crater is 95 m high and 1200 m wide. This landscape is marked by a single volcanic edifice that shows a subalkaline basaltic composition due to the consequent assimilation of quartz-rich xenoliths from the Hercynian basement (Fig. 13.16b) (El Azzouzi et al. 2010), which are particularly abundant in the lavas covering the volcanic landscape of El Koudiate. These subalkaline basaltic flows (Fig. 13.16c) are very fluid and cover, in chaotic layers, the karst paleotopography and the inequalities of the Ifrane Causse, creeping northward through various valleys such as that of the Oued Tizguit which crosses the city of Ifrane.

13.3.1.3 Jbel Hébri [33°21′20.38″N;5°9′17.31″W]

Jbel Hébri corresponds to an annular cone landscape (Fig. 13.17) with a summit crater 1250 m wide and 220 m high. This volcanic landscape is characterized by a slight opening to the south due to an emission of lava flows and some cone rafting. The colors of the pyroclastic deposits encountered along this landscape vary from reddish to grayish and consist of layers of slag and bombs interspersed with discontinuous levels of lava spatter. Xenoliths can be encountered in abundance despite their strongly weathered state.

The landscape of the volcanic cone of Jbel Hébri is marked by important structures of tumuli and hornitos in the foothill of the cone, which rise and seem to be concentrated at the cone's northern base.

13.3.1.4 Taiissout [33°19′11.63″N;5°6′40.02″W]

Taiissout corresponds to a conical landscape (Fig. 13.18a) in the shape of a horseshoe 60 m high and 800 m wide. This unique volcanic landscape in the Middle Atlas is shaped by a transition of two types of lava: pahoehoe and aa. Pahoehoe-type lava units have blanketed the entire northwest slope and are cascaded as a toe front on the slopes of the crypto-karst

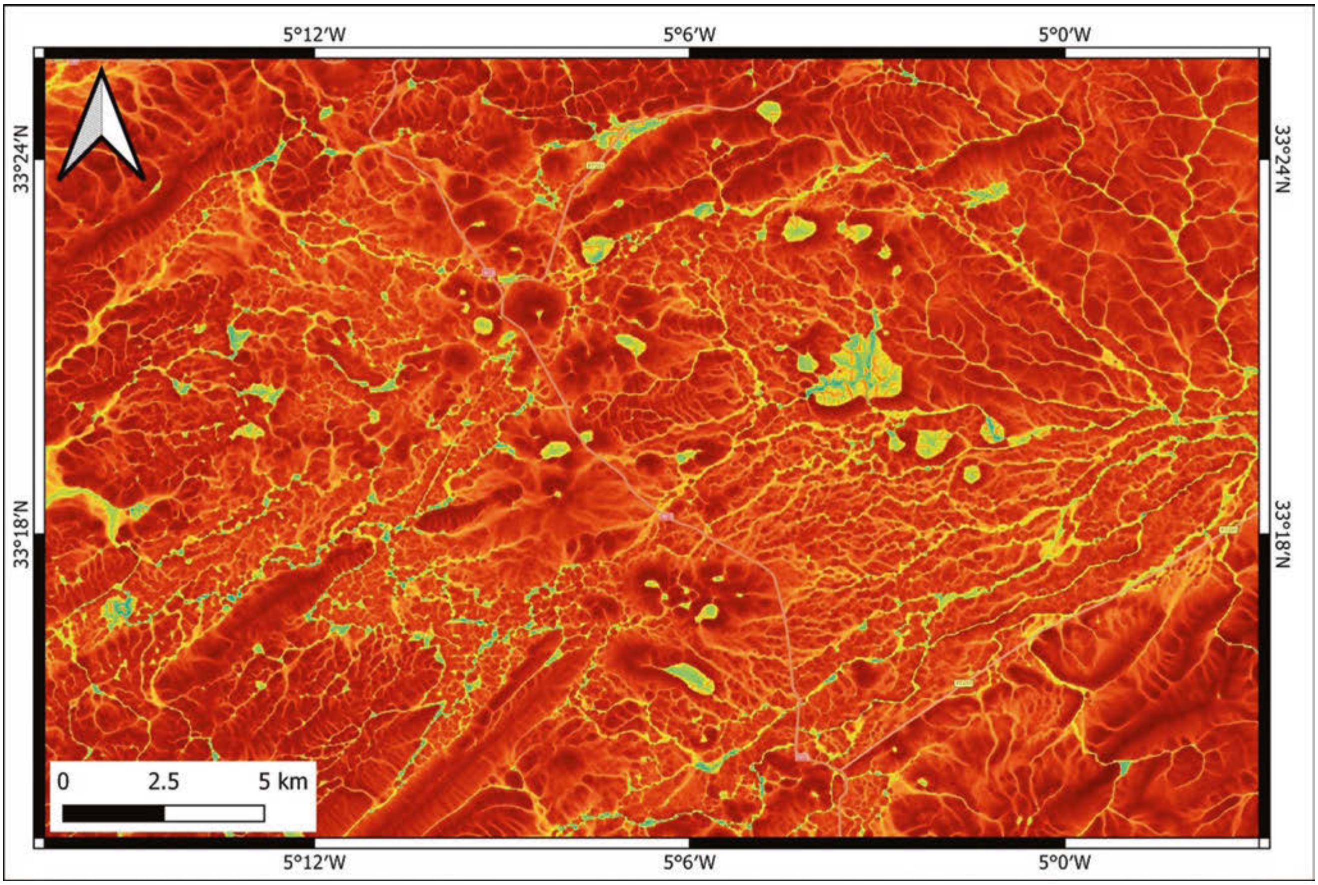

Fig. 13.8 Topographic wetness map generated within the QGIS environment SAGA plug in showing those areas where water accumulation is expected. These regions are light yellow and coincide with the location of phreatomagmatic volcanoes such as maars

cavity. The western slope is gentle while the eastern slope is steep and dominated by a dislocated scree of lava blocks, showing superb corded and folded lavas formed during the collapse of the cavity and the descent of the lava units. Regarding the aa-type lava (Fig. 13.18b), composed of boulders with a rough surface, is unable to progress further (Amine et al. 2019). This morphological transition, commonly recognized as irreversible (Hon et al. 2003), is controlled by the viscosity and the speed of movement of the lava (Peterson and Tilling 1980).

13.3.2 Phreatomagmatic Style Landscapes

Twenty-six percent of volcanoes crossing the landscape of the Middle Atlas chain are of phreatomagmatic origin due to the extent of the underlying water-rich carbonate aquifer, which is responsible for several explosive phreatomagmatic interactions in contact with the rising magma. This phreatomagmatic dynamic generates a diversity of landscape in tuff rings associated with maars. The size and depth of these spectacular craters carved out during syn-eruptive activity are intimately linked to the lithological nature of the bedrock, the depth, and the ratio of the explosive magma-water interaction (Németh and Kósik 2020). These volcanic landscapes are usually located in a lower area.

13.3.2.1 Lechmine Aït el Haj [33°22′53.75″N;5°4′12.41″W]

Lechmine Aït el Haj corresponds to a simple maar landscape (Fig. 13.19a), 900 m wide and 110 m deep, surrounded by a ring of subcircular tuffs. This maar landscape is bordered by pyroclastic cliffs rising 80 m above the limestone bedrock, composed of breccias, surges, lapilli (Fig. 13.19b), cinders, bombs, phreatomagmatic lapilli tuff beds and blocks of lava (Baadi et al. 2021). In its periphery and especially in its northern part, the karstified limestones of the Lias are cut by the diatreme. Toward the summit, the phreatomagmatic tuffs are overlain by a semicircular ring of scoriaceous juvenile breccias (Fig. 13.19c). They are formed by phreatomagmatic fragmentation (Fig. 13.19d) of an incoming lava flow, which descends the southwest slope before the end of phreatomagmatic activity (Mountaj et al. 2014, 2020a, b).

The volcanic landscape of Lechmine Aït el Haj is marked by distal deposits to the east, considered among the largest pozzolan deposits in the Middle Atlas chain. This landscape is borrowed by a structural and karstic heritage which manifests itself by a common configuration between the direction

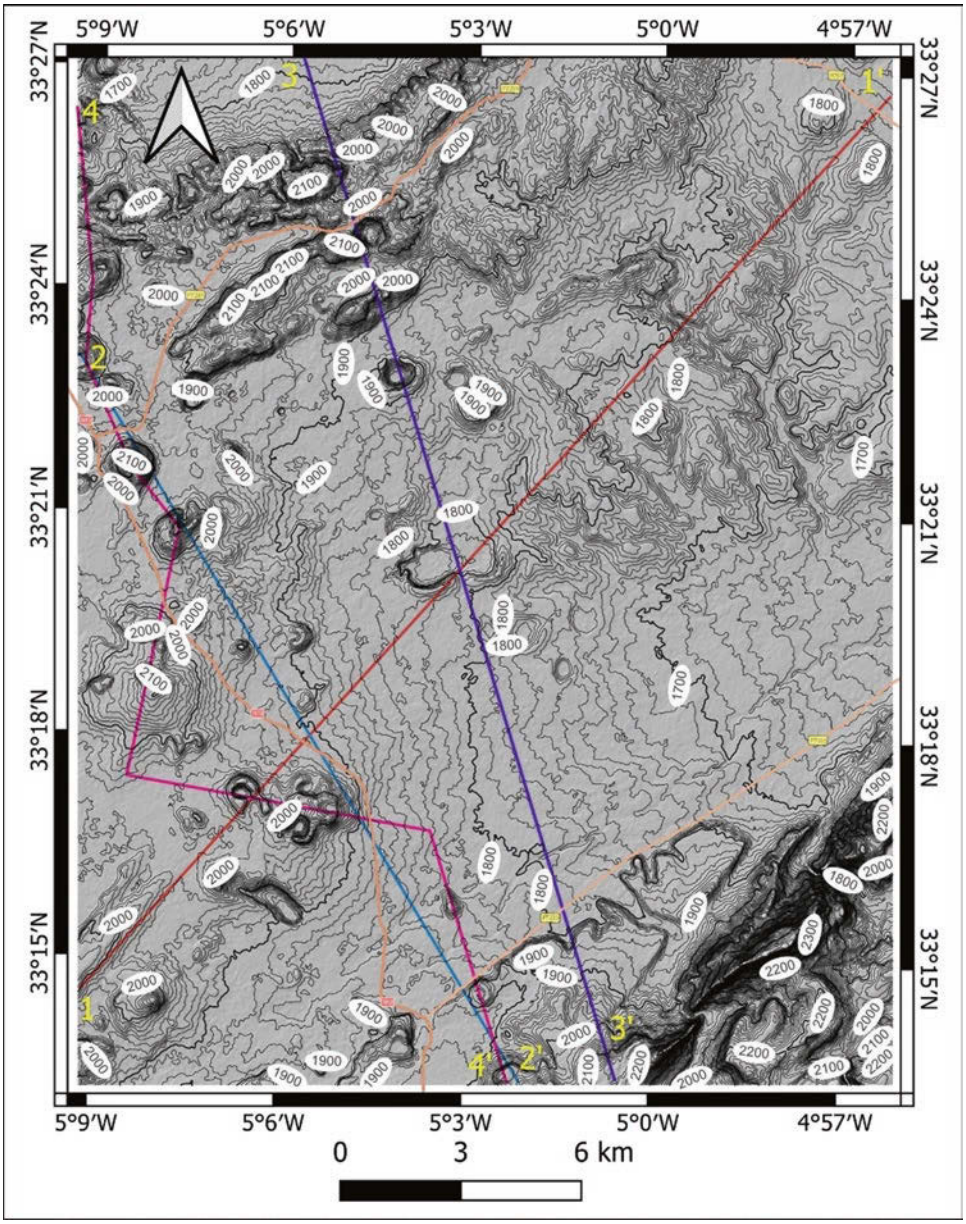

Fig. 13.9 Hillshade map overlain by contour lines (with 20 m intervals labeled in every 100 m) showing the general morphological trend of the central part of the volcanic field. Cross section lines are marked that are presented in Fig. 13.10

oriented N60° of the maar and the surrounding sinkholes (Amine et al. 2019; Baadi et al. 2021).

13.3.2.2 Bou-Ibalrhatène [33°20′21.31″N;5°2′52.56″W]

Bou-Ibalrhatène (Fig. 13.20a) corresponds to an immense landscape complex of four coalescing maars of different diameters ranging from 500 to 1300 m^2. Their depth reaches 60 m. This landscape of maars is surrounded by rings of pyroclastic breccia tuffs. The shallow water-magma interaction carried away the Liassic substrate which is well preserved on the walls.

This volcanic complex essentially shows a form of stripping and gullying. The pyroclastic sequences of the two large maars which are positioned to the south show maximum thicknesses between 20 and 50 m. Their outer sides are distinguished by an important ravine shape composed of finely stratified lapilli and pyroclastic breccias. They contain large blocks of limestone substrate and cauliflower bombs. The northern slope of the northern maar is absent, which could be produced by a continuous reactivation of the Jbel Irfoud-Bou-Ibalrhatène fault. A major karst collapse in the center of the crater confirms an active dissolution and a continuous mobilization of this fault.

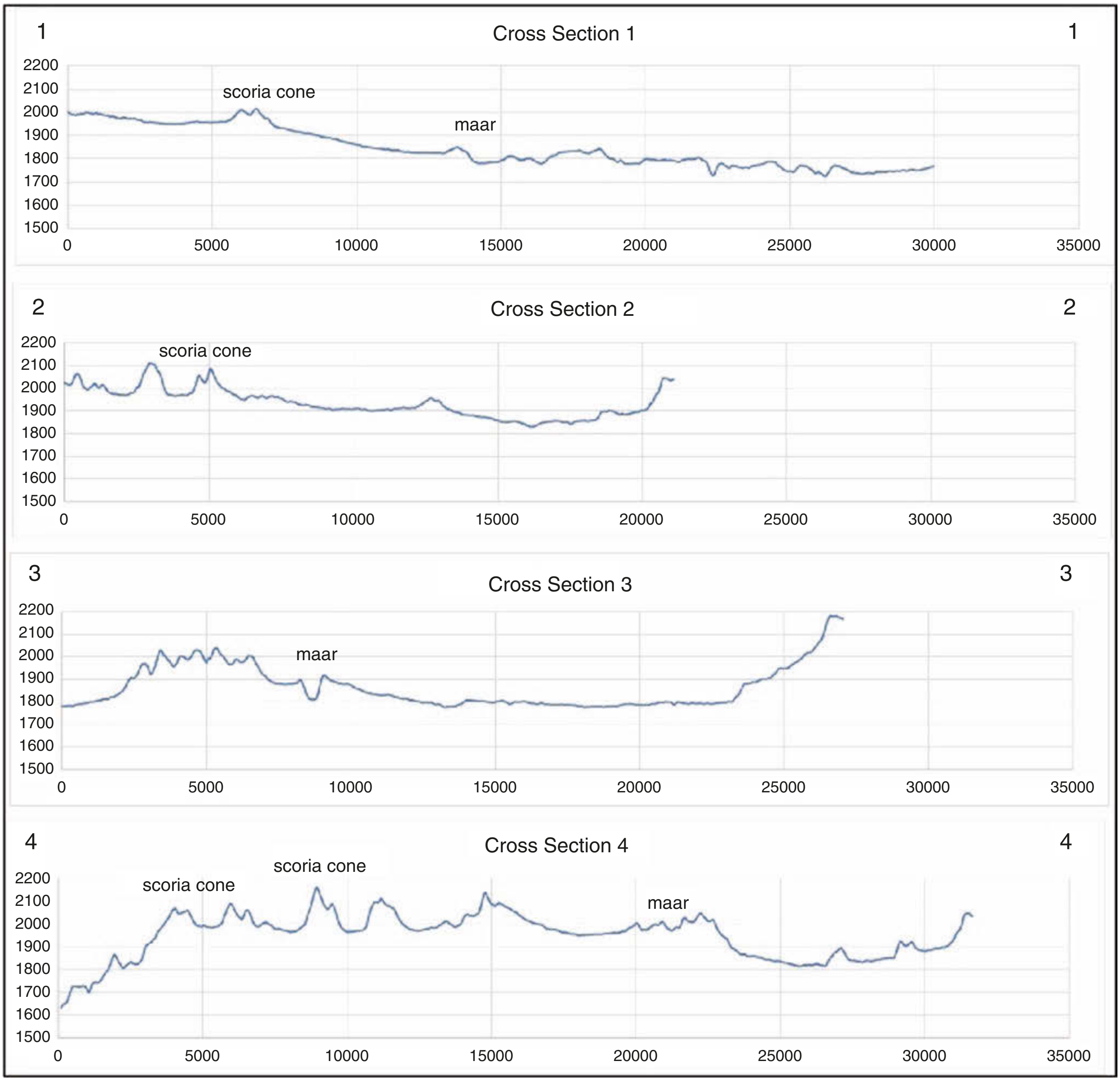

Fig. 13.10 Cross sections of the central part of the volcanic field. Note the presence of scoria cones in the higher ground while maar volcanoes appeared in the lowlands

The volcanic complex of Bou-lbalrathène is considered the richest site in enclaves derived from the mantle and the lower crust in the Middle Atlas. The volcano-sedimentary sequence (Fig. 13.20b) includes both sedimentary bedrock materials and juvenile volcanic materials. They are rich in enclaves from the lower crust (metagabbros, granulites) and from the lithospheric mantle (peridotites, pyroxenites, amphibolites), as well as in megacrystals of amphiboles, clinopyroxenes, olivines, even sapphire and corundum. The detailed study of mantle xenoliths (Fig. 13.20c) (Moukadiri 1999; Raffone et al. 2009) shows that they result from the metasomatism of the base of the African lithosphere by alkaline basaltic liquids and magmas of asthenospheric origin.

13.3.2.3 Lechmine n'Ikettane [33°22′34.08″N;5°7′31.46″W]

Lechmine n'Ikettane corresponds to a maar landscape (Fig. 13.21a) with a subcircular shape in map view that cut into the Liassic limestones basement and form a 95 m deep and 1300 m wide depression with steep walls. The flat bottom of this maar is located at 1801 m above sea level.

This volcanic landscape is marked by the total absence of its outer slopes fits well to a typical maar volcanic edifice

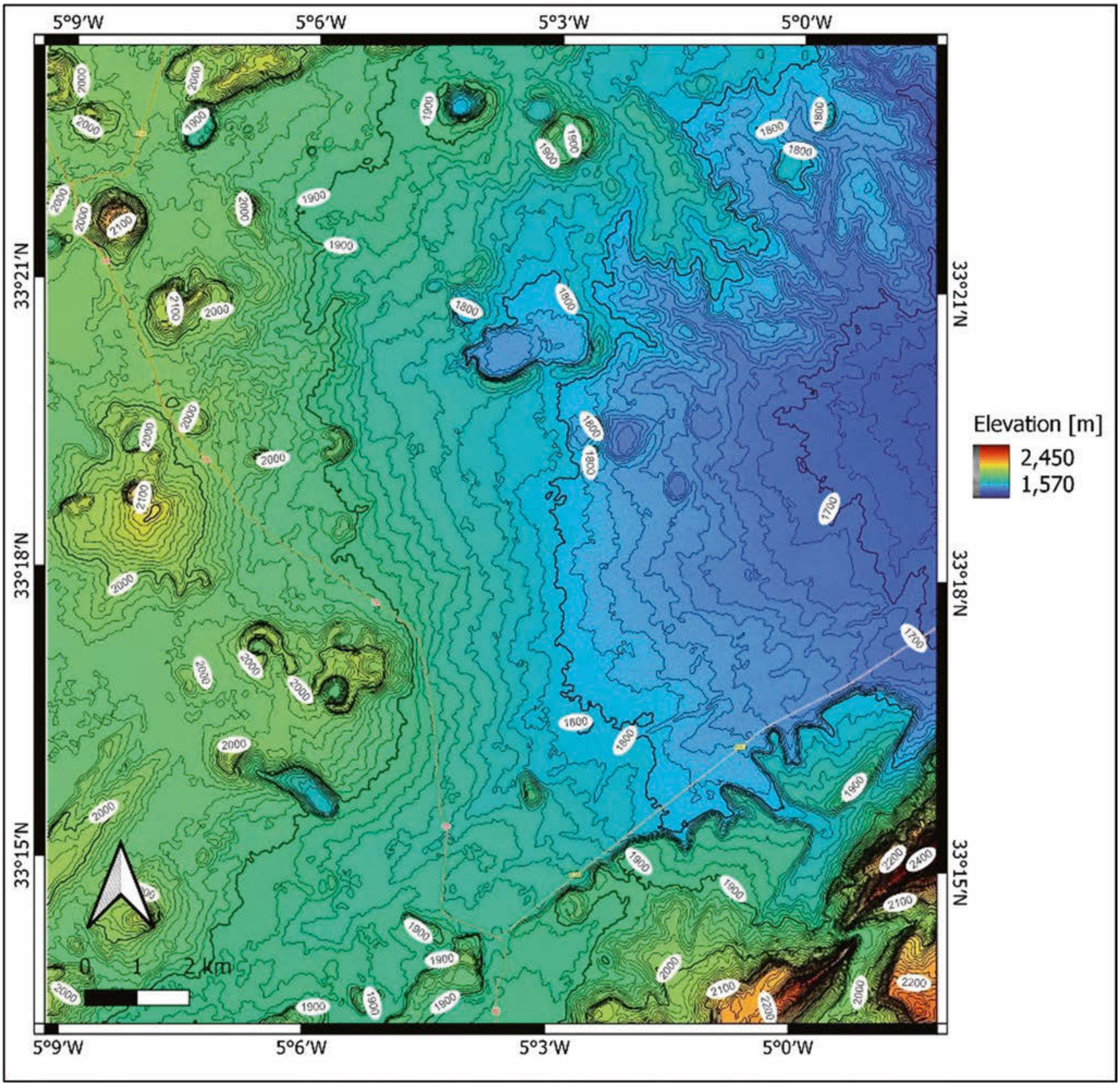

Fig. 13.11 DEM based on the ALOS-PALSAR 12.5 m resolution digital elevation data demonstrate the gentle eastward sloping of the field and the relative position of specific volcano types such as having scoria cones in higher ground while maars in the lowlands

with subhorizontal bedding within its tuff ring. Its northern part corresponds to the faulted downthrown side of the Bou-Teguerrouine whose limestone beds dip toward the SE. This part of this landscape is crowned by a bench of pyroclastic breccias as part of the proximal pyroclastic facies of the tuff ring surrounding the maar crater (Fig. 13.21c). To the east and west, the beds of these pyroclastic breccias clearly dip outward from the maar crater. At the foot of this volcano and its slopes, the volcanic ash is masked by an irregularity generated by the syn-depositional surface of the underlying lava. The northern slope presents the maximum thickness of the pyroclastic deposits, reaching over 60 m in thickness. The lowest units of this volcanic landscape are generally composed of erosional top surface of lavas flows, common accumulation of large volcanic bombs (Fig. 13.21b), and some scoriaceous lapilli, attesting to an early drier explosive activity of the evolving maar volcano. The pyroclastic deposits are covered over two-thirds of the circumference of the maar by a lava flow, which mapped downslope toward the center of the crater on the south side, where the tuff ring is essentially missing (Martin 1981).

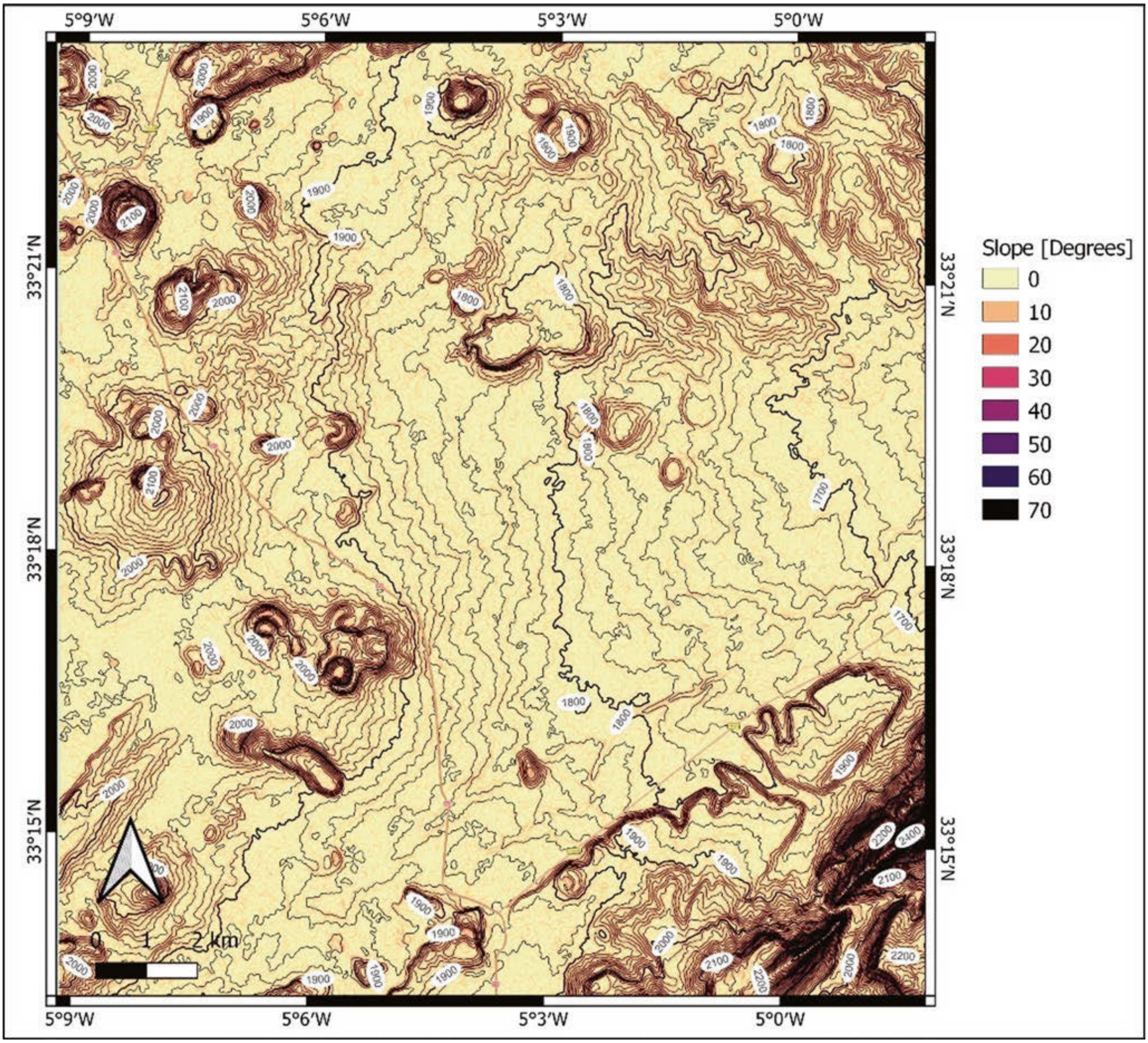

Fig. 13.12 Slope angle map of the central part of the volcanic field clearly shows the morphological asset of the region. Along the SW and NW fault-controlled escarpments can be recognized, while the entire region itself is relatively gentle sloping. The only exceptions from this trend were scoria cones or maar craters present

13.3.3 Mixed Style Landscapes

Only 8% of volcanoes mark the volcanic landscape of the Middle Atlas assigned to be formed by mixed eruption styles, and they are generated by complex structures resulting from multiple eruptive activities. This volcanic architecture is characterized by pyroclastic beds demonstrating alternating wet and dry explosive eruption styles responsible for their formation.

13.3.3.1 Lechmine Izgar [33°15′51.13″N;5°6′17.54″W]

Lechmine Izgar is a mixed cone-maar volcanic edifice with a relative height of 250 m and a width of 2600 m from the crater. This volcanic edifice (Fig. 13.22) has an ellipsoidal shape (1400 × 600 m) elongated along a NW-SE axis reaching a crater depth of 80 m, surrounded by a basaltic cliff 5–10 m high corresponding to the flows of some lava spatter cone.

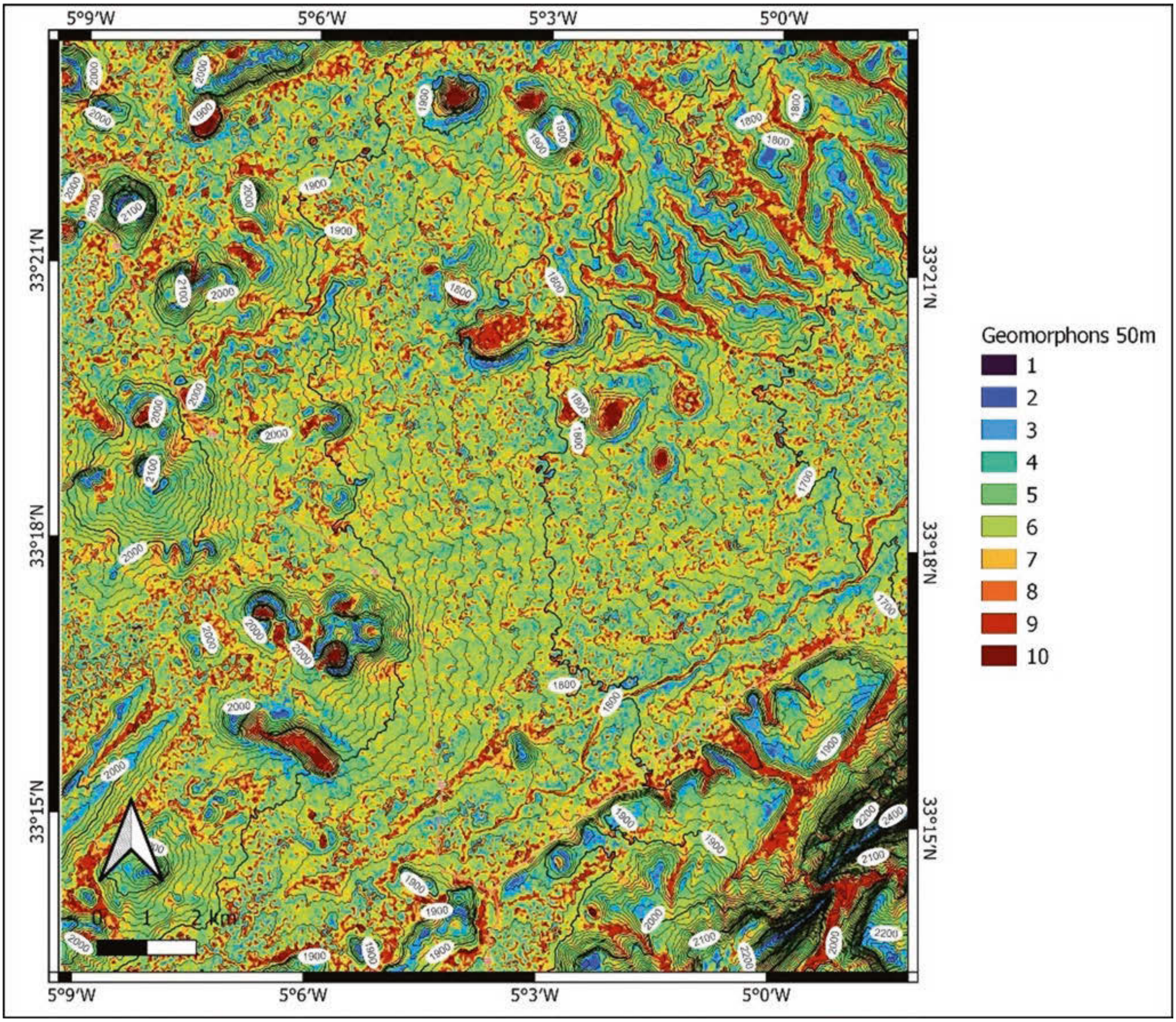

Fig. 13.13 Geomorphon map of the central part of the region applying 50-m calculation distances capturing fine details of the ruggedness of the lava flow surface and details of each individual volcanic landforms

The landscape structure of Lechmine Izgar is marked by two units (El Messbahi et al. 2015). The first is a succession of pyroclastic rocks typical for Strombolian style explosive eruptions. The crater is horseshoe shaped and open to the SE. Its relative height is about 100 m while the diameter of the edifice is 1200 m. Its pyroclastic successions are typically alternating scoria and bomb-rich beds. The second pyroclastic succession of the edifice is dominated by phreatomagmatic origin pyroclastic rocks forming an irregular tuff ring composed of tuff and lapilli tuff beds and subordinate proximal pyroclastic breccias.

On the outer southwest slope to the bottom of this landform, there are Cretaceous limestones beds crop out. Typical karstic collapses feature appears on this slope, which slips along a fault striking to the N70° that is perpendicular to the elongated map view outline of the maar (Martin 1981). Thus, the nature of the depression best interpreted to be an ovala, that formed by the coalescence of a series of dolines on the same fault zone responsible for the emergence of the cinder cone (Baadi et al. 2021).

13.3.3.2 Ouest Hébri [33°21′37.69″N;5°8′29.99″W]

Ouest Hébri corresponds to a scoria cone landform, cut in its southwestern part by a younger maar that is 65 m deep and 500 m wide. This landscape is marked by a scoria cone-maar mixture that illustrates the transition from the initial dry dynamic explosive eruptive style to the wet explosive eruption style toward the closing stage of the volcanic evolution of the system. In its NE part, of the Strombolian style pyro-

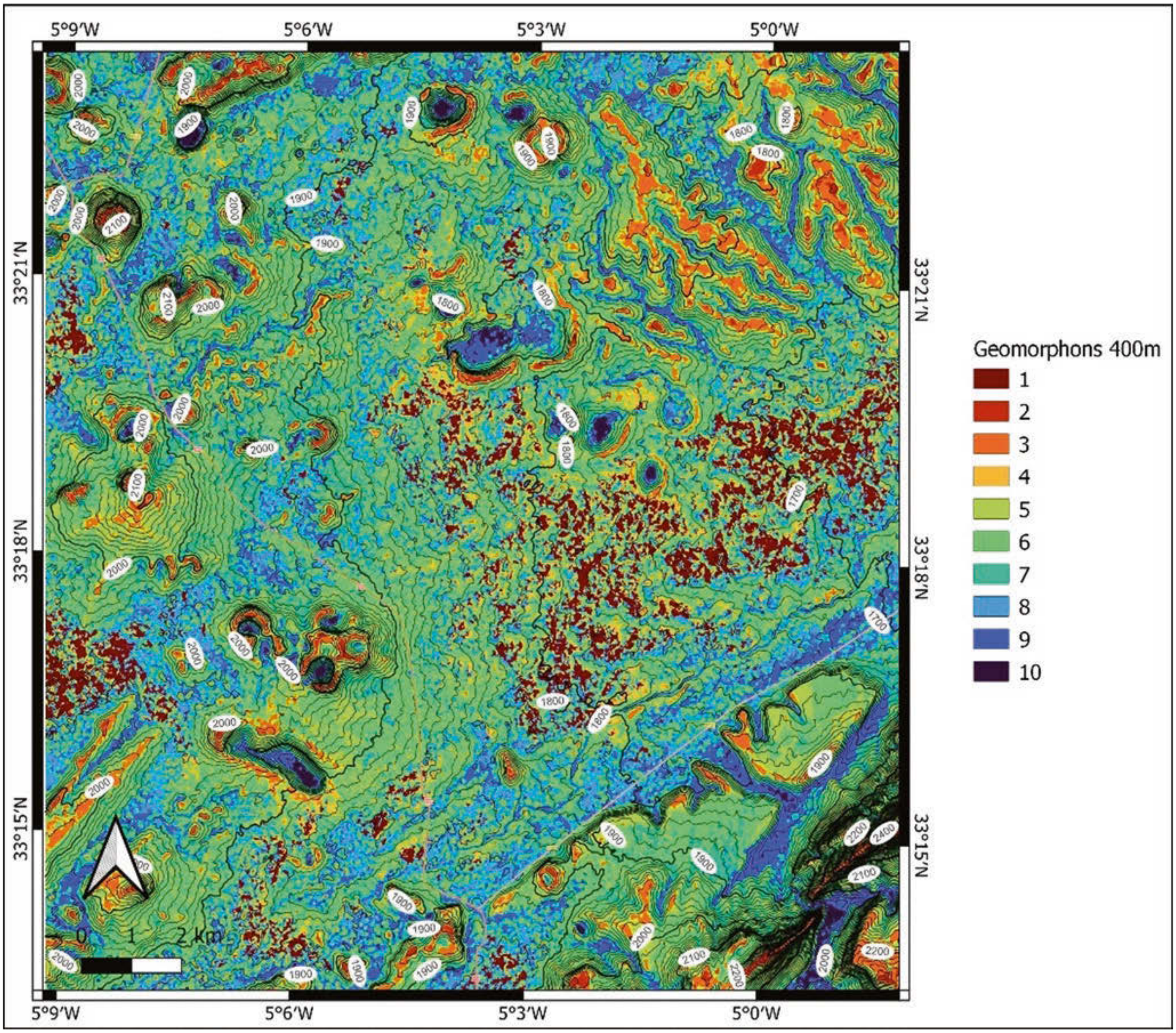

Fig. 13.14 Geomorphon map of the central part of the volcanic field applying 400 m calculation radius reveal large landform elements as valley floors or general trends of the lava flow surfaces

clastic unit of the volcano (Fig. 13.23a), fine grained highly vesicular volcanic ash-dominated pyroclastic successions forming a pozzolan pile that is currently quarried for cement production. The pozzolan quarry fronts rise to 20 m, exposing decametric-scale alternation of scoriaceous ash and bombs and lava spatters. Bread crusted (Fig. 13.23b) and cauliflower-shaped (Fig. 13.23c) bombs are abundant.

Excavation work at the abandoned quarry testifies to the existence of an elongated scoria cone, cut to the southwest by a maar crater (Fig. 13.23d), partially surrounded by tuffs and massive pyroclastic breccias with a small fraction of accidental lithics derived from the limestone basement (phreatomagmatic pyroclastic breccias).

13.3.3.3 Tahbrite [33°20′46.49″N;5°7′48.73″W]

Tahbrite corresponds to a volcanic complex (Fig. 13.24a) composed of a maar and three scoria cones, together forming a 170 m high and 2500 m wide volcanic edifice complex. The maar is formed following the first phase of volcanic activity characterizing the initial formation of a shallow maar surrounded by a tephra ring, followed by the emergence of two cinder cones to the west. The western tuff ring (Lechmine Ouezdem) has an ellipsoidal shape in map view (1200 × 800 m) reaching more than 40 m in height and culminating at 1927 m above sea level. The scoria cone, in the central position, has a round shape with a diameter of 750 m, a height of 60 m and reaching an altitude of 1982 m. The lat-

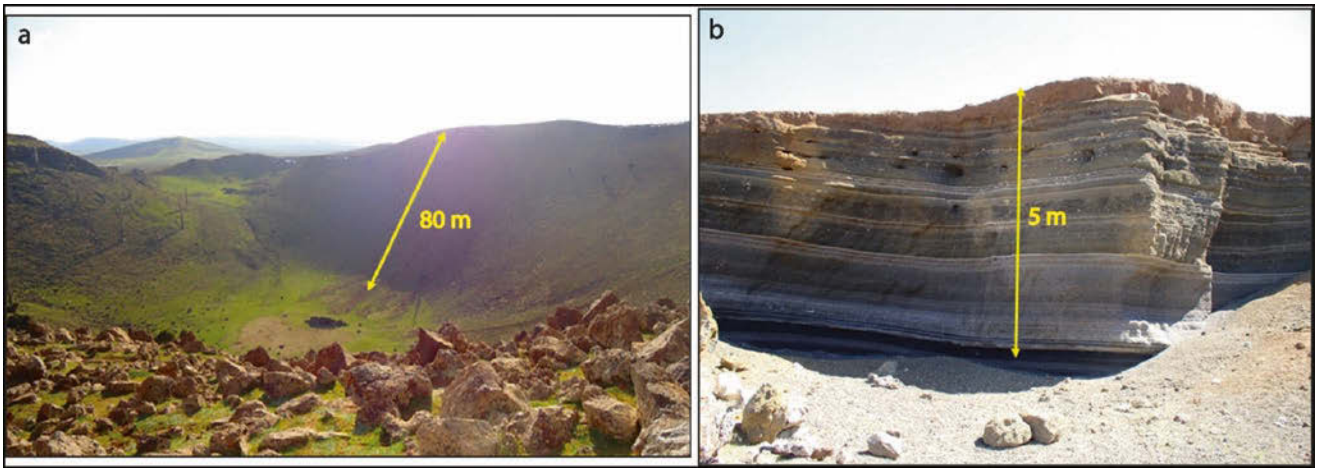

Fig. 13.15 Bou-Teguerrouine volcanic complex: (**a**) West crater of the complex is 400 m in diameter and having an 80 m deep crater clearly recognizable; (**b**) Layered deposits of a typical edifice-building scoria cone succession (alternation of dark scoria levels and light ash levels with small calcareous blocks) at the base of the volcanic complex

Fig. 13.16 (**a**) View of the southern part of the El Koudiate geosite; (**b**) Basalt rich in quartz xenocrysts; (**c**) Subalkaline basaltic flow from the El Koudiate

Fig. 13.17 View of the southern part of the northern slope of the Jbel Hebri volcano 200 m high and nearly 1600 m in diameter

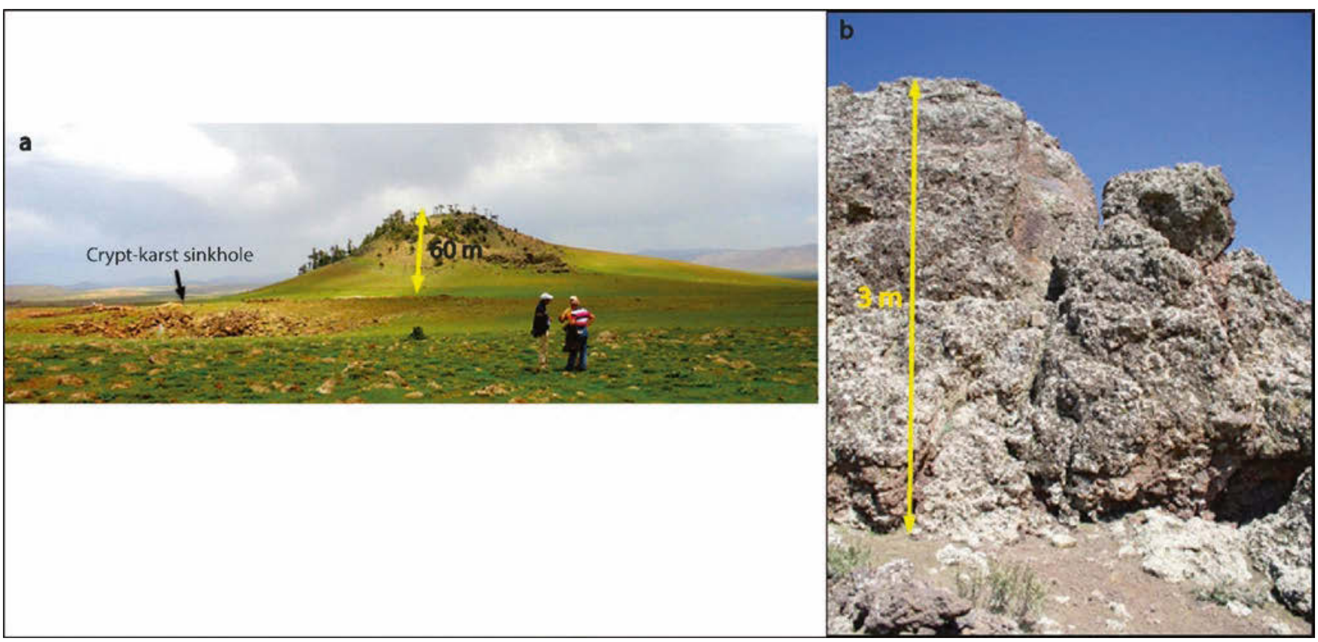

Fig. 13.18 (**a**) Panorama of the Taiissout in the presence of a crypto-karstic collapse on its NW piedmont; (**b**) aa lava front at the foot of this volcano (Baadi et al. 2021)

ter partially overcomes the western flank of the tuff ring. The scoria cone, in a western position, has an ellipsoidal shape (1000 × 750 m) elongated along an NS axis, reaching more than 95 m in height, and reaching 2015 m above sea level absolute height. The third cone is formed during the second eruptive phase, which consists of the emergence of a scoria cone above the two pre-existing scoria ones, and it has an ellipsoidal shape (100 × 700 m) that is elongated along an NS axis. It reaches more than 110 m in relative height standing at 2051 m above sea level.

The lavas emitted by this volcanic complex cover the topography of several volcanoes such as Lechmine n'Ikettane, Lechmine Aït el Haj, and Lechmine Bou-Ibalrhatène. Due to the huge amount of solidified pahoehoe-

Fig. 13.19 Lechmine Aït el Haj: (**a**) General view of the southern flank of the maar; (**b**) Magmatic pyroclastic breccia resulting from the fragmentation of a lava flow in the center of the crater; (**c**) Levels of coarsely stratified tuffs at the level of the maar pyroclastic succession within its tuff ring; (**d**) phreatomagmatic lapilli tuff beds at the level of the eruptive sequence of the maar

like lava (Fig. 13.24b), several tumuli and hornitos formed. The emitted lava sheet is affected by the presence of the syn-eruptive karstic collapses features around the Tahabrit volcano that reach 200 m in diameter.

13.3.3.4 Timahdite [33°13′50.62″N;5°3′59.07″W]

Timahdite corresponds to a mixed maar-scoria cone volcanic landform. Its structure can be divided into three pyroclastic succession units derived respectively from dynamic phreatomagmatic, Strombolian and Hawaiian activity (Amine et al. 2019). Constituents of the scoria cone are located (Fig. 13.25a) on the Eocene limestone slab, which is cut by the NE-SW trending Timahdite Fault. The basal part consists of finely bedded phreatomagmatic sediments and pyroclastic breccias. The summit part is dominated by juvenile pyroclast-rich deposits composed of scoria and bombs commonly covered by layers of agglutinated lava.

The first volcanic unit of this landform is a phreatomagmatic pyroclastic rock succession characterized by a subelliptical tuff ring that is NS-elongated with a diameter of almost 1 km, an average height of about 50 m with a maximum deposit thickness on the NE flank. The bottom of the crater is at the top of the tuff ring. This initial phreatomagmatic phase consists of cross-bedded pyroclastic deposits dominated by ash, and explosion breccias rich in limestone blocks and bombs excavated from the Eocene substrate during the explosive eruptions. These vent opening deposits are classified as fine to medium bedded tuffs and lapilli tuffs (Fig. 13.25b).

The base of the northwest flank shows a special structure of "*Sun's Stones*" with radial cracks in the phreatomagmatic breccias.

The second unit of this landscape is a pyroclastic succession associated with volcanic cones, typical of Strombolian-style explosive eruptions (Fig. 13.25c). Preserved pyroclastic deposits are represented by scoria, bombs (in spindle, cow dung), and lava spatters, forming nearly 30 thick pyroclastic successions, capping the northern part of the basal tuff ring. With the depletion of the water supply, the dynamic phreatomagmatic style was gradually replaced by magmatic volatile-driven Strombolian style explosive activity developing a scoria cone on the northern part of the tuff ring. Pozzolan quarry working faces exhibits dm-t-m thick pyroclastic rock

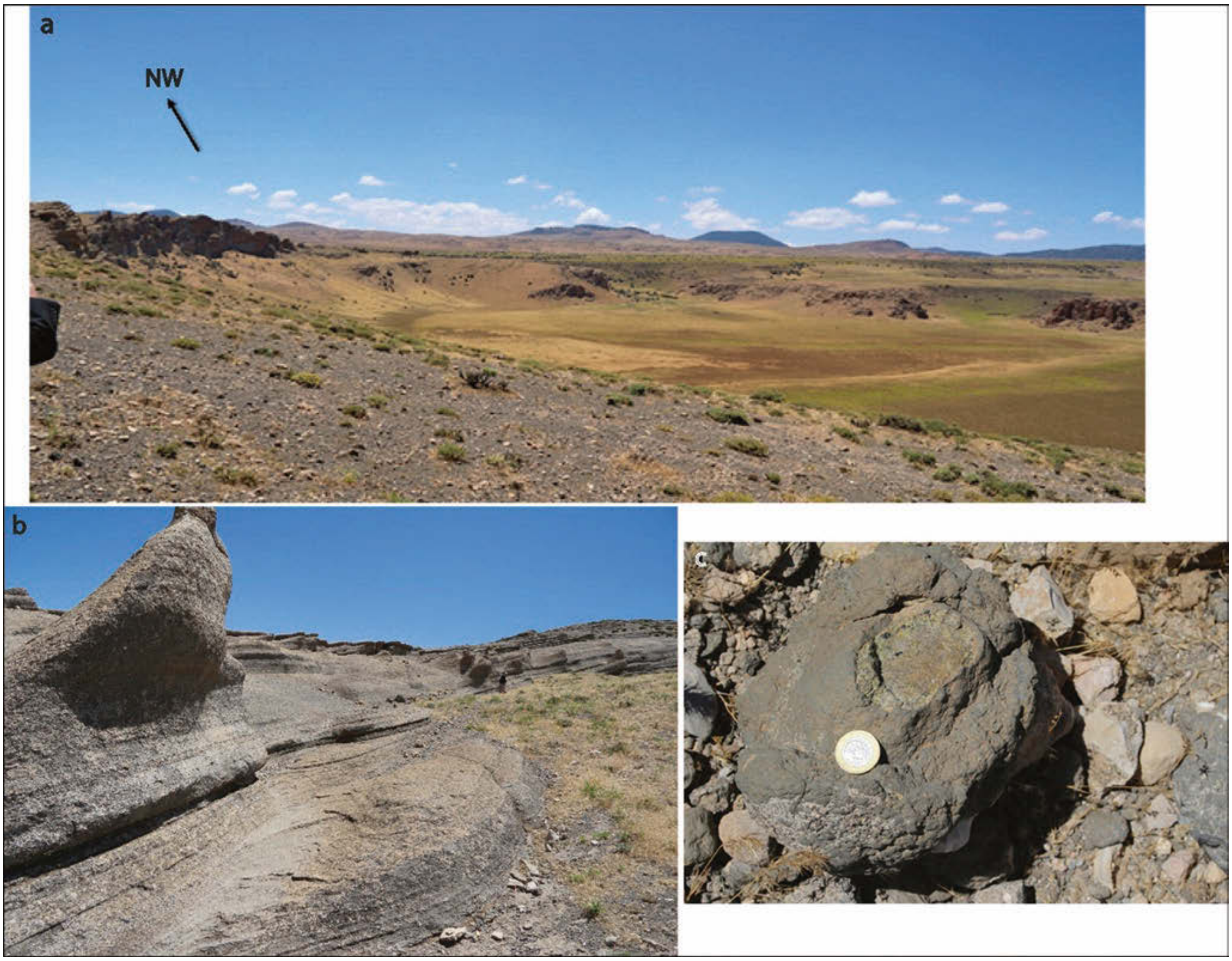

Fig. 13.20 (**a**) General view of the NE part of the Bou-Ibalrhatène maar with the outcrop of its phreatomagmatic pyroclastic successions; (**b**) Pyroclastic deposits of the maar of Bou-Ibalrhatène; (**c**) Peridotite xenolith packed in a juvenile pyroclastic block

beds showing alternating spatter-rich layers and laterally discontinuous lithic boulder-rich layers.

The third unit of this volcanic edifice is a pyroclastic succession of overlapping lava spatters and flows typical of mild explosive Hawaiian style eruptions with localized, mostly clastogenic lava flow dominated coherent facies. It is represented by a spatter cone that covers the entire Strombolian type of scoria cone, as well as massive lava flows overflowing from the crater on the SE slopes of the volcano. Due to outgassing and the eruption rate fluctuation, Strombolian style activity becomes distinctly Hawaiian style. Spatter erupted from a lava fountain to form small cascading clastogenic lava flows on the southwest flank near the crater rim (Amine et al. 2019). The end of the eruption is characterized by the overflow of lava from the crater, which flooded the perimeter of the base of the Timahdite volcano. Subhexagonal prisms as columnar jointing (Fig. 13.25d) developed in these lava flows along the Guigou River valley, by cooling in contact with air and moist soil (Spry 1962; Goehring et al. 2006; Goehring and Morris 2008; Boivin and Thouret 2014).

13.4 Conclusion

In the Mio-Quaternary, the volcanism of the Middle Atlas produced innumerable volcanic units. Their lava flows covered the entire carbonate karstic surface of the Lower and Middle Lias, impacting the landscape of the region. These landscapes are diverse and occupy more than 7% of the area of the region. These are (i) landscapes of Strombolian-style cinder cones distinguished by their slightly higher height from other surrounding landscapes (the case of the geosites

Fig. 13.21 (**a**) Photo of the Lechmine n'Ikettane maar from the Boutajtiout volcano cut in the limestone substrate; (**b**) Lava of the maar Lechmine n'Ikettane; (**c**) Outcrop of phreatomagmatic pyroclastic breccias on the eastern section of the maar close to its crater rim

of Bou-Teguerrouine, El Koudiate, Jbel Hébri and Taiissout), (ii) landscapes of maars of phreatomagmatic style (geosites of Lechmine Ait el Haj, Bou-Ibalrhatène and Lechmine n'Ikettane) and (iii) landscapes of mixed style resulting from multiple eruptive activities (geosites of Lechmine Izgar, Ouest Hébri, Tahbrite and Timahdite).

The morphodiversity of the region is well marked by well-preserved morphostructural and volcanic characteristic structures. Spatial data showed a categorization of landforms revealing this morphodiversity with the presentation of fine geomorphological variations provided by several maps by locating all types of volcanic units and the extent of lavas in the majority in the Azrou-Timahdite Plateau. This data was used to create basic terrain analysis models and overviews of geomorphological features "geomorphons" to demonstrate the morphodiversity of the region that underlies the geoheritage features of the study area. These features illustrate the location of cinder cones, maars, complex edifices, valleys, ridges and depressions.

The morphodiversity of the region was unveiled using satellite images putting a perfect link between the underlying lithology, structure, volcanism and hydrogeology. This link between all these elements presents the value of the volcanic geoheritage of the region and makes it possible to trace the distribution of the different volcanic units and their lava flows throughout the Middle Atlas.

Acknowledgments We thank Professor Ali Moukadiri of the Faculty of Sciences Dhar El Mahraz for his help and interpretation in the field.

Fig. 13.22 Maar of Lechmine Izgar stretched over nearly 2 km in a WNW direction (El Messbahi et al. 2020)

Fig. 13.23 (**a**) View of the Strombolian style deposits to the NE of the volcano exploited for pozzolan; (**b**) Bread crusted bomb at the level of the Strombolian style deposits; (**c**) lava block; (**d**) The SW part of the scoria cone (right) cut by the maar (left)

Fig. 13.24 (**a**) View to the south of the Tahabrit; (**b**) Pahoehoe-type lava with solidified fluidal structures

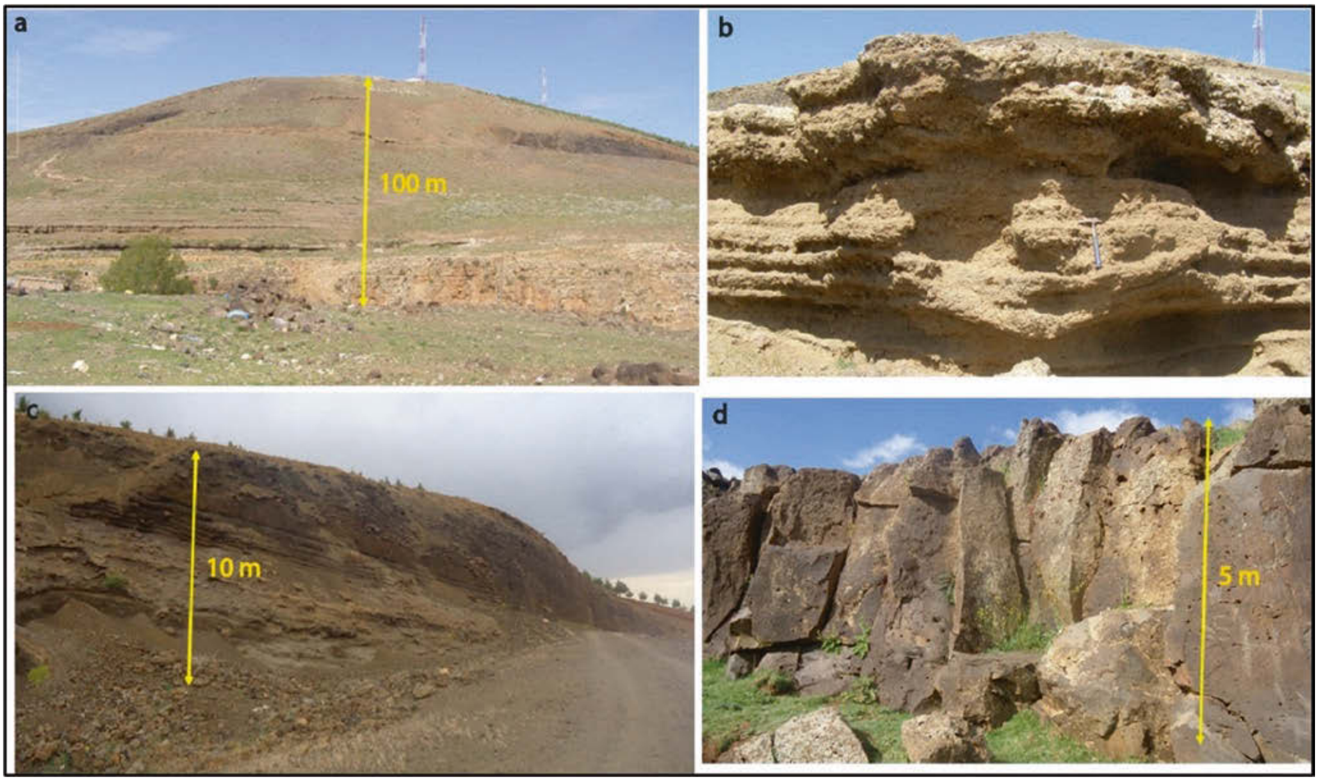

Fig. 13.25 (**a**) North-east face of the Timahdite which rests on the pink limestone slab of the Eocene; (**b**) Fine levels of tuffs and lapilli at the base of the volcano; (**c**) Dark strombolian deposits which surmount the summit of the pyroclastic series of phreatomagmatic influence; (**d**) Subhexagonal colonnades of the flow on the east bank of Oued Guigou at the level of the eastern base of the volcano

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14 The Volcanism of the Plio-Quaternary of Azrou-Timahdite Plateau (Central Middle Atlas, Morocco): Potential for Geotourism Development

Khaoula Baadi, Ghislain Zangmo Tefogoum, and Abdelmounji Amine

Abstract

In the Plio-Quaternary, the central Middle Atlas, considered to be "the country of lakes and volcanoes", was the seat of alkaline volcanism, located on the Azrou-Timahdite Plateau. The latter is the most recent and largest volcanic field in Morocco. It includes countless volcanic devices over a length of 50 km. These volcanic devices constitute by their form, genesis and representativeness an example of an exceptional volcanic heritage through a varied volcanic range and a typicality of sites unique in Morocco. Of these, height (8) were selected for this study. They include the Cone-Maar (Ouest Hébri), the maars (Lechmine Ait el Haj, Michlifène, Lechmine Bou-Ibalrhatène and Lechmine n'Ikettane) and the cones (Bou-Teguerrouine, El Koudiate and Outgui). The elevations of these geosites range between 1747 and 1905 m with diameters and depths up to 1300 and 110 m respectively. The outcrops of volcanic rocks, in particular pyroclastic products (lapilli, bombs, breccias, etc.), basalts and associated reliefs make them exceptional sites. The different eruptive dynamisms that presided over the construction of these geosites give them an undeniable educational value. These are real natural potentialities whose enhancement through geotourism will contribute to their sustainable management. In this work, valuation strategies for geotourism purposes are proposed for local development.

Keywords

Volcanic geosite · Promotion · Geotourism Azrou-Timahdite Plateau · Middle Atlas

14.1 Introduction

The geological heritage is often dominated by numerous exceptional geosites. A geosite is a delimited space which offers the possibility of observing geological elements and/or phenomena of interest for the understanding of Earth sciences (De Wever et al. 2006). One can distinguish as many types of geosites as there are disciplines and sub-disciplines of Earth Sciences. However, we distinguish the volcanic geosites which result from several processes among which we find explosions (strombolian), effusions (fissures), extrusions (domic and pelean). All these processes give natural forms to diversified reliefs because their formation takes place outside of human intervention (Portal 2010). These forms, like geosites, contribute to the formation of the landscape and include, among others, domes, cones, maars, cone-maar, multiple cones, tuff rings, lava flows, etc.

These volcanic geosites are undeniable assets for the promotion of geotourism. The purpose of geotourism is to promote consciously and voluntarily the objects of study of the Earth sciences (Reynard 2004). It is a type of tourism through which tourists can acquire more information and a full understanding of the geological and geomorphological processes of the area concerned (Komoo and Kadderi 1997). More recently, Newsome and Dowling (2010) define geotourism as a form of tourism in natural areas that focuses specifically on landscape and geology, and their promotion, interpretation and conservation through appreciation and education. Over the last decade, many researchers have taken an interest in the study of volcanic geosites (Erfurt-Cooper 2010a, b; Erfurt-Cooper 2011; Thomas 2012; Moufti and

K. Baadi (✉)
Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, Fez, Morocco

G. Z. Tefogoum
Faculty of Sciences, University of Maroua, Maroua, Cameroon

A. Amine
University of Hassan II, Casablanca, Morocco

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Németh 2013; Erfurt-Cooper 2014; Moufti et al. 2015; Rapprich et al. 2017; Gałaś et al. 2018; Różycka and Migon 2018; Pijet-Migon and Migon 2019; Scarlett and Riede 2019; Pérez-Umaña et al. 2020). In Africa, we can cite the works of Andrianaivo and Ramasiarinoro (2011); Asrat et al. (2012); Errami et al. (2015); Henriques and Neto (2015); Zangmo Tefogoum et al. (2014, 2017, 2019), Ziem à Bidias et al. (2020); Baadi et al. (2021). All this work aims to enhance the geological heritage of the volcanic type while seeking the most obvious ways in terms of their management and conservation. In recent years, geotourism has experienced considerable growth worldwide and it is appreciated and accepted as a useful tool to promote natural and cultural heritage and to foster local and regional economic development, especially in rural areas (Kubalíková and Bajer 2018). For Alexandrowicz and Alexandrowicz (2022), the main areas of interest for geotourism are geological features and, in particular, geological and/or geomorphological sites. Its development offers opportunities for the promotion of geological knowledge and supports the conservation of geodiversity (Alexandrowicz and Alexandrowicz 2022; Gordon et al. 2018).

In Morocco, research on geological heritage for geotourism purposes is quite developed for paleontological, archaeological, karstic sites, etc. (Fröhlich et al. 1998; Malaki 2006; Ezaidi 2007; Beraaouz et al. 2010; Lefebvre et al. 2010; Baadi et al. 2020). However, work on the geological heritage in a volcanic environment, with a view to setting up geotourism, remains very limited. However, Malaki (2006) studied some volcanic geosites of the central Middle Atlas, more precisely in the region of Ifrane and Azrou. This study highlights the scientific and cultural interest of these geosites for economic purposes. Later, De Waele and Melis (2009); Eddif et al. (2017, 2018); Abdelmounji et al. (2019) carried out a geomorphological and heritage study of the central Middle Atlas. Subsequently, Baadi et al. (2020) carried out a systematic inventory and quantitative assessment of the volcanic geosites of the Azrou Timahdite Plateau. However, this work has focused on the study of certain geosites.

We propose, within the framework of this work, to study in more detail certain volcanic geosites of the Azrou-Timahdite Plateau. This would make it possible to enhance these exceptional geological and geomorphological entities by their form, their rarity and their geological characteristics in order to establish geotourism in the region. This study is part of the Moroccan geological heritage relating to volcanoes and more particularly to those of this plateau. The interest we have in this concept of geosites of great diversity which constitutes a scientific database, stems from two main reasons: on the one hand, a still incomplete knowledge of the volcanic heritage and on the other hand, the urgency to promote this heritage in order to make it known to the general public.

14.2 Geological and Geomorphological Context

The Middle Atlas is an alpine intracontinental chain and has undergone a long period of structuring which began in the Upper Cretaceous. It is subdivided longitudinally into two large units separated by the North Middle Atlas Fault (NMAF) which runs NE-SW (Termier 1936; Colo 1961). It is subdivided into the northern Middle Atlas and the central Middle Atlas. The latter, it is subdivided in subtabular Causse, in the NW, and in pleated Middle Atlas, in the SE.

The subtabular Causse, composed mainly of Lower Jurassic carbonates, is structured in tiered plateaus that reflect an organization in tilted blocks where more than 80% of the volcanoes are located, largely covered by Quaternary basalt of the monogenetic volcanoes. The folded Middle Atlas is organized in anticlinal ridges which separate large synclinal depressions whose outcrops are from the Dogger and the Cretaceous and Tertiary formations. Between these synclines, which are sometimes very wide, the anticlines form narrow faulty links which can reach an altitude of 2797 m at Jbel Tichoukt.

The overall geomorphology of the Azrou-Timahdite Plateau is essentially the product of a combination of mainly inherited and active landforms. The current morphodynamics is mainly correlated with the processes of karst denudation, the weathering of alkaline basalts and the dynamics of the slopes, reinforced by strong agricultural activities, with the formation of badlands, ravines, etc. heavy precipitation in the form of rain and snow, make the subtabular Causse the water tower of Morocco and the land of lakes and volcanoes. Most of the volcanic units cover the flat karst surface of the Lower Jurassic dolomitic limestone tabular plateau and appear to be continuous in the central part of the range between Azrou and Timahdite. This karst surface is dominated by innumerable closed depressions (Fig. 14.1).

Quaternary volcanic activity occupies a large part of the Middle Atlas Causse. The karstic phenomena did not only occur on the margins of the flows; they are also responsible for a large number of closed depressions (Fig. 14.1) of varying shapes and sizes. More than 300 cavities have been identified. The most spectacular are the cylindrical or funnel sinkholes, with steep sides towering over the slopes of large blocks of fallen basalt. As explained by Gentil (1916), the genesis of these karstic cavities is due to the collapse of the roof of certain basaltic caves formed by the digging of a fairly thick mass of lava, and therefore to lava tunnels. They are considered as false craters, which would result either from a progressive landslide, or from a sudden collapse of the basaltic cover above the collapses of the underlying karstic galleries (Termier and Dubar 1940).

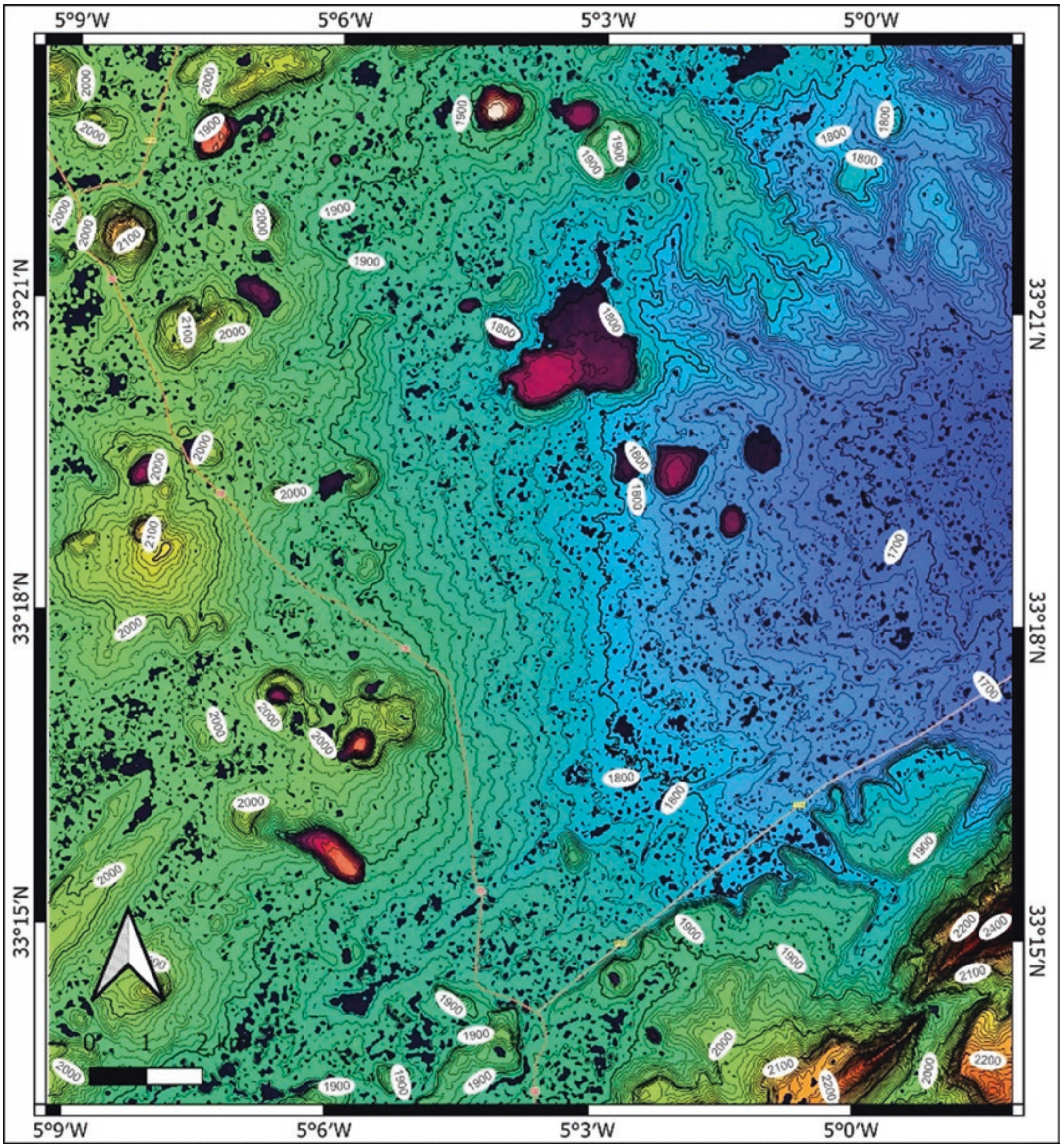

Fig. 14.1 Map of closed depressions in the Azrou-Timahdite Plateau

In some areas, the lava has formed underground tunnels. The Ifri-Ouska hole is a 15 m long cave with two close entrances, containing some small lava stalactites. It is in fact the remnant of one of these underground tunnels.

Several volcanic devices dot the landscape, the most important of them are Jbel Habri, Jbel Hébri, Tit Ouagmar, Lechmine Izgar, Bou-Ibalrhatène, Chedifat-Tit Ouagma, Bou-Teguerrouine, Tahebrite and Sidi Aziz. Lava flows overlying karst topography has led to a convergence of forms with large cryptokarst sinkholes sometimes collapsing due to the presence of underlying lava, but usually related to deep karst tunnel collapse in the Liassic limestone (Martin 1981).

14.3 Identification of Volcanic Sites

Our results come from a bibliographic research, a cartographic study and field work which allowed us to select all the volcanic geosites of the Azrou-Timahdite Plateau for their geotourism value. The inventory and selection of the various proposed geosites were carried out based on the work of Baadi et al. (2021). The choice of geosites for the geotourism promotion was based mainly on altitude, surface area and accessibility. These geosites constitute a crossroads of nationally renowned sites that deserve to be recognized by the general public.

14.3.1 Lechmine Ait el Haj

The Lechmine Ait el Haj geosite (Figs. 14.2 and 14.3a) culminate to an altitude of 1747 m. It is located south of Michlifène, it is a maar 900 m in diameter and 110 m deep. It is located east of the main volcanic alignment. It is subcircular in shape surrounded by walls of volcanic breccias (Fig. 14.3b), lapilli and ash rising up to 95 m above the crater floor. In its borders and especially in its northern part, the Liassic limestones are cut by the chimney and covered by a ring of tuff. Towards the top, the phreatomagmatic tuff is covered by a semicircular ring of juvenile scoriacal deposits and in blocks, formed by the phreatomagmatic fragmentation of the incoming lava flow (Mountaj et al. 2014). The basanites of Lechmine Ait el Haj cover the alkaline basalt flows and are dated 0.5 Ma (Harmand and Cantagrel 1984). Part of this flow came from the Tazouta volcano in the north.

Lechmine Ait el Haj holds the largest pozzolan deposit in the region. The existence of significant quantities of pozzolan at the edge of the maar implies progressively drier conditions or alternating with wet phreatomagmatic and dry strombolian eruptions (Houghton et al. 1996; Saucedo et al. 2017; Abdelmounji et al. 2019).

14.3.2 Michlifène

The Michlifène geosite (also called Lechmine-Chreb-ou-Horb) (Fig. 14.4a), culminates at an altitude of 1868 m. It is located in the southern part of Ifrane Causse. It corresponds to a maar (Fig. 14.4b) of wet phreatomagmatic activity, accompanied by a settling of the chimney, like a sort of closed funnel, with a depth of more than 100 m and nearly 850 m in diameter. The Michlifène geosite is inscribed in the Lower Lias dolomites, covered by Middle Lias limestones, the sills of which retain volcanic breccias with Liassic fragments.

This volcanic geosite has been very largely covered, at least in its central part, with volcanic products which form enormous spreading spread over almost 300 km^2. This geosite contains ski facilities and a small lodge-hotel.

14.3.3 Lechmine Bou-Ibalrhatène

The Lechmine Bou-Ibalrhatène geosite (Fig. 14.5) culminates at an altitude of 1806 m. It is a huge complex of five coalescing craters that exhibit Liassic dolomites on their sides. The craters reach 1300 m in diameter and 45 m in depth. The origin of these craters is very similar to that of the Michlifène crater, whose explosion washed away the Liassic substratum which is well preserved on the walls. The volcanic edifice of Lechmine Bou-Ibalrhatène essentially shows a form of stripping and gullying. It is associated with a grouping of phreato-magmatic apparatuses which form a complex of maars. To the south (Fig. 14.6a), an important relief ravined with lapilli and breccias stands out. The northern part of the maar (Fig. 14.6b) collapsed following the passage of the N60 direction fault; giving rise to sinkholes.

The deep Bou-Ibalrhatène maar contains abundant xenoliths as well as granulites. The Bou-Ibalrhatène xenolith suite includes metasomatic lherzolites and harzburgites bearing amphiboles, wehrlites, websterites, clinopyroxenites and horblendites (Raffone et al. 2009).

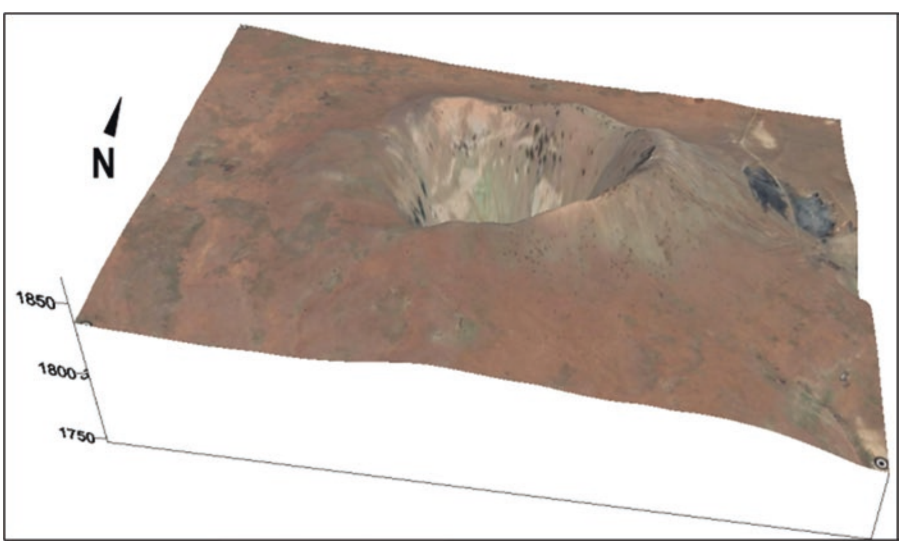

Fig. 14.2 3D profile of Lechmine Ait el Haj Volcano

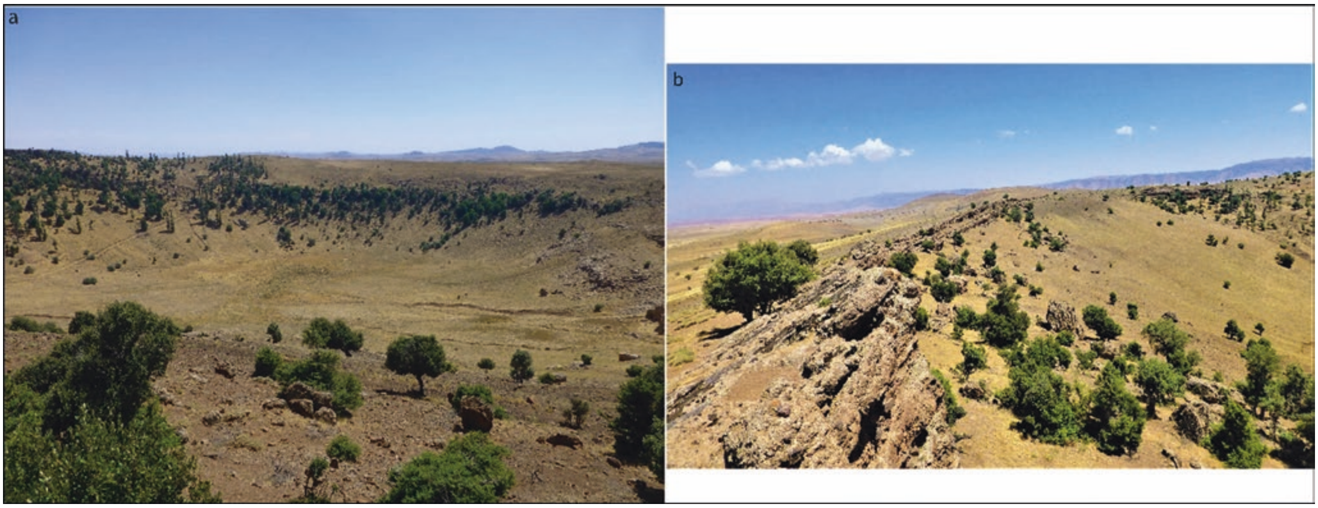

Fig. 14.3 (**a**) Volcanic site of Lechmine Ait el Haj, (**b**) Volcano-sedimentary deposits of the eastern slope of the volcano

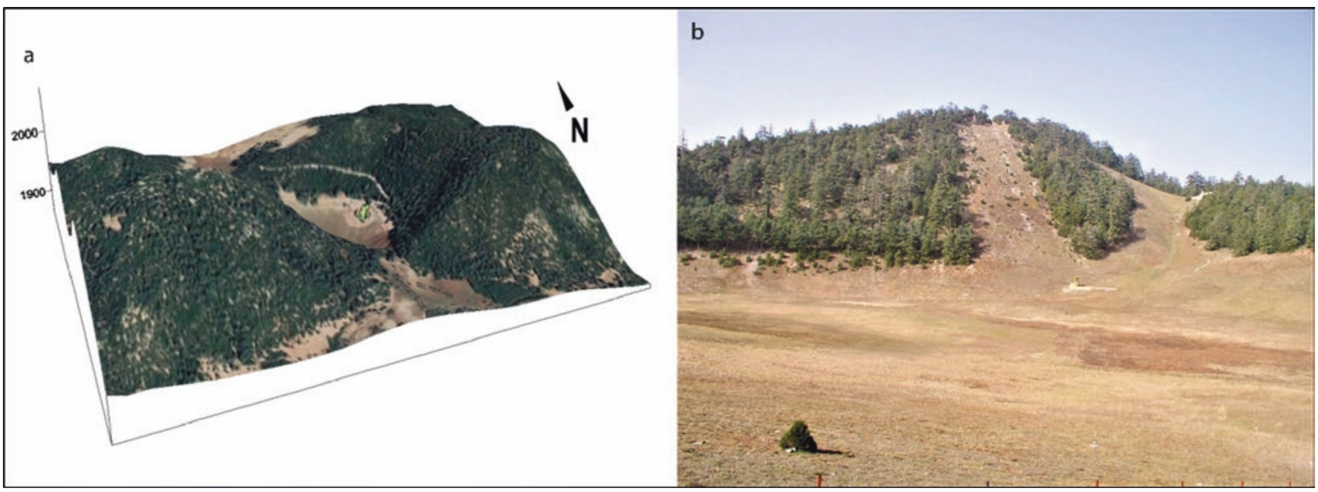

Fig. 14.4 (**a**) 3D profile of the Michlifène volcano, (**b**) North slope of the Michlifène maar

14.3.4 Ouest Hébri

A few meters west of the open summit cone of Jbel Hébri is the geosite of the Ouest Hébri (Fig. 14.7). This one, 70 m high and 850 m wide, culminates at an altitude of 1863 m. It is a cone-maar couple which illustrates the transition from strombolian activity followed by phreatomagmatic activity towards the end of the eruption. The cone in the NE part of the volcano (Fig. 14.8a) is eaten away by the work of extracting pozzolan from the strombolian deposits. The face that cut the cone into two parts rise up to 20 m, showing a decimetric alternation of levels rich in slag and levels rich in bombs and ragged lava. These reddish deposits are typical of Strombolian dynamism in the open air. The SW part is rather occupied by a regular maar (Fig. 14.8b) 400–500 m in diameter and 40–50 m deep, surrounded by massive levels of volcanic breccias with basement elements. The mixture of cone and maar is linked to the appearance of a mass of water during the eruption.

This geosite is unique throughout the Middle Atlas region and exhibits a typical and rare process of a Cone-Maar pair. A few hundred meters away there is a ski area obtained at the expense of the famous cedar groves of Ifrane National Park (*Cedrus atlantica*).

14.3.5 Lechmine n'Ikettane

The Lechmine n'Ikettane geosite (Fig. 14.9) culminate to an altitude of 1905 m and is located at the southwest end of the Bou-Teriouine monoclinal. It is a large closed cavity, perfectly circular, 95 m deep and 1200 m in diameter. It is a maar with a conical structure without root, characterized by a flat bottom which is located at an altitude of 1801 m, or

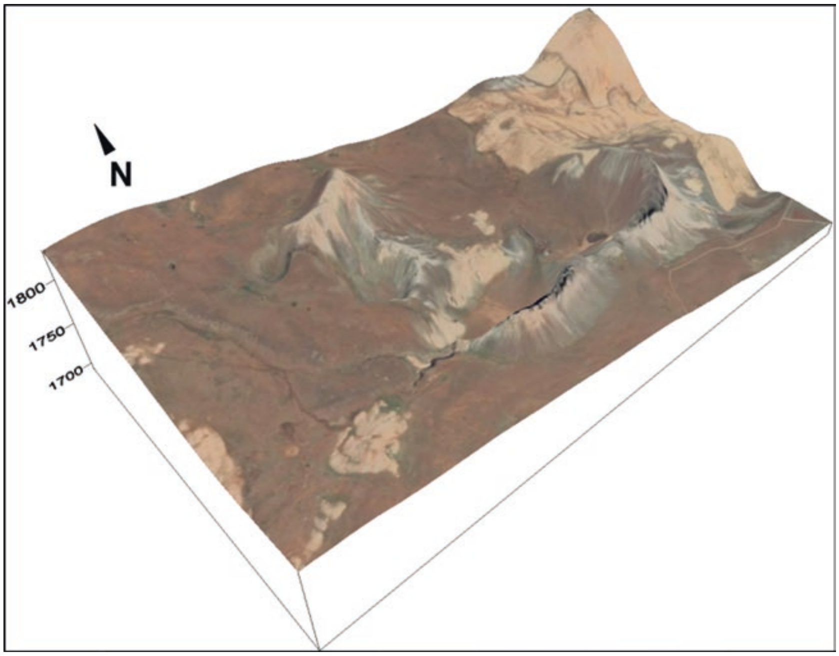

Fig. 14.5 3D profile of the Bou-Ibalrhatène volcanic complex

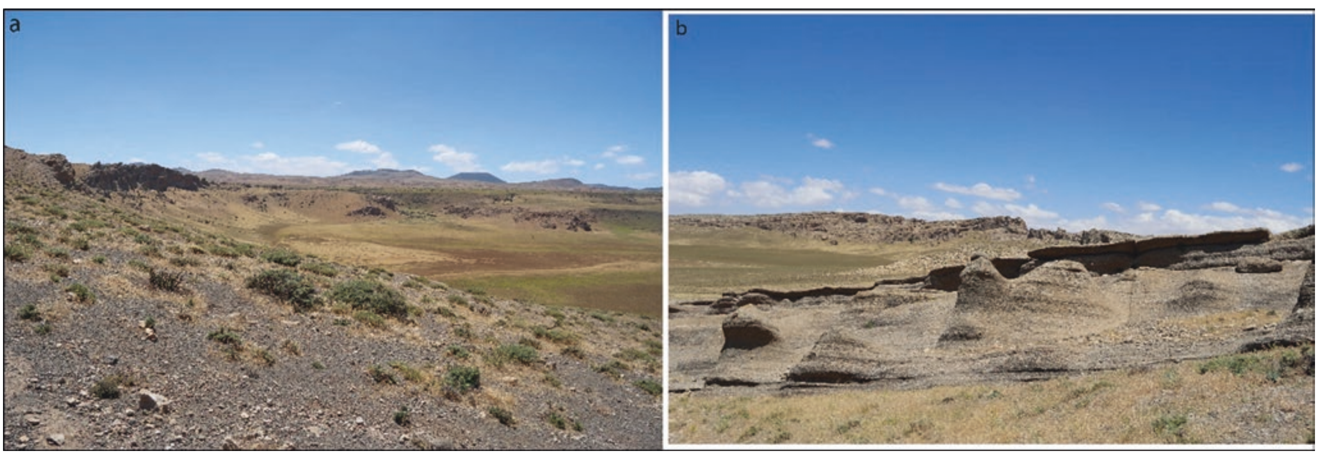

Fig. 14.6 (**a**) View of the southern part of the maar complex of Bou-Ibalrhatène; (**b**) Northern part of the complex on the flank appears volcano-sedimentary deposits

90 m below the basalt plateau. On its south side, there are several hornitos.

The originality of the Lechmine n'Ikettane geosite consists precisely in the total absence of external slopes. Its northern slope corresponds to the faulted fallout of Bou-Terioine whose limestone banks plunge towards the SE. The lapilli slope exposed to the SE is crowned by a bank of pyroclastic breccias. To the east and west, the beds of these pyroclastic breaches clearly show an external dip. At the foot of the geosite and its slopes, the volcanic ash, a gentle slope, is masked by an irregularity of the underlying lava. From the base to the top, we find pahoehoe lavas, coarse slag, a large layer of lapilli and finally well-read breccias.

14.3.6 Bou-Teguerrouine

The Bou-Teguerrouine geosite (Fig. 14.10a) culminates at an altitude of 1871 m, it is 560 m high and 4500 m wide and is located 10 km north of Timahdite. It is a complex geomorphological (Fig. 14.10b) entity composed of eight nested conical volcanoes, of different sizes, resulting from simultaneous and juxtaposed eruptions, arranged along two faults of

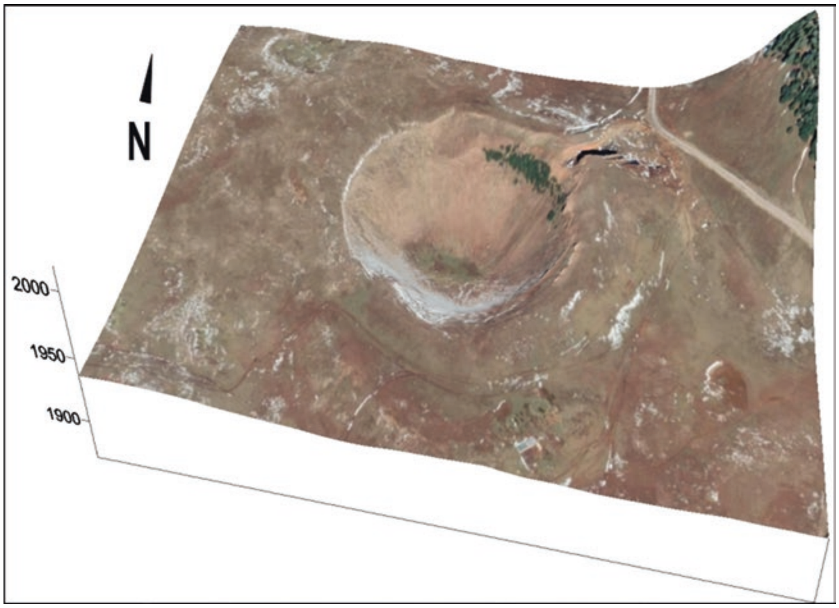

Fig. 14.7 3D profile of the cone-maar Ouest Hébri

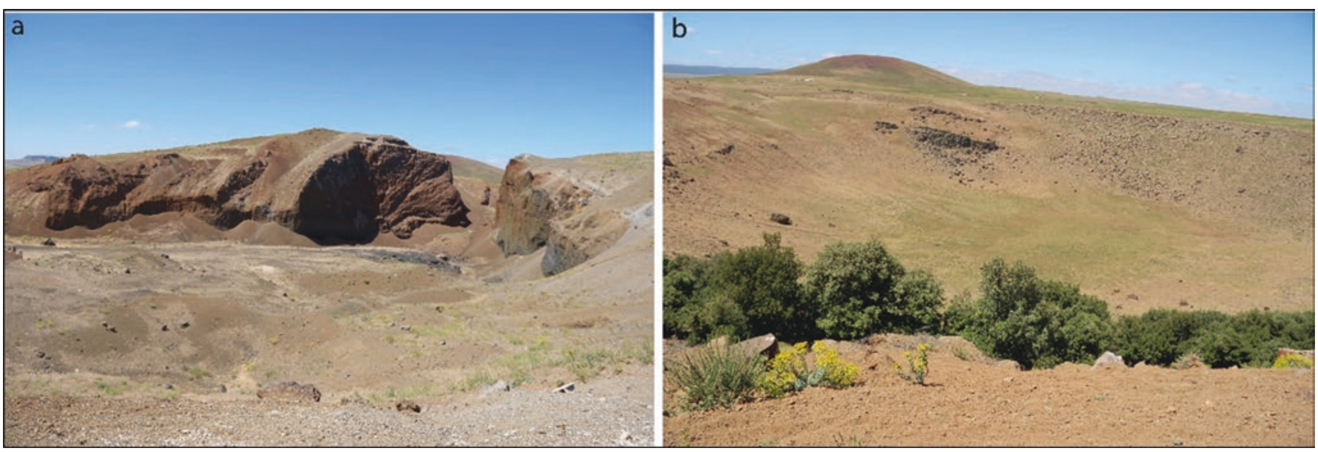

Fig. 14.8 (**a**) View of the NE part of the Cone of Ouest Hébri; (**b**) View of the SW part of the Maar of Ouest Hébri

direction N60° and N140°. Three of them reach an altitude of 2006 m, or a drop of around 200 m, and are taller than the others. Bou-Teguerrouine was formed by the accumulation of slag, bombs, scraps of lava and large lava flows towards the end of its activity. This volcano gave birth to the great basaltic layer of Adaou.

The very steeply sloping Bou-Teguerrouine composite volcano has a crater at the top and features a cluster of air vents. Highly explosive eruptions produced a larger volume of pyroclastic material than lava flows. These lavas are scoriaceous and bulleous and have a rough topography. The Bou-Teguerrouine geosite is the only volcanic device made up of eight craters in the Middle Atlas.

14.3.7 El Koudiate

The El Koudiate geosite (Fig. 14.11a) culminates to an altitude of 1785 m, it is 95 m high and 1200 m wide, it is widely spread out and is located 5 km west of Ifrane. It is a volcanic complex made up of three volcanoes called El Koudiate, Ariana and Tamahrart. These last are twin volcanoes and are found to the west. The sub-alkaline basalt flows of this set are very fluid and cover, in chaotic layers, the inequalities of the Ifrane Causse, creeping into the various valleys such as that of Oued Tizguite and heading north. The strombolian cone of El Koudiate (Fig. 14.11b),

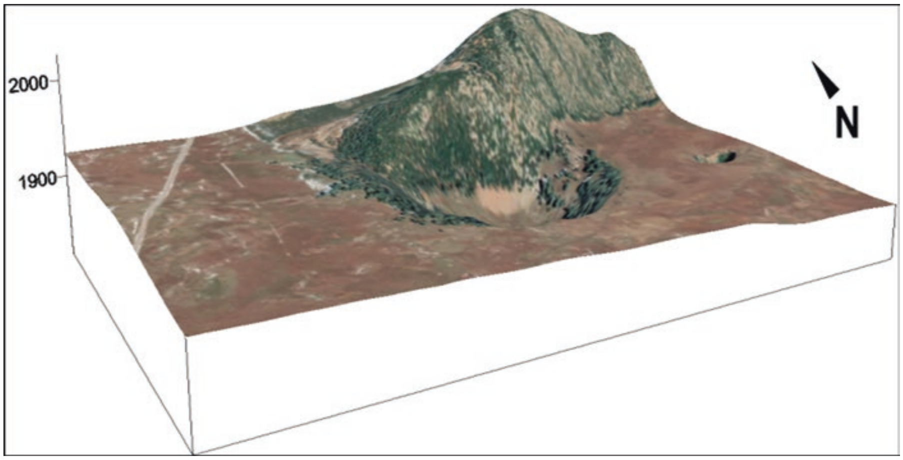

Fig. 14.9 3D profile of the maar Lechmine n'Ikettane

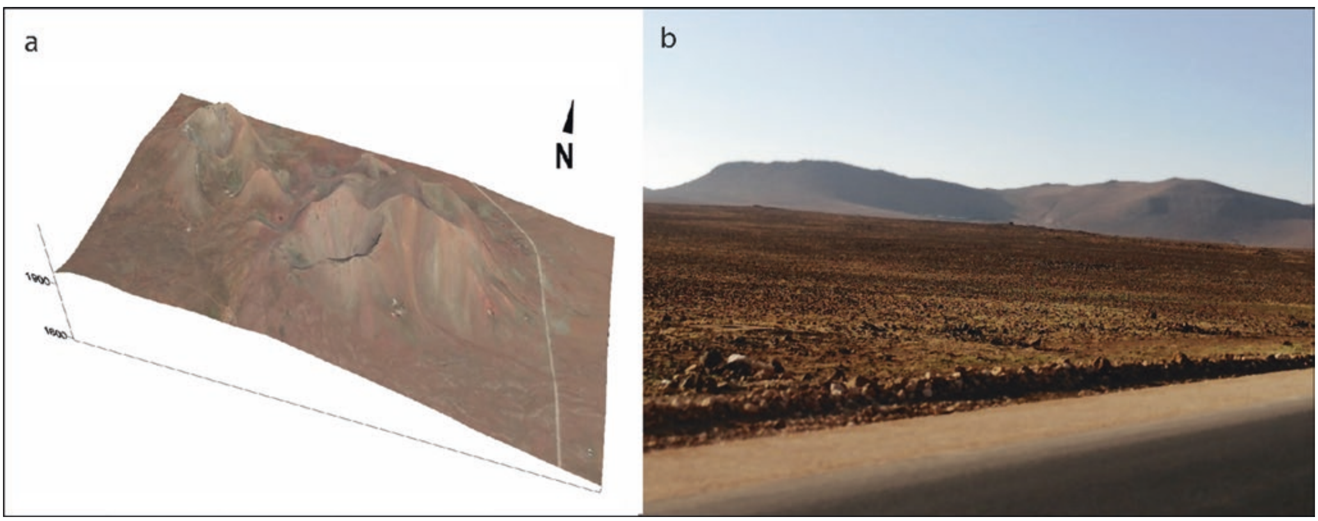

Fig. 14.10 (**a**) 3D profile of the geomorphological complex of Bou-Teguerrouine; (**b**) View of the northern part of the complex of Bou-Teguerrouine

the very rough top part of which is nested in the center of the dismantled crater. This geosite presents one of the most important volcanic structures in the Plateau.

14.3.8 Outgui

The Outgui geosite culminates to an altitude of 1411 m and is located 15 km southeast of the city of El Hajeb. It is a shield volcano, 100 m high and 500 m wide (Fig. 14.12), clearly visible in the landscape of the El Hajeb and Ifrane Causses. Along with El Koudiate, it presents one of the most important volcanic structures in the Ifrane and El Hajeb region. Its pahoehoe lava flows, of alkaline type, spread over more than 30 km and fill different valleys by changing the beds of rivers.

Its basaltic flows seem fresh and relatively intact. They covered a vast area of karst. Its volcanic activity has been characterized by both effusive and explosive eruptions. This volcanic cone probably started its eruptions at the end of the Pliocene although the K/Ar dates gave ages between 0.6 and 1.8 Ma (El Azzab and El Wartiti 1998).

14.4 Promotion of Azrou-Timahdite Plateau Sites

Thus, the implementation of strategies for the promotion of Azrou-Timahdite geosites will be an important way to developed geotourism activities in the area Some strategies have been developed and proposed by several authors in many countries across the word to solve that issue (Edgell 2006;

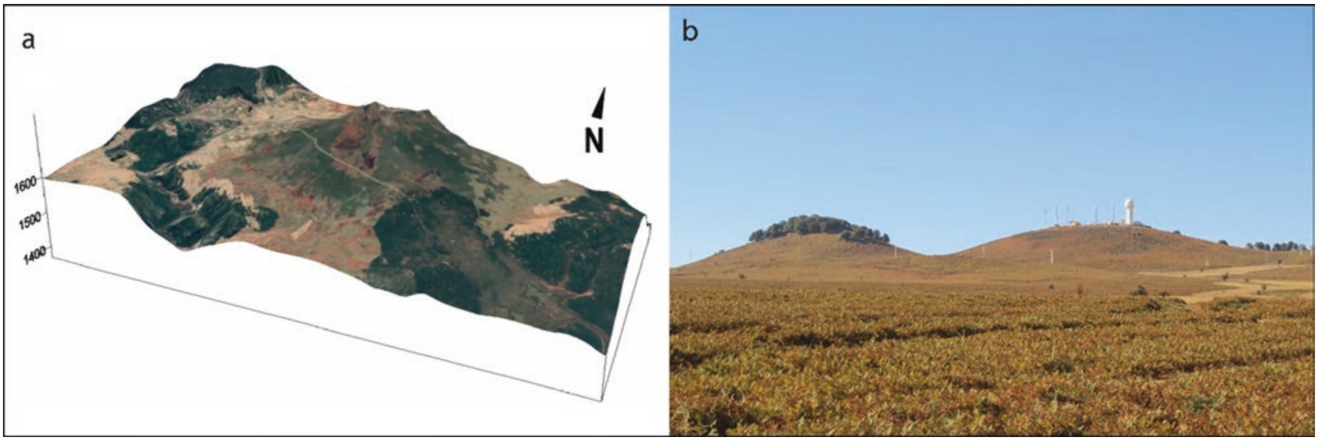

Fig. 14.11 (**a**) 3D profile of the volcanic complex of El Koudiate; (**b**) Overview of the southern part of the El Koudiate cone

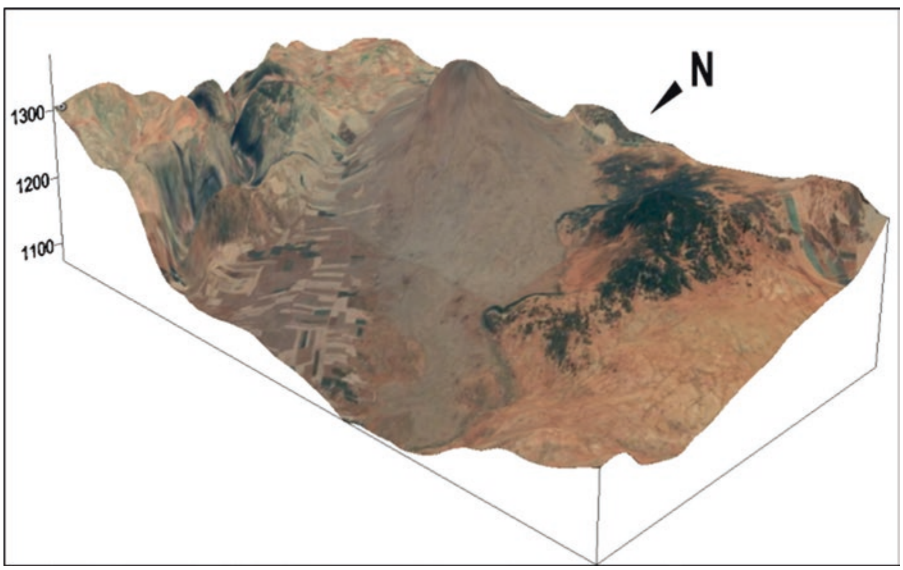

Fig. 14.12 3D profile of the cone of Outgui

Reynard 2008; Han et al. 2018; Abdou et al. 2019; Frey 2021; Alexandrowicz and Alexandrowicz 2022). Among those strategies the following suit very well with the context of Azrou-Timahdite:

Develop and establish geo-interpretative panels near selected geosites by using the data provided in this work. Interpretation is a very important component of geotourism, that is, to explain, perhaps visually, how the rocks were formed; how if crops out, how it changes with time, etc.;

Raising the awareness of the local and international community about the importance of geosites for the economic development of the region;

Involving the local community in the sustainable management plans of geosites for geotouristic purposes. This will be accompanied by the training of guides about the main geotouristic attractions of the region;

Networking (cooperation between scientists, tourist offices, municipality and other stakeholders) and influencing regional planning, policy development and practice;

Establishing regular guided tours for students from universities and secondary schools and, the civil society actors during the main season;

Developing a communication network with a functioning distribution and marketing structure with existing tourism organizations present in the region, and, the local competent authorities;

The marketing of geotourism should begin with an awareness campaign that will target the local, national and international community developing, creating, and utilizing media and communication forms; e.g., flyers and leaflets to websites, newspapers, magazines, television, radio, Facebook, and Instagram. For local people, the marketing must be done using sometime the local languages;

Another interesting way for the promotion of geological issues can be the development of special applications that can be downloaded to mobile phones for free. It is also important to ensure that these attractions are well-marked, and potentially dangerous places are secured.

14.5 Discussion

For nearly a decade, scientific research has accelerated in the field of geoheritage in general, and in that of volcanic heritage in particular. Thus, we can note the book by (Erfurt-Cooper and Cooper 2010) *Volcano and Geothermal Tourism, sustainable geo-resources for leisure and recreation*, entirely devoted to this subject. In addition, there is an issue of "special issue", entirely devoted to volcanic heritage, entitled "Volcanic Geoheritage" in the journal *Geoheritage*, Volume 9, Issue 3, of September 2017, and a special issue, in progress. and titled "Geomorphology, Geoheritage, Geoparks and Geotourism in Volcanic Areas" in the *Geosciences journal of 2020*. In addition, in recent years, several articles dedicated to volcanic heritage have been published in specialist journals. It is therefore clear that the interest of researchers in geo-heritage in the volcanic environment is growing today.

In Morocco, as in several African countries, the geological heritage remains, in the majority of cases, unknown to the competent authorities and the general public (Asrat et al. 2012; Bakka Male 2011; Henriques and Neto 2015; Errami et al. 2015; Zangmo Tefogoum et al. 2017; Williams 2020; Baadi et al. 2020; Baadi et al. 2021). Volcanic buildings, as geosites, ultimately offer very diverse landscapes rich in impressive geological "monuments" and therefore constitute a real heritage. According to Schmincke (2004), volcanic activity is generally covered by the media when the lives of surrounding populations are in danger or infrastructure is damaged. Moreover, although tourism to volcanoes is increasingly popular in many countries around the world (Hansell and Oppenheimer 2004), academic and general literature on volcanic environments rarely mentions established tourism in these areas.

The geoheritage study on the Azrou-Timahdite Plateau (Central Middle Atlas) is part of this perspective. This study area experienced very diverse volcanic events between the Pliocene and the Quaternary. These events were at the origin of several geosites, 8 of which were selected in this work. The geosite of El Koudiate and Bou-Teguerrouine are composed of several explosion products including volcanic breccias, lapilli and ashes. These solid products are arranged in layers, reflecting the rhythm of the explosions that animated the history of these volcanoes. Similar structures are observed on several cones on the slopes of Mount Manengouba (Cameroon), in particular on Njombé, Njom, Ndom and Ekoh (Zangmo Tefogoum et al. 2014), in Mt Scoria, Australia; Wizard Island, Crater Lake/Oregon, USA; Cerro Negro, Nicaragua; Pu'u O'o, Hawaii (Erfurt-Cooper 2010a, b) and the cones of Harrat Khaybar, Saudi Arabia (Németh and Moufti 2017). The peculiarity of the Bou-Teguerrouine geosite, with its eight volcanoes, is that it is disgusted. Its breaking is due to the bottom cones flows which occur at the terminal phase of the volcanic manifestations and which carry with them a side of the cone mainly composed of loose pyroclastic rocks. The same phenomenon was at the origin of several cones as in the Valley of the Volcanoes in Andagua, in Peru (Gałaś et al. 2018) and in Gabal Mayesra in Egypt (Khalaf et al. 2019).

The El Koudiate and Bou-Teguerrouine geosites are examples which perfectly illustrate the strombolian dynamism in the region. They give an overall illustration of the activity of the majority of the volcanoes of the Azrou-Timahdite Plateau which have experienced this type of dynamism. In addition, the drained cones can be used as drainage basins for teaching hydrology.

On the other hand, the geosites of Lechmine Ait el Haj, Lechmine Bou-Ibalrhatène and Bou-Teguerrouine consist of an alternation of flows and pyroclastic products thus defining stratovolcanoes which dominate in several volcanic environments in the world, notably the Snaefellsjökull from Iceland; St Helens, Washington; Mt. Fuji, Japan; Cotopaxi, Ecuador; Mayon, Philippines; Vesuvius and Stromboli, Italy; Nevado del Ruiz, Colombia; Merapi, Indonesia; Nyiragongo, in the Democratic Republic of Congo, and Mount Manengouba and Mount Bambouto in Cameroon (Kagou Dongmo et al. 2005; Wood 2009; Erfurt-Cooper 2010a, b; Wantim et al. 2013; Zangmo Tefogoum 2016). Stratovolcanoes have a strong educational value because they allow us to understand the transitions between the effusive and explosive phases (Németh and Moufti 2017) of the history of a volcano. Thus, stratovolcanoes are sufficiently represented in the World Heritage list (Wood 2009). The Lechmine Bou-Ibalrhatène geosite and the Lechmine Ait el Haj geosite are made up of different coalescing structures. In addition, coalescing volcanoes are also observed on Nyiragongo (Kazadi Sanga-Ngoie 2010) and on the Erazu volcano in Costa Rica (Pérez-Umaña et al., 2020). This testifies the degree of fracturing of the basement and the internal geodynamic processes which took place on the Azrou-Timahdite Plateau in particular and in the central Middle Atlas and Morocco in general. The presence of maars as in the environment of the geosites of Lechmine Bou-Ibalrhatène, Lechmine Ait el Haj, Michlifène and Lechmine n'Ikettane, improve the educational value of the study area because it tells us about the phreatomagmatic dynamism which sums up the meeting of an ascending magma and an underground or subsurface water table leading to significant explosions. Maars according to Joyce (2010), are destructive volcanic forms because they cause the pre-existing reliefs to collapse.

The presence of xenoliths in the rock formations of the Lechmine Bou-Ibalrhatène geosite tells us about the magmatic source of the different rocks of this geosite. The composition of these xenoliths, namely spinel lherzolites, harzburgites and pyroxenites, allows us to conclude that these rock formations are of mantle origin. The outcrop of volcanic products in strata and the presence of xenoliths in certain rocks make it possible to make a relative chronology of the geological events that have occurred in certain sites of the study area, thus giving them significant educational value.

Beyond the possibilities offered by the Michlifène geosite for recreational activities, it has a ski facility, promoting the practice of this sport as on the Hokkaido volcano in Japan. This is what Erfurt-Cooper (2010a, b) calls volcanic sports like surfing.

The Outgui geosite is a shield volcano which is materialized by very fluid lava flows in several directions. We can cite the case of the Piton de la Fournaise (Gaudru 2010); the Hallasan shield volcano in South Korea (Woo et al. 2010); the Bambouto Mountains, in Cameroon (Tchoua 1972; Youmen 1994).

It clearly appears that the geosites of the Azrou-Timahdite Plateau, although little known, are of very high scientific and educational value. They constitute a geological heritage which deserves to be valued. Since the main objective of geotourism is education in Earth Sciences, this enhancement would be more effective through the implementation of geotourism in the study area. Geotourism in volcanic environments is attracting increasing numbers of visitors (Erfurt-Cooper 2010a, b). These include countries that are sufficiently advanced in this area such as Japan, New Zealand, Greece and Italy. Certain that active volcanoes which offer observable eruptive phases attract more geotourists than dormant or extinct volcanoes. The latter category nevertheless offers unique landscapes for the development of geotourism and recreational activities. geosites of the Azrou-Timahdite Plateau which, despite the absence of volcanic activity nowadays, present several assets that can help attract a large number of visitors through geotourism. This geological heritage remains very even unknown and little protected. According to Zafeiropoulos et al. (2021), the importance of establishing a legal framework for the protection of geosites is underlined by the fact that their promotion and rational management create opportunities for sustainable development, as well as to become quality tourist destinations (geotourism) through nature protection and education. It would be important for the competent Moroccan authorities to promote the Azrou-Timahdite Plateau geosites through education through geotourism, which would indirectly secure their protection and conservation for future generations. In addition, educational values of the sites presented above will contribute to the promotion of the knowledge of Earth science and, eventually, to the intensification of activities aiming at conservation of the geological heritage (Alexandrowicz and Alexandrowicz 2022).

14.6 Conclusion

Morocco, called the "Paradise of geologists", has aroused growing interest in recent years for the scientific study of its geoheritage. Geosites are an integral part of geoheritage. The Azrou-Timahdite Plateau has 81 geosites of variable volcanic and morphological structures representing 70% of the geosites in the region (Baadi et al. 2021). Their good state of conservation is due to their location in the Ifrane National Park (INP). This work proposed the study of 8 volcanic geosites of high scientific, educational and geotouristic value. They display spectacular volcano-morphological characteristics, emphasizing the style of eruptive dynamism, shapes, position, crater size, and pyroclastic products. Information on geology, geomorphology and geodiversity is also given.

On the Azrou-Timahdite plateau, there are volcanoes of both Strombolian and phreatomagmatic origin or of both origins (strombolian and phreatomagmatic). This is the case of the Ouest Hébri geosite. It is the originality of the volcanic geosites of the Plateau compared to the other volcanic geosites of Morocco. The diversity of geosites in the region is linked to the karstic and hydrogeological setting due to the carbonated aquifer of the underlying Lias revealing superb hydro-volcanic reliefs.

The Azrou-Timahdite Plateau is known for the quality and state of preservation of its outcrops. It has the full range of existing volcanological phenomena and therefore constitutes an excellent educational region to attract the attention of researchers, students, pupils as well as the general public. These geosites therefore constitute a veritable open-air "museum" by providing a large database usable for geotourism purposes and for promoting the socio-economic development of the region.

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Part VII

Conclusion

15 Geoheritage: Between Geological Heritage Protection Initiatives

Khaoula Baadi

Abstract

The set of chapters that make up this book covers all the main domains and themes related to geoheritage, its promotion and preservation. The book would attract the attention of researchers in geoheritage and geodiversity and also local authorities. It presents a thorough synthesis and critical review of the geoheritage of the Middle Atlas region that would be a significant contribution and remain a fundamental resource not only for geoheritage experts but in the broader geoscientific community.

Keywords

Geoheritage · Geodiversity · Promotion · Preservation · Protection · Middle Atlas

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This final section presents the major initiatives of natural heritage preservation and protection laws in general and discusses proposed alternatives for the protection of geological heritage.

K. Baadi (✉)
Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, Fez, Morocco

15.1 Natural Heritage Protection Initiatives: National Environmental Standards

Morocco has adopted in its development strategy the concept of sustainable development which favors the balance between environmental, economic and social dimensions, with the objectives of improving the quality of life of its citizens, strengthening the sustainable management of natural resources and promoting environmentally responsible economic activities. The capital of geological knowledge that has accumulated on the Moroccan national territory, commonly called geoscientific infrastructure, is of primary importance for any economic and social development project.

The Moroccan legal system for the protection of natural heritage offers an arsenal of tools, several of which are particularly adapted to the protection of geological heritage. The main protection tools that have been used to preserve remarkable natural sites concern regulatory tools (classified sites, national parks and nature reserves). Concerning national parks, since 1942, several parks have been created to protect the natural heritage of Morocco. The Middle Atlas is home to three national parks: the Tazzeka National Park (TNP) in 1950, the Ifrane National Park in 2004 (INP) and the Khénifra National Park (KNP) in 2008.

In conformity with the engagements at the international level within the framework of the Earth Summits of Rio de Janeiro (1992) and Johannesburg (2002) and the relevant conventions, Morocco has set up the foundations aiming at establishing sustainable development in the country through several political, institutional, legal and socio-economic reforms. This process has been reinforced by the adoption of the National Charter for the Environment and Sustainable Development, whose elaboration was launched following the directives of His Majesty King Mohamed VI, during his Throne speech of July 30, 2009.

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Table 15.1 List of laws and Dahirs on the preservation and protection of natural resources in Morocco

Years	Laws	Type of laws
26 Safar 1397; February 16, 1977	Dahir 1-76-265	Dahir 1-76-265 on the publication of the convention for the protection of the world cultural and natural heritage
18 Rabii I 1416; August 16, 1995	Dahir 1-95-154; law 10- 95	Law 10-95 on water
10 Rabii I 1424; May 12, 2003	Dahir 1-03-59; law 11-03	Law 11-03 relating to the protection and the development of the environment
May 12, 2003	Dahir 1-03-60; law 12-03	Law 12-03 on environmental impact studies
July 16, 2010	Dahir 1-10-123; law 22-07	Law 22-07 on protected areas
December 18, 2014	Project of law 81-12	Notice of the draft law 81-12 on the principles and fundamental rules for an integrated and sustainable management of the coastline for its protection, development and conservation
14 Ramadan 1436; July 1, 2015	Dahir 1-15-76; law 33-13	Project of decree taken for the application of the provisions of article 116 of the law 33-13 relating to mines
22 Jumada 1437; March 2, 2016	Dahir 1-16-25; law 91-14	Dahir 1-16-25 on the promulgation of the law 91-14 on external commerce

The national strategy for sustainable development and preservation of Moroccan natural resources is supported by legal measures. These are laws that have contributed to a better preservation and protection of the country's natural resources (Table 15.1).

Water resources have received more attention from local authorities to control their use. This is the case of the Water Law 10-95, which deals with the right to use these water resources. These are quality standards controlling (i) surface water used for drinking water production, (ii) water for irrigation, (iii) surface water and (iv) fish water.

For the protection of nature, the law 11-03 relates to the protection and the development of the environment to state the guiding principles of protection and management of the environment. It deals with the obligations which present a risk for the environment and the provisions aiming at fighting against the pollutions and the nuisances and to protect all natural resources.

For the preservation of biological and ecological sites and natural heritage, in 2010 was enacted the law 22-07 on protected areas. This law covers the various categories of protected areas and national parks whose purpose is the preservation, conservation, development and rehabilitation of natural and cultural heritage, scientific research, awareness and entertainment of citizens, promotion of ecotourism and contribution to sustainable economic and social development. In the 41 articles of this law, the geological heritage was not proposed as part of the natural heritage. Instead, in Articles 4 and 7, designated to the natural park and nature reserve, geological and geomorphological formations, of special interest, are preserved for scientific research and environmental education.

The law 11-03 relating to the protection and the development of the environment has treated in all the chapters and sections all the sectors that affect the environment. In Chap. 4 of this law, which concerns the protection of nature and natural resources, biodiversity and natural parks have taken a large part. However, geodiversity and geoparks were not part of the environmental protection topic.

In 2015, Morocco presented a draft decree that is prepared pursuant to the provisions of Article 116 of Law 33-13 on mining, promulgated by Dahir 1-15-76. It includes various regulatory provisions aimed at organizing and regulating the activities of extraction, collection and marketing of mineralogical specimens, fossils and meteorites, while appropriating the issues of preservation of national geological heritage. This draft decree was elaborated to fix the modalities:

- granting of authorization for the operations of extraction and collection of mineralogical and fossil specimens according to their classification in categories;
- of withdrawal of the authorization relating to the operations of extraction and collection of mineralogical and fossil specimens;
- pronouncement of the technical opinion of the governmental authority in charge of geology for the export of mineralogical and fossil specimens;
- import and export of meteorites;
- of the governmental authority in charge of geology of preemption on mineralogical specimens, fossils and meteorites intended for export.

This bill joins the law 91-14 on external commerce which is also aimed at controlling the conditions of import and export of national objects. This bill initiative was intended for the management and control of the extraction and export of ex-situ mineral and fossil objects. However, this bill did not include the protection and preservation of any in-situ geological objects which is paramount to ensure the conservation of the national geological heritage.

15.2 Recommendations and Proposals

Finally, we present some recommendations on opportunities for geoscientists and particularly geoheritage researchers.

Since the 2000s, much research has focused on discussions of geoheritage and its application in geotourism and geoeducation projects. This research lacks dedicated works on inventory and assessment methods adaptable to the Moroccan territory, with the exception of the methodology of inventory and assessment of geosites by Baadi et al. (2020). However, there is a lack of geopatrimonial work on specific themes. Thus, these works have not been generalized over the entire Moroccan territory. While the national geosites are under increasing pressure, both natural and anthropogenic require a comprehensive inventory study for preservation and conservation. It is necessary to strengthen efforts supporting the awareness of the better understanding of the rarity and also the fragility of the national geoheritage.

Being part of the natural heritage, the geological heritage has not yet had its legal place in the Moroccan legislation as the cultural and biological heritage (fauna and flora). The lack of a legislative framework protecting geoheritage of any kind accelerates any form of degradation of in-situ sites and the sale and export of this ex-situ heritage in an informal way despite the efforts of the authorities. Therefore, it is necessary that the local authorities establish a law protecting the national geological heritage and framing any nonrational use of the sites. Thus, it is necessary to draw up strategies of geoconservation allowing and guaranteeing a better conservation of the sites in the future.

In conclusion, the inventory, assessment, promotion and preservation of the geoheritage of the Middle Atlas proposed in this book will present a key initiative for the implementation of a regional geopark to frame all initiatives and establish geoconservation strategies leading to the conservation of the geological richness of the region.

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