Geoheritage, Geoparks and Geotourism

Ezzoura Errami
Margaret Brocx
Vic Semeniuk
Editors

From Geoheritage to Geoparks

Case Studies from Africa and Beyond

Springer

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Foreword

The African continent possesses a rich and varied geoheritage which is regrettably not well known by the public and which does not contribute in a sustainable way to local development. Linking geoheritage to local socioeconomic development through the promotion of geotourism and geoparks offers an opportunity to increase awareness of the local communities and to inform decision makers about the need to evaluate and promote better the sustainable use of their geoheritage. In the absence of legislation that allows the preparation of inventories and the conservation and economic use of African geoheritage, the creation of geoparks would provide an opportunity to establish a local inventory and to institute local laws to protect the geoheritage in different regions on the continent.

To increase this awareness of the importance of geoheritage in local socioeconomic and human sustainable development, the African Association of Women in Geosciences created, in 2009, the African Geoparks Network. Both these organizations are arranging numerous activities, such as conferences, seminars, workshops and courses, throughout Africa and the Middle East.

This book is a direct outcome of the First International Conference on Geoparks in Africa and the Middle East, held in 2011 in El Jadida, Morocco.

Ezzoura Errami
African Association of Women in Geosciences
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Preface

The aims of this Special Volume are to provide examples of the valuable geoheritage of countries in Africa and the Middle East, and to document international case studies related to geoheritage, geotourism and geoparks more widely in China, Australia and Europe. The book consists mainly of papers presented at the First International Conference on Geoparks in Africa and the Middle East. The Conference was held in El Jadida (Morocco) from 20 to 28 November 2011 and was organised by the African Association of Women in Geosciences and the African Geoparks Network in collaboration with UNESCO Cairo Office. All manuscripts were reviewed to ensure that they be considered as fully "peer-reviewed scientific papers". In order to allow wider access all the abstracts are translated into Arabic and French.

The book is organized into two parts. Part I, dedicated to the history of Geoheritage, Geoparks and Geotourism, consists of three papers. The paper by Errami et al. gives an overview of the present status of Geoheritage and Geoparks in Africa; Mabvuto Ngwira reviews geotourism and Geoparks with a focus on Africa's current prospects for sustainable rural development and poverty plleviation; and Brocx and Semeniuk provide a brief history of Geology from antiquity to the present day and focus on geoheritage and geoconservation in Britain.

Part II, dedicated to Geoheritage and Geoparks case studies globally, consists of 15 papers. Five of these address the geoheritage of different regions in Morocco. Errami et al. provide an overview of the geological features of the Anti-Atlas region, identifying geosites, Sites of Special Scientific Interest (SSSI) and potential geoparks. Druguet et al. introduce geological features of the geoheritage of the Kerdous Inlier (Western Anti-Atlas, Morocco). Saddiqi et al. recommend two geoheritage trails in Southern Morocco. Enniouar et al. provide an inventory of geosites in the Doukkala-Abda, a region rich in natural heritage, with the aim of making it an important tourist attraction for national and international visitors. Turning to more specific geological features in Morocco, Noubhani describes the late Cretaceous and lower Paleogene phosphate deposits as one of the best examples of the country's geological heritage.

To illustrate the geoheritage potential of Tunisia, Ben Haj Ali et al. take the El Kef region as an example. They illustrate the need to increase the awareness of the local communities and decision makers for the importance of protecting and promoting the nation's geoheritage to enhance local sustainable development. Bendaoud et al. describe the use of websites and GIS databases to compile an inventory and enhance major geosites in Algeria.

Two contributions describe dinosaur footprints and trackways as a key aspect of the geoheritage of northern Africa and the Arabian Peninsula. Chabou et al. describe dinosaur track sites in Algeria as a significant example of the country's national geoheritage that needs urgent protection. The second paper, by Al-Wosabi and Al-Aydrus, outlines the conservation of internationally significant dinosaur footprints in the Arhab Area of Yemen and they propose the creation there of a geopark.

In Cameroon, Zangmo et al. argue that the geomorphological features of the Manengouba Volcano (Cameroon Line) should be viewed and conserved as assets for geotourism and other social and development activities.

Moving away from Africa and the Middle East, other authors provide global case studies. Amorfini et al. outline the geoheritage values of the Apuan Alps geopark in Italy. They describe how to popularise geology through environmental education, publications, websites and partnerships with universities and agencies for research and environmental protection. Zhizhong et al. provide a general overview of the classification and development of geoparks in China. Also in China, Chen et al. describe karst types and present a model on how geoparks are designated in regard to karst features.

Brocx and Semeniuk describe how to use a Geoheritage Tool-kit systematically to compile inventories of the full geodiversity in a given area, taking as examples three areas in Western Australia. Semeniuk et al. describe the microscale geology and micropalaeontology of the Becher Point Cuspate Foreland in Western Australia and highlight the application of the term "geoheritage" at even the small scale.

This book would not be possible without the participation of the contributors. We thank them warmly for their submissions and their patience. Colleagues from various institutions who participated in the review of the papers in the Volume are sincerely thanked for their valuable contribution. Their names are listed below.

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Ezzoura Errami
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الجيوتراث والجيومنتزهات بافريقيا والشرق الأوسط : التحديات والآفاق

Ezzoura Errami, Gabi Schneider, Nasser Ennih, Hasina Nirina Randrianaly, Abderrahmane Bendaoud, Abdelmajid Noubhani, Nick Norman, Mamoon Allan, Lopo Vasconcelos, Luis Costa, Mohammed Al-Wosabi, Abdulkarim Al-Subbary, Percy Mabvuto-Ngwira, Gbenga Okunlola, Salisu Lawal Halliru, Lala Andrianaivo, Sophie Siby, Béatrice Ketchemen, Marcelle Gauly, Mohsen Hassine, Fawaz Azki, Tea Juliette, Kmar Lattrache, Monica Omulo, and Peter Bobrowsky

Abstract

Africa and the Middle East consist of a rich geodiversity, which is regrettably not well known by the public. This is due partly to limited research and studies undertaken in geoheritage and geoconservation in these parts of world, especially those with the intent to explore, inventory and valorize such inherent geodiversity. With the aim to improve this situation, the African Geoparks Network (AGN) was created to increase the awareness of the local population and decision makers regarding the need for sustainable use and management of geoheritage in particular for the benefit of local socio-economic sustainable development targets through the promotion of both geotourism and the creation of unique geoparks.

Résumé

L'Afrique et le Moyen-Orient sont dotés d'une riche géodiversité. Cependant, cette dernière reste mal connue par le grand public. Cette méconnaissance est en partie due au faible nombre d'études et de travaux de recherches sur le géopatrimoine et la géoconservation menés dans

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cette partie du monde, afin d'explorer, de découvrir, d'inventorier et de valoriser cette géodiversité. Pour aider à palier à cette situation, le Réseau Africain des Géoparcs (AGN) a été créé pour sensibiliser la population locale et les décideurs sur la nécessité de l'utilisation durable de leur géopatrimoine pour un développement socio-économique local durable à travers la promotion du géotourisme et la création des géoparcs.

ملخص

تتميز أفريقيا والشرق الأوسط بجيوتنوع غني ليس معروفا لدى الجمهور العام. ويعزى هذا الجهل جزئيا إلى العدد الصغير من الدراسات والأبحاث حول الجيوتراث والجيومحافظة التي أجريت في هذا الجزء من العالم، من أجل استكشاف واكتشاف وجرد وتعزيز هذا الجيوتنوع. و للمساهمة في تحسين هذا الوضع, تم إنشاء الشبكة الأفريقية للجيومنتزهات لتحسيس الساكنة المحلية وصانعي القرار بضرورة الاستخدام الدائم لمواقعهم الجيوتراثية من أجل تنمية سوسيو اقتصادية محلية مستدامة من خلال تعزيز الجيوسياحة وخلق جيومنتزهات.

Keywords

Geoheritage • Geoparks • Africa • Middle-East • African geoparks network

Mots-clés

Géopatrimoine • Géoparcs • Afrique • Moyen-Orient • Réseau africain des géoparcs

الكلمات الرئيسية

جيو تراث • جيومنتزه • افريقيا • الشرق الأوسط • الشبكة الافريقية للجيومنتزهات

1 Introduction

The geological history of the Earth from the Archean to the Quaternary is well inscribed in the rocks and sediments of Africa and the Middle East. Such deposits are very well exposed in spectacular and varied geological landscapes of both areas having being shaped and modified by different orogenies and repetitive processes of deposition and erosion. Many sedimentologic, paleontologic, petrographic and structural features document a variety of Earth historical events that are of exceptional quality in these two regions of the world. Indeed many of the features are quite unique, potentially very educational and warrant attention for conservation and preservation practices that will ensure access to the general public in a manner that is less academic than is now typically examined. Many of these sites are even more attractive as their geographical, historical, architectural and traditional frameworks are truly outstanding.

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Despite the richness and diversity of the geological and geomorphic resources in Africa and Middle East, few studies have actually investigated the different dimensions of geoheritage, geodiversity and geotourism in these regions. A Geoheritage Inventory for Africa and the Middle East is underway, but is still in its early stages (Errami et al. 2013a); nonetheless this effort promises to fill a significant gap in our knowledge base. National inventories are rare and limited to a few initiatives in a handful of countries often as part of geoheritage research activities conducted by national Geological Surveys or local universities. Despite the large number of examples of legislation that is in place which show that most African and the Middle East countries possess laws to protect their cultural and natural heritage, the delay in instituting geoheritage inventories and protection as well as effectively addressing the economic utilization of geoheritage in Africa and the Middle East falls short when compared to other regions of the world.

2 The African Geoparks Network (AGN)

2.1 Introduction

In order to help to improve the situation regarding geoheritage in both Africa and the Middle East, the African Association of Women in Geosciences (AAWG) created the African Geoparks Network (AGN) during the preparatory meeting of its fifth conference entitled "Women and Geosciences for Peace" held in Abidjan, Ivory Coast May 2009 (Errami 2009, 2013). This move proved successful, given widespread support and subsequent adoption of the AGN as an affiliate organization of AAWG.

2.2 AGN Objectives

The aims of AGN include but are not limited to:

(i) Identifying geosites;
(ii) Making an inventory of geosites of outstanding value in Africa and the Middle East;
(iii) Creating and maintaining dynamic GIS data bases;
(iv) Promoting and increasing the awareness amongst policy makers and the general public in Africa and the Middle East, in particular local communities, about the necessity for the protection of and benefits incurred in the utilisation of geological heritage through the creation of geoparks for local socio-economic sustainable development; and
(v) Building the capacity of the local population in the field of geoheritage and geo-conservation through a strong network including the organization of conferences, seminars, symposia, training courses and workshops focussing on the non-professional community.

Such a network can also serve as a platform to share ideas, exchange information on experiences, best practices, new developments and trends in geoheritage and related disciplines. The resulting synergies will benefit sustainable socio-economic development in numerous regions in Africa and Middle East.

2.3 Definition of a Geopark

According to AGN, a geopark is an area where the geoheritage and all heritage components (archaeological, ecological, historical, tangible and intangible cultural elements) should be used as a tool to:

(i) improve the infrastructure of rural areas through the development of geotourism by building roads, creating and improving accommodation, supplying remote areas with electricity and drinking water, creating adequate spaces to sell local products, including the development of museums and cultural/information centres;
(ii) enhance human development; and
(iii) promote sustainable peace in all regions of Africa and the Middle East.

Geoparks, like other managed areas such as biosphere reserves, national parks, and world heritage sites, should be used as space to promote sustainable peace. Local communities should use their territories and become more involved in their development and their protection, and thus benefit directly from the revenues generated by activities conducted, such as geotourism. Geotourism is a form of tourism that sustains and enhances the identity of a territory, taking into consideration its geology, environment, culture, aesthetics, heritage and the well-being of its residents (*Arouca Declaration—International Congress of Geotourism, Arouca Geopark (Portugal), 2011)*. Encouraging the creation of trans-boundary Geoparks in Africa will help address conflicts by empowering local communities from different countries to work together in managing their natural resources, and to accept and manage their differences and diversity. Like other managed natural or cultural areas, Geoparks could be used to promote tolerance and a culture of dialogue between African countries. This could be achieved through the promotion of diversity by encouraging cultural and artistic exchange; by promoting education, science, information sharing and creativity; by participation in effective preservation and enhancement of natural and cultural resources through education and the creation of museums to carry out environmentally friendly and sustainable tourism development; by creating and participating in any action that could improve the well-being of local populations so they can live together in peace and prosperity. In the African context, geoheritage could be used as a tool to reinforce African integration and to promote a South-South dialogue through geotourism and exchange of local products.

A World Bank report published in 2012 states that "African countries are losing out on billions of dollars in potential trade earnings every year because of high trade barriers with neighbouring countries, and that it is easier for Africa to trade with the rest of the world than with itself". Trans-boundary Geoparks like any other managed areas could play a key role to highlight the opportunities for African countries to trade goods, services and investments across borders, they could help to remove barriers to trade in Africa and reinforce African integration. African Geoparks will help to improve local socio-economic sustainable development, especially in areas with a high poverty level, and in areas suffering from the negative effects of climate change.

Geoparks could be also used as an area where best practices in mining governance, such as rehabilitation and economic utilisation of abandoned mines and their geotourism potential, environmental sustainability and social responsibility are actively adopted and demonstrated.

2.4 The AGN Logo

The main languages of the AGN are the most spoken languages of Africa: Arabic, English and French (Fig. 1). Portuguese will soon follow on to the list. In addition, all local languages will be highlighted as a part of the cultural diversity of the continent.

Fig. 1 AGN logo

The green color of the AGN logo relates to peace, which is crucial for any sustainable development on the continent. The AGN and the AAWG strongly believe that the economic utilization of the African natural heritage could play an important role in establishing sustainable peace in the different regions of the continent.

The interconnected circles in the logo represent the network activities which are strengthening African integration which is so crucial for any sustainable development on the continent.

2.5 AGN Activities

AGN is organizing, in collaboration with local, national and international stakeholders, conferences, workshops, roundtables, scientific sessions, meetings with local populations, field trips, multidisciplinary research groups, and geotrails, and promotes them locally.

In 2010, AGN organized a roundtable on geoheritage and Geoparks during the fifth conference of AAWG in Grand Bassam (Côte d'Ivoire), entitled "Women, Geosciences for Peace". As part of this dialogue a visit was organized to the Fresco Escarpment Aspiring Geopark (Fig. 2).

The network organised its first international conference on Geoparks in Africa and Middle East under the title "*Aspiring Geoparks in Africa and Arab World*" from 20th to 28th November 2011 in El Jadida (Morocco) (Errami et al. 2012). The conference with its pre-conference short course and its field trip was the first introduction to representatives from Africa and Middle East countries to the understanding of Geodiversity, Geoconservation and Geoparks (Fig. 3a–c). The event was an opportunity to reflect on the outstanding geological, geomorphological, ecological, cultural and traditional diversity of Africa and the Middle East. Elements which deserve to be preserved, economically utilised, and presented to the public at large in a less academic and more widely accessible manner, in order to make them catalyst for local socio-economical sustainable development. The main targets of the conference were capacity building of participants interested in geoheritage, geoconservation, geotourism and Geoparks, in order to allow them to promote the concept in their respective countries. This contribution and the remainder of this volume is an outcome of that first conference.

As a follow up of the conference, AGN organized in collaboration with other stakeholders a number of workshops, meetings, roundtables, field trips, and presentations, in numerous countries (Morocco, Tunisia, Senegal, Cameroon, Lebanon, Ethiopia, Nigeria, Ivory Coast, and Madagascar). Presentations of AGN and its activities were given in and outside Africa (Ghana, UK, Portugal, France, Turkey, Italy and Iran).

Fig. 2 Visit to the Fresco Escarpment Aspiring Geopark (Côte d'Ivoire)

In 2012, a workshop was organized in Dakar (Senegal) in parallel with the International Mine Salon (Fig. 4a–d). In addition, three meetings in Tunisia (Fig. 5), various meetings in Morocco (Fig. 6), a scientific session during the 6th Conference of the AAWG meeting held in Yaounde (Cameroon), and participation in a scientific session on geoheritage and co-organisation of a workshop and a roundtable during the 24th Colloquium of African Geology held in Addis Ababa (Ethiopia), were further activities.

The second international conference on Geoparks in Africa and the Middle East is being organized in Dakar (Senegal) in 2014 under the title "Geoheritage in the service of local sustainable development".

2.6 Day of Earth Sciences in Africa and Middle East

To achieve their objectives, in 2013 AAWG and AGN proclaimed the 20th of March as a "Day for Earth Sciences in Africa and the Middle East, DESAME". This initiative aims to promote earth sciences for society and to increase the awareness about the role that earth scientists can play to help in building a peaceful, healthier and wealthier continent.

The 20th of March was chosen because equinoxes have long been celebrated in cultures all over the world as a sign of respect for our planet Earth. In the northern hemisphere the March equinox marks the start of spring and has long been celebrated as a time of rebirth. The 20th of March is generally viewed as corresponding to the time where night and day are nearly of the same length all over the world. However, even if this is widely accepted, it isn't entirely true. The March equinox occurs at the moment the sun crosses the celestial equator from south to north. This happens either on March 19, 20 or 21 every year. In that way, the activities, related to the DESAME, can be extended to 19th and 21st March.

The DESAME is supported by the Geological Society of Africa (GSA*f*), the Society of African Earth Scientists (SAES), the International Association to Promote Geoethic (IAPG), the International Association of Geoethics (IAGETH), the ArabGU, the YES Network, the Research Group on Geodynamics, Geoeducation and Geoheritage (EGGPG) of the Faculty of Sciences of El Jadida (Morocco), G.C.E.E.M (Romania), Azki Geological Museum (Syria) and many national organizations, institutions, and local governments, such as the Faculty of Sciences and the Chouaïb Doukkali University (El Jadida, Morocco), the municipal Council of Ben Guerrir (Morocco), the Center for Education and Leadership Development (CELDEV) of Kano (Nigeria), El Manar Tunis University (Tunisia), the National Agency of Applied Scientific Research (ANSRA) (Senegal), the Ministry of Higher Education and Research (Senegal), Cheikh Anta Diop University (Senegal), Institutul Geologic al Romaniei (Romania), the Al Hoda Association (Morocco), the Centre for Research and African Documentation

Fig. 3 First international conference on Geoparks in Africa and Middle East, 20–28 November 2011. **a** Participants to the conference pre-course. **b** Opening ceremony. **c** Participants to the post-conference field trip

(CERDAF) (Bukavu, RDC) and the Geological Mining Association of Mozambique (AGMM).

The day was first celebrated in 2013 in five countries (Morocco, Nigeria, Senegal, Tunisia and Romania), where workshops, conferences, exhibitions and field trips were organized (Fig. 7a–e). In 2014, the day was celebrated under the theme “Geoeducation, Geoheritage and Peace building in Africa and Middle East”.

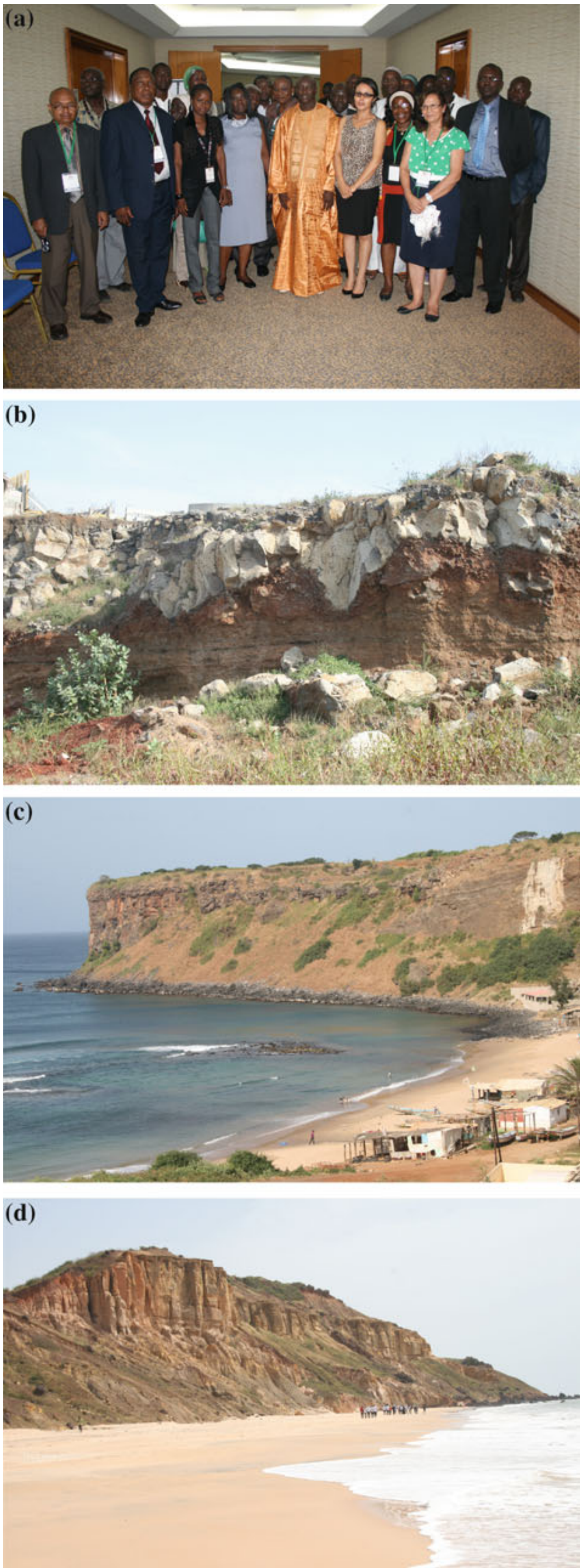
3 National and Regional Activities

3.1 Morocco

Bordered to the north by the Mediterranean Sea and to the west by the Atlantic Ocean, Morocco supports a diverse geography and climate, from the temperate Rif in the north, to the Sahara desert in the south, and possesses a rich bio and geodiversity with varied landscapes. Pioneering French geoscientists described the country as a “Paradise for geologists”. Moroccan geoheritage spans for more than 2,700 Ma from the Archaean to the Quaternary. The mainly arid and semi-arid climate of Morocco has contributed to the development and preservation of excellent exposures of many of these features. The paleontological record of Morocco has yielded fossils of many kinds throughout nearly all geological periods, including dinosaurs, trilobites, cephalopods (Orthoceras, goniatites and ammonites), Devonian and Liassic reefs and human fossil remains such as *Homo erectus and* modern *Homo*.

The geostrategic position of Morocco, at the juncture of Africa and Europe, makes it a land where many civilizations have met through time leaving as witness archaeological evidence of outstanding value. The Moroccan geodiversity is thus even more attractive as it is related to exceptional historical, archaeological, architectural, cultural and traditional frames which vary with the range of its geodiversity.

Morocco has long recognized the value of this heritage and, since the beginning of the 20th century, has introduced national legislation for the protection and the conservation of its natural and cultural heritage. The Cherifian Dahir of the 29th November 1912, related to the conservation of historic monuments and historical inscriptions, was the starting point of this policy. Since then, significant changes and modifications have been made to the legislation, and Morocco has ratified most of the conventions relating to cultural and natural heritage at regional and international levels (Kassou 2012). However, Morocco does not have any laws to protect its



◀ **Fig. 4** Workshop to launch the geoparks initiative in Senegal (**a**) and some visited geosites during the related field trip: the “Mamelles” recent volcanism (**b** and **c**) and the Popenguine Escarpment (**d**). Dakar, the 7th and 9th November 2012

Fig. 5 Meetings in Tunisia, with local population during the visit of the Zaghouan aspiring geoparks (**a**) and with representatives of the Geological Survey (**b**)

geoheritage, especially its fossiliferous sites, that are of global interest and need to be preserved, for example those of the Palaeozoic of southeast Morocco, such as the Erfoud and Tazarine areas, which are being overexploited either as ornamental rocks or as rare specimens that are sold for private collections (Errami et al. 2008, 2013a; El Hadi et al. 2011) (Fig. 8). These sites are at risk of irreparable destruction. It is important to note that the geoheritage inventory in Morocco is still in its early stages, despite some localized endeavors by earth scientists resident in universities.

Morocco has nonetheless created its first geopark and the first in Africa and Middle-East, M'Goun geopark, in 2004 in the Central High Atlas mountains. The geological history of the territory goes back to the Triassic (250 Ma ago) and is mainly characterized by dinosaur remains and footprints.

Three other geoparks projects are in progress:

(1) The Doukkala-Abda aspiring geopark is located in the northwestern part of central Morocco and is characterized by a varied and rich natural heritage, which includes geomorphological, geological and cultural features (Fig. 9a, b). Its biodiversity and geodiversity and significant geotouristic potential offer the prospect of cultural geotrails for both education and tourism (Errami et al. 2013b; Ennouar et al. this volume).

Fig. 6 Meeting with local associations and decisions makers of the Tazenakht aspiring geopark (Zenaga inlier, Central Anti-Atlas, Morocco

Fig. 7 Celebrated of the day of earth sciences in Africa and Middle East in Nigeria (**a**), Morocco (**b**1–**b**5), Senegal (**c**), Tunisia (**d**) and in Romania (**e**)

(2) The Tazenakht aspiring geopark consists of the Zenaga Precambian inlier and its Palaeozoic sedimentary cover. The Zenaga inlier, located in the central Anti-Atlas, represents the northern margin of the WAC. The area is a good example of an ensemble of geological features that have a regionally important geological story and geodiversity (Errami et al. 2013c; Errami et al. this volume). It is limited to the North by the Major Anti-Atlas Fault which represents classically the Pan-African paleosuture underlain by ophiolitic complexes in the Bou-Azzer and Siroua surrounding inliers. It consists mainly of a Paleoproterozoic basement. All these formations are crosscut by pre-Pan African basic dykes. Within the inlier and along its margins, there are a

Fig. 7 continued

number of key geosites that exhibit lithological and structural features within the Precambrian inlier, and its relationship of to the surrounding geology (Fig. 10a–d).

(3) The third candidate area focuses on the end-Cretaceous and lower-Paleogene marine phosphates deposits, which are globally known by their fossil richness representing several vertebrate groups (Noubhani this volume). Apart from the Selachians' fishes (sharks and rays), whose teeth are collected by millions, several groups are present; these deposits comprise: (i) Well represented reptiles with approximately 50 species divided between turtles, squamates (snakes, Rage and Wouters 1979), crocodiles (Arambourg 1952; Jouve 2004; Jouve et al. 2005), sauropods (Pereda Suberbiola et al. 2004), plesiosaurs and elasmosaurs (Vincent et al. 2011), mosasaurs (Bardet et al. 2004, 2005), and pterosaurs (Pereda Suberbiola et al. 2003); (ii) Birds with five species that may be the oldest modern seabirds in Africa (Bourdon 2006, 2011), and (iii) Mammals with about ten species belonging to the orders of Proboscideans, Hyaenodontids, Hyracoids and Condylarths, which might be among the oldest placental mammals of Africa and the oldest modern ungulates known in the world.

The collections made by the cooperative excavations' work of the local populations, will be exhibited in the planned "Museum of Paleontology". Together with the natural beauty of the landscape, including geological sections presenting a panoramic view of the lithology and the stratigraphy of the phosphate series.

To promote and preserve a part of its geoheritage, Morocco is creating geological museums. The first one was launched in 2013 at the University of Fez. Two other museums are in progress, one focused on Dinosaurs in Tazouda (southern Morocco) and the other in Mgoun Geopark.

3.2 Algeria

In Algeria, the geoheritage is theoretically protected by legislation related to various areas (environment, urban planning, rural development, coastal protection), and as a component of the natural heritage (Bouzidi and Rabhi 2011). Several national parks support a remarkable wealth of geological sites (Fig. 11a–c), including biodiversity and archaeology such as Hoggar, Tassili and Taza which consist of structures for which the primary mission is to ensure their preservation (e.g., Ahaggar National Park Office and Tassili National Park Office) (Fig. 11a–c). Some sites were classified, by order of the Minister of Energy and Mines, solely because of their geological heritage, such as the bio-clastic limestone slab known as the Great Wall of China that

Fig. 7 continued

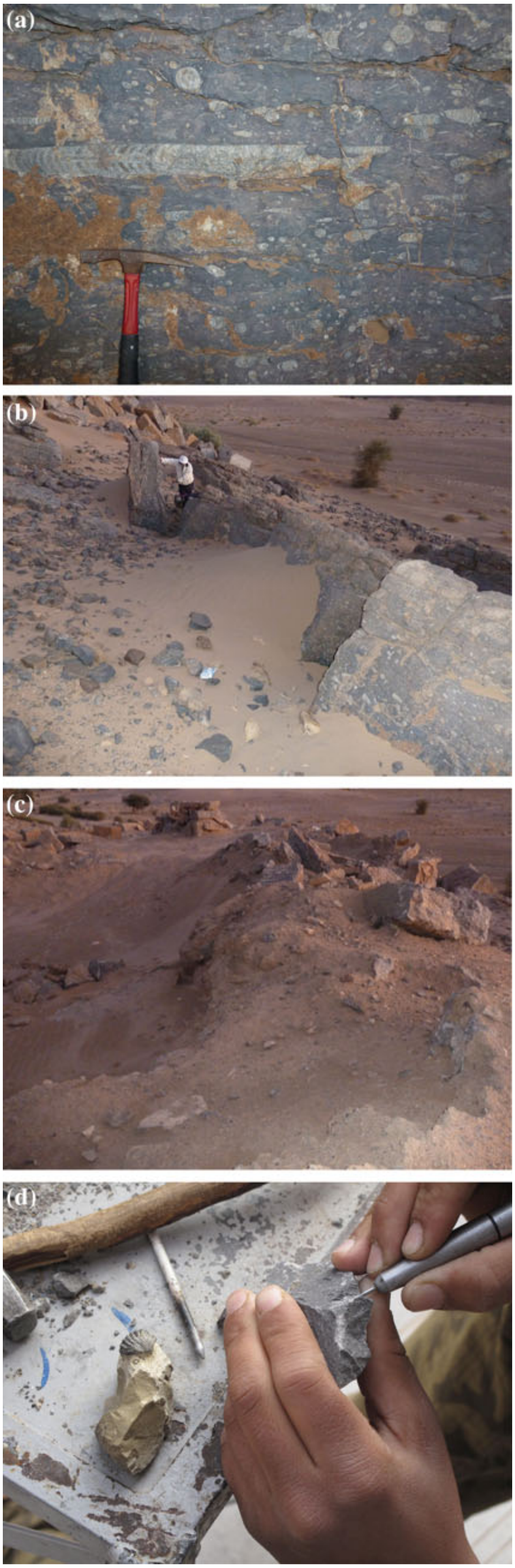


Fig. 8 **a**–**e** Fossiliferous sites of Erfoud and Tazarine areas, which are being overexploited either as ornamental rocks or as rare specimens sold for private collections

Fig. 8 continued

includes giant Devonian *Orthoceras*, trilobites, bivalves and some placoderm (battleships fish) fragments.

3.3 Namibia

Namibia has a good inventory of its geological heritage (Schneider 2003). Information on Namibia's geoheritage has been maintained for many years at the Geological Survey of Namibia, and includes magmatic structures such as the Brandberg, the Dolerite Hills, the Etendeka Plateau, the Erongo, Messum, the Organ Pipes, and the Spitzkuppe, sedimentary structures such as Burnt Mountain, Dieprivier, the Gamsberg, Mount Etjo, Mukorob, the Omatako Mountains, the Sesriem Canyon, the Fingerklip and the Waterberg; landscapes such as Etosha Pan, the Kalahari, the Namib Desert, the Naukluft, and Sossusvlei and Tsondabvlei; canyons such as the Fishriver Canyon and the Kuiseb Canyon; karst structures such as Lake Otjikoto and Lake Guinas, palaeontological sites such as the Dinosaur footprints at Otjihaenamaparero and the Petrified Forest; and meteorites such as the Hoba Meteorite and the Gibeon Meteorite shower. In addition, the historic diamond mining village of Kolmanskuppe is considered to be of significance as industrial heritage.

Fig. 9 **a** *Panoramic view* of Sidi Said Maachou Basin and **b** Boulaouane geosite with its Kasbah (Doukkala-Abda aspiring geopark, Morocco)

The National Heritage Act (Act No 27 of 2004) makes provision for the establishment of a heritage register, and puts all paleontological objects as well as meteorites under protection as national heritage objects. A number of the sites listed above are proclaimed National Heritage Sites, and the Namibia Desert has been proclaimed a World Heritage Site in 2013.

Namibia is also in the process of establishing its first Geopark, the Gondwana Geopark in the central western part of the country (Schneider and Schneider 2005). This area comprises a complete geological record of the time from the formation of Gondwanaland to its break-up, hence the name. It represents also the densest cluster of geoheritage sites in Namibia. A management plan is already in place, as well as a design for a visitor´s centre and promotional and educational material. Proclamation is envisaged after relevant legislation will have been passed.

3.4 South Africa

In 1999, the South African government established the "South African Heritage Resources Agency" (SAHRA), with the main mission to promote the proper management of cultural heritage of significance and with a particular value for the community and for future generations. These assets are regarded as national assets and may include landscapes and natural elements of cultural, geological and scientific

importance, sites of paleontological and archaeological importance, objects of South African collections including archaeological and paleontological objects, meteorites and rare geological specimens (Errami et al. 2013a). South Africa is well endowed not only with extraordinary mineral deposits, but also with geological resources which are of great value for their contribution to the geoheritage base of the country. There are a number of cases where these assets are grouped in such a way that they could be assembled into coherent packages suitable for geoparks of exceptional interest value. One example of such a cluster is the Pretoria-Johannesburg area where, within a circle of 100 km diameter, lie the:

- Tswaing meteorite crater, an exceptionally well-preserved feature;
- world-renowned Cradle of Humankind, with its uniquely important palaeo-anthropological legacy and world-class museum;
- discovery site of the Witwatersrand gold fields, a mineral field of unequalled value in mining history; and
- Cullinan (formerly Premier) Diamond mine, producer of many celebrated diamonds, including the 3,106 carat Cullinan diamond, largest gem ever found, and a number of other extraordinary geological phenomena.

In the Eastern Cape Graaff-Reinet is a treasure trove of Permian mammal-like reptile fossils of unequalled richness, and north of Cape Town, the West Coast Fossil Park is a lagerstätte of Miocene life visited by palaeontologists from around the world (Fig. 12a, b). The Barberton Mountainland, a deeply dissected and easily accessible terrain, offers exposure of Archaean geology that has afforded geologists the opportunity to assemble a more detailed reconstruction of the earliest days of our planet than has been possible anywhere else on Earth. And the Bushveld Complex is a phenomenon of igneous geology that has fascinated geologists, both economic and academic, for nearly a 100 years and continues to do so. It is not unreasonable to suppose that within a few years, when the administrative structures are in place, South Africa will be contributing generously to AGN's portfolio.

3.5 Madagascar

Madagascar consists of a rich geodiversity and paleodiversity that remain unknown to the local authorities and the public (Krause et al. 2006; Raharimahefa 2012) (Fig. 13a, b). To improve this situation, Madagascar had started to

◀ **Fig. 10** *Panoramic views* of the Tazenakht aspiring geopark (Zenaga inlier, Central Anti-Atlas, Morocco) (**a** and **b**). Didactic unconformities between the Palaeoproterozoic basement and the late Neoproterozoic (**c**) and between the late Neoproterozoic and the early Cambrian formations (**d**) (Tazenakht aspiring geopark, Zenaga inlier, Central Anti-Atlas, Morocco)

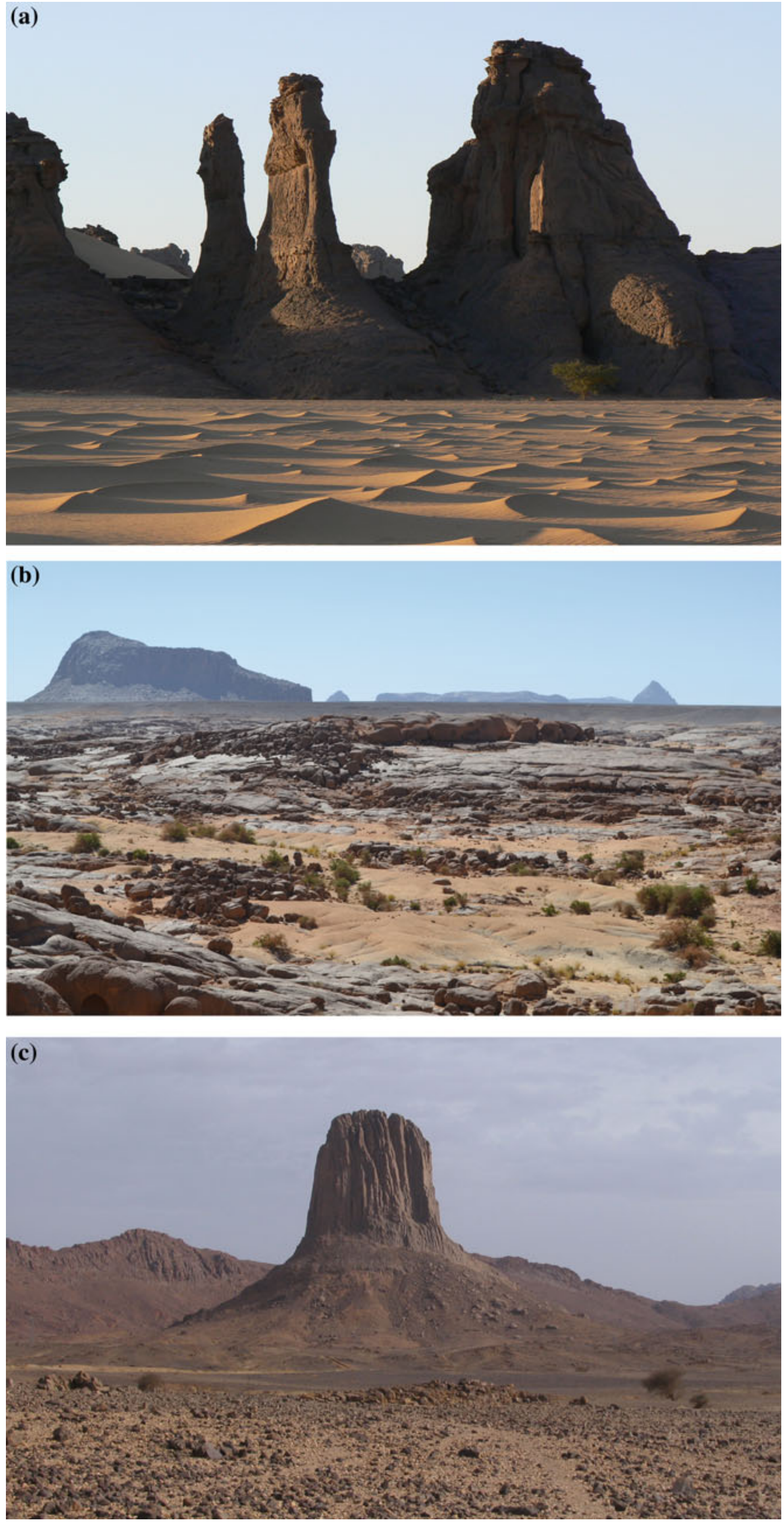


Fig. 11 Tassili sandstone sculptured by wind (**a**), granitic and volcanic landscape of Hoggar (**b**), Volcanism in the Natural Park of Hoggar (**c**)

Fig. 12 **a** Fossil dig site at WCFP with riverside scene. **b** Sivatherium hendeyi lower jaw of sub adult. West Coast Fossil Park (South Africa)

initiate the creation of Geoparks in current protected areas already managed by the Madagascar National Parks (MNP) (Raharimahefa 2012). Under the supervision of the Ministry of Environment and Forests (MEF), MNP is an association of private partners that are recognized to be of public utility. It assures the management of the national network of the national parks and reserves of Madagascar (2011).

The splendor and the richness of geoheritage coexist with the high endemic biodiversity (e.g. the botanic garden in the massif ruiniform of Isalo Park (Fig. 13c) and the cave with Bats of Ankarana). The valorization of geoheritage will improve the promotion of tourism, thus providing another way to alleviate poverty in Madagascar.

Due to the poverty, and in spite of efforts of rising the awareness done by MNP, the local communities continue to ignore the importance and the significance of the natural heritage. For example, the Isalo National park area and its vicinity are under human pressure due to grazing, burning and forest clearing (Świerkosz 2007). Fossils (vertebrate and invertebrate) are big part of the nonrenewable resources. These are currently being lost due to illegal commercial exploitation (Krause et al. 2006).

In spite of these dangers threatening the natural heritage in Isalo National Park and taking in account that it is the most visited area in Madagascar, it has been adopted as a pilot site for the establishment of a Geopark. The expectation is to start the geosite inventory and increase the awareness of the local population through education.

3.6 Mozambique

Mozambique does not have a specific legislation concerning geoheritage, geoparks and/or geosites. However, in 2005–2007, the Mozambican National Museum of Geology proposed a project aiming at developing the field of geoheritage in the country. For that, one of its staff members pursued a post-graduate term at Minho University (Portugal) on Geoheritage (Cumbe 2007). He later presented a report on the Mozambican Geoheritage, describing various sites that should be considered for preservation (Cumbe 2011). In the same year, a graduation thesis on the geoheritage of Maputo Province was defended (Madeira 2011).

Presently some activities are underway to create (i) the Geological Parks of Chitima (Fig. 14a) and Gorongosa Mountain, and (ii) the Geosites of the Cheringoma Caves, the columnar basalts of Lebombo Range, and the Karoo area in Niassa Province where a new species of fossil has been recently described (Castanhinha et al. 2013). Other proposals, such as the Boane Formation (Fig. 14b), are under discussion including the creation of a center for developing paleontology and conservation.

3.7 Nigeria

Bordered to the south by the Atlantic Ocean and the north by the Sahel and the Sahara deserts, Nigeria presents a unique geography and climate, from the humid wet in the south to the dry sometimes hazy but soothing climate in the north.

Nigerian heritage spans for more than 3,000 Ma from the Archean to the Quaternary resulting in the picturesque landscape of Precambrian rocks derived luscious inselbergs. Notably, the human faced (exfoliated) carved Zuma rock of the Suleja area, close to the Federal Capital, to the Luscious Olumo batholiths in the south west, and the Cretaceous to Jurassic Younger Granites ring complex defining the plateau. The most prominent of such anorogenic ring like dykes in the world. It also comes with an admixture of semi temperate/tropical weather carved (denudated) rocks such as the 'Gog and Magog' rock.

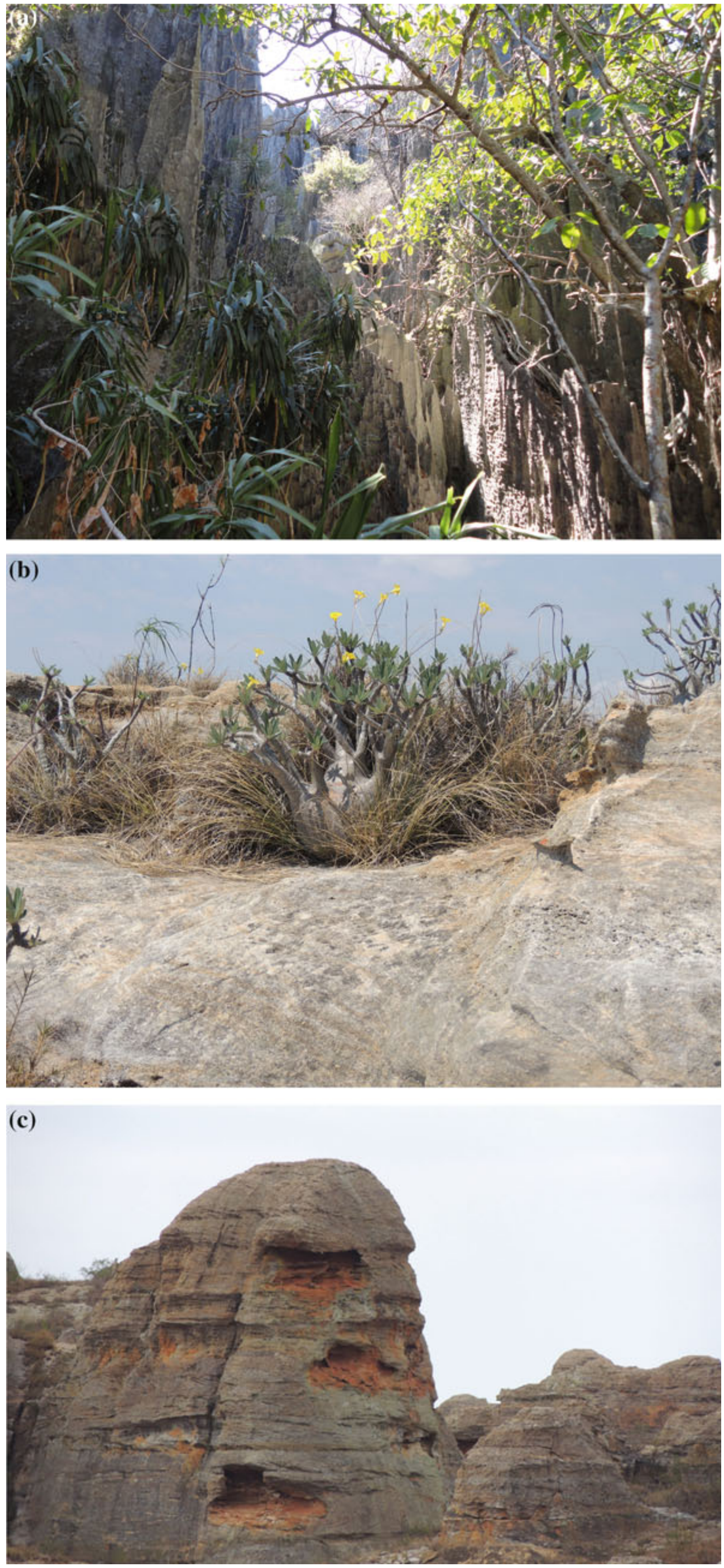


Fig. 13 The Tsingy (**a**) and the Flora (Pachypodium) (**a**) in the Park of Bemaraha (Northern Madagascar). The Tsingy, characterized by sharp *peaks* resulting from limestone erosion, are linked in the local culture to the world of spirits and ancestors. **c** Isalo Massif ruiniform (Southern Madagascar) is a continental sandstone strongly eroded by wind and water

Fig. 14 **a** The Chitima Fossil Forest (Carangache area) has an area of about 18 km^2 (6 × 3 km^2) and contains a high concentration of laying silicified trunks, with a maximum length of 17 m (the unearthed part) with diameters varying up to 0.80 m (Ferrara 2004). **b** The Boane Formation occurs in small polygons in the southern Mozambique, and the type location is near the railway bridge south of Boane village (at the coordinates 26° 3′8.44″S/32°19′34.95″E). The outcrop is a cliff of ca 20 m high, composed of ferruginous siltstones and sandstones. The *image* shows cross-bedding and slumping structures. The age is supposed to be Paleocene (GTK 2006)

With such a long geological history, the resulting intensive tectonism, fractures, folds and shears have brought up scenic waterfalls, (about 15 of them have been identified) in all the six geopolitical zones with the most famous being the 55 m Assop falls near Jos plateau in central plateau area, Erin Ijesa in the south west (45 m), the Arinja falls (50 m) also in the south west.

The fractured controlled Ikogosi heritage sites where the unique warm and cold spring flowing convergently, meets at a spot creating a luke warm spring that had been judged medicinal by the locals. It is a unique geosciences heritage that had been developed and designated into a park. Where world class chalets, roads and even a natural water bottling firm had been established attracting tourists and developing the economy of the local community immensely.

A similar one is also in the Bauchi (Yankari) park in the north western parts where the warm springs had served as a swimming and medicinal water bath for tourists. This had also been developed in addition to the diversified games that had made it a compulsory geo and games reserve park.

The famous confluence of the river Niger which has flowed through five African countries and the Benue River at Lokoja is also a developing geosite. This confluence is arguably the biggest confluence of rivers in the West African sub region creating a flat scenic inland beach that is unique. The State government of Kogi state had been developing the site into a full geoheritage sites complete with tourist chalets boat ways and annual regatta.

Other geomorphic based sites such as the sandstone Ogbunike caves of about 200 m in length in the south east, the Osun grove, which had since been declared a World Heritage site since 2006, is also a remarkable archaeological/geomorphic geosite. This site is developed around the mythical Osun river, a tributary of the River Niger with its grove like forest and scenic stone carvings made more popular by the late Austrian artist Susan Wenger.

Rock paintings sites dating back to about 20,000 years are also being developed in the Birni kudu rocks of kebbi state.

Efforts are being made through statutory declarations of the Tourism acts to preserve and promote these geosites as the Government at different levels are getting aware of the social cultural and importantly the economic benefits of these sites by the Governments at different levels. The main challenge is the political will to implement the statutes designated for the preservation and promotion of the sites.

The Nigerian geological Survey agency has commenced making concrete attempts to compile and study these potential sites with a view to promoting and preserving them.

3.8 Jordan

Jordan has varied and rich geological and geomorphic features (Allan 2012). It has the lowest point on the earth at—400 m below the sea surface (Jica and Mota 1996). It also has a high quality, varied and abundant biodiversity. Most geosites have the possibility of linking the geology to the historical, cultural and archeological heritages. It has many sacred geosites. In 2014, Jordan is working to set up its first geopark in Wadi Al Mujib based upon its geological rich diversity, which extends from the Precambrian to Quaternary. The 66 km^2 proposed park meets the scientific requirements in terms of rarity, outstanding scientific value and beauty. However, the geoheritage and geosites in Jordan have confronted many barriers, such as the accessibility and infrastructure issues, the lack of awareness and information about the local geoheritage and its value, the interpretation issues, and the lack of sustainability of geoheritage.

3.9 Yemen

Yemen is a very rich country in geological and cultural diversities; the geology of Yemen comprises a number of geoheritage and geotourist sites of special scientific importance, rarity and beauty, and may not be solely of geological significance but also of archaeological, ecological, historical and cultural value. There is no doubt that geoconservation of the geological heritage and care of the geotourism could play a vital role in the socio-economic development of the country, where we have noticed recently the deterioration of important geological heritage, for example Protected Natural areas such as Socotra Island and Bura'a mountains, in addition to the caves, high mountain ranges, and remarkable geological features such as ancient pillow lavas, dinosaur foot prints, lava flows, glacial and polygonal structures, silicified wood, and other landscapes and ancient structures such as Marib dam pay tribute to the magnificent feat of early engineering and masonry techniques.

Yemen is facing challenges, because understanding and awareness of geodiversity and geoconservation is limited, and may be virtually non-existent. On the other hand, there is lack of inventories of features of geological interest (geosites) developed with scientific rigor. Many relevant sites of high geological value hold no protection at all. In most cases, there is no adequate geological conservation strategy being taken by the government who are responsible for the implementation of nature conservation policies. The non-existence of a systematic inventory of the geological heritage and its adequate management may lead to the definitive destruction of geosites with its scientific importance and with its national and international relevance.

Important to these, there is an urgent requirement to develop a database to describe and record all preserved geological features of Yemen, which will help to conserve the geological heritage and improve the geotourism of Yemen. Initiation of this work is immense and will lead us to establish a Geopark in Yemen in near future.

4 Conclusion

In summary, Africa and the Middle East countries have started to pay more attention to the significance of their geoheritage and geodiversity. Some notable developments related to geoconservation and geotourism have occurred in both regions. The link of geoheritage to local socio-economic sustainable development through the promotion of geotourism within geoparks will help to increase the awareness of the local population and decision makers about the necessity of sustainable use of their geoheritage assets in economic and social dynamics. In the absence of a legislation that allows the inventory, the conservation and the economic utilization of geological sites in Africa and the Middle East, the creation of geoparks could be an opportunity to establish a local inventory and to institute local laws to protect geoheritage of different regions in Africa. Protection of geoheritage within geoparks should further be done through the education of the local population.

AGN in collaboration with AAWG and many local stakeholders is creating the first African geoparks in different countries. Many projects are in progress.

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Geotourism and Geoparks: Africa's Current Prospects for Sustainable Rural Development and Poverty Alleviation

Géotourisme et géoparcs: perspectives contemporaines pour le développement rural durable et la réduction de la pauvreté en Afrique

جيوسياحة وجيومنتزهات : وجهات نظر معاصرة من أجل تنمية قروية مستدامة والتخفيف من الفقر بافريقيا

Percy Mabvuto Ngwira

Abstract

Geotourism is a relatively new type of tourism with significant growth potential. Initially defined in Europe, USA and Australia, it is an international developing academic, economic and sustainable rural development investigation field. The term geotourism has been in use since the early 1990s, although its precursor activities can be traced back to the 17th century. Benefiting from its significant social, historical and industrial archaeological underpinnings, the concept is still undergoing redefinition and refinement. This paper explores current literature on geotourism and geoparks in relation to sustainable development in Africa. Furthermore, it explores current literature on the direct and indirect sustainable development impacts from geotourism and geoparks, and their implications on social, environmental and economic development on rural communities. The literature has shown that these concepts, relatively new in Africa, present essential credentials for poverty alleviation and sustainable rural development on the continent.

Résumé

Le géotourisme est un type de tourisme relativement nouveau avec un potentiel de croissance significatif. Initialement développé et défini en Europe, aux Etats-Unis d'Amérique et en Australie, c'est un domaine de recherche, académique, économique, et de développement rural durable, en développement. Le terme géotourisme est utilisé depuis le début des années 1990, bien que ses activités précurseurs remontent au 17ème siècle. Bénéficiant de ses fondements sociaux, historiques et archéologiques industriels significatifs, ce concept est encore en cours de redéfinition. Cet article explore la littérature actuelle sur le géotourisme et les géoparcs et leurs impacts sur le développement social, environnemental et économique des communautés rurales. Il montre que ces concepts, relativement nouveaux en Afrique, présenteraient des atouts essentiels pour le développement rural durable et la réduction de la pauvreté sur le continent.

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ملخص

الجيوسياحة هي نوع من السياحة جديدٌ نسبيا، بإمكانات نمو كبيرة. تم أولا التعريف بها وتطويرها بأوروبا، الولايات المتحدة الأمريكية و أستراليا، وهي مجال، في طور النمو، للبحث الأكاديمي، الاقتصادي والتنمية القروية المستدامة. لقد استخدمت كلمة جيوسياحة منذ مطلع سنة 1990، على الرغم من أن أنشطتها الرائدة تعود إلى القرن السابع عشر. مستفيدة من أسسها الاجتماعية،التاريخية وآثارها الصناعية الهامة، فإن هذا المفهوم لا يزال قَيْدَ إعادة التعريف.هذا المقال يستطلع المؤلفات الحالية حول الجيوسياحة والجيومنتزهات وآثارها على التنمية الاجتماعية، البيئية والاقتصادية للمجتمعات القروية. فهو يظهر بأن هذه المفاهيم، الجديدة نسبيا بافريقيا، ستقدم مؤهلات أساسية للتنمية القروية المستدامة والتخفيف من الفقر بالقارة.

Keywords

Geotourism • Geoparks • Africa • Sustainable and rural development

Mots-clés

Géotourisme • Géoparcs • Afrique • Développement rural et durables

الكلمات الرئيسية

جيوسياحة • جيومنتزهات • أفريقيا • تنمية قروية مستدامة

1 Introduction

Geotourism, or tourism related to geological sites and features, including geomorphological sites and landscapes, can be seen as a relatively new phenomenon (Dowling 2009a) and a subgroup of geology and tourism. Though still in infancy stage and emerging as tourism niche markets awaiting further development and commercialisation, geotourism and geoparks have been credited as tools for rural development, local community participation and poverty alleviation. It is noteworthy that through involving local communities in innovative strategies and geomarketing, such as creating geotours, geoproducts, geomuseums, geotourism and geoparks try to promote the local economy and public knowledge about geology (Farsani et al. 2010).

Moreover, promoters of geotourism and geoparks engage local people in conservation activities, education and tourism development. According to the European Geoparks Network (EGN) charter and Global Geopark Network regulations, all geoparks have to be established in rural areas. Therefore, geotourism and geoparks are opportunities for rural development, and they contribute to efforts in alleviating poverty, unemployment and migration to urban areas.

Thus far the concepts of geotourism and geoparks play an important role in local economic development and sustainable rural development, by increasing the number of tourists. They have to support the establishment of local crafts and replicas, as well as support local products. Consequently, visitors to geoparks can actually take with them, together with emotions and knowledge, locally manufactured goods (Frey et al. 2006). This paper focuses on a review of the contemporary prospects of geotourism and geoparks for sustainable rural and economic development.

Key findings show that the concepts of Geotourism and Geoparks are relatively new but, since they are both opportunities for rural community development, they present essential credentials for poverty alleviation and sustainable development in Africa. The other key finding is that geotourism and geoparks are new phenomena with limited data—further research is needed to improve the understanding of their capabilities, especially in Africa.

2 Geotourism and Geoparks—A Review

2.1 Geotourism and Sustainability

The roots of geotourism can be traced as far back as 1956 when one pioneer of Italian geology, Michele Gortani, stated that; "to the geologist's mind, the landscape comes alive and talks. Every stone, every form of coast or mountain or valley tells its story, evoking the vicissitudes of its history and it's becoming" (Neto de Carvalho and Rodrigues 2009). Hose (1995) documents that the geotourism concept was developed and promoted from the early 1990s onwards. Joyce (2006) argues that geotourism is a relatively neoteric term not yet appearing in dictionaries. It can be seen as an augmentation of tourism generally and parallel to ecotourism in particular. Perhaps geotourism is looking back to the 18th century Grand Tour, the aims of which were learning, education and self-improvement. Joyce (2006) adds that "Geotourism, or tourism related to geological sites and features, can be seen as an innovative phenomenon". National Geographical Centre for Sustainable Development defines geotourism as "Tourism that sustains or enhances the geographical characters of a place, its environment, heritage, aesthetic, culture, and the well-being of its residents". In presenting this definition, National Geographic sparks a debate on whether "geo" means geographical or geological. Joyce (2006) contends that the definition of geotourism needs to be explored further; as a contemporary concept, geotourism draws on both geology and tourism. He provides a working definition for geotourism in his paper as "Geotourism could be people going to a place to look at and learn about one or more aspects of geology and geomorphology". Coenraads and Koivula (2007) view geotourism as having the same objectives as ecotourism, but particularly seeks to explain the beauty and origins of the Earth, all landscapes, landforms, plants and animals.

According to Dowling (2010), geotourism is a form of natural area tourism that specifically focuses on geology and landscape. It promotes tourism to geosites and the conservation of geodiversity and an understanding of the Earth Sciences through appreciation and learning. Dowling outlines geotourism characteristics which are, that while geotourism is geologically based, it can occur in natural, rural or urban environments; it fosters geoheritage conservation through appropriate sustainability measures, it promotes sound geological understanding through interpretation and education, and it generates tourist or visitor satisfaction. Like ecotourism, geotourism promotes a virtual circle whereby tourism revenues provide a local incentive to protect what tourists are coming to see, but extends the principle beyond nature and ecology to incorporate all characteristics that contribute to a "sense of place". It incorporates sustainability principles, but in addition to the do-no-harm ethic, geotourism focuses on the place as a whole.

"Geotourism" has emerged as a much talked about topic that is frequently linked to the term "sustainable tourism" (Farsani et al. 2009). It is a developing segment of tourism based on geodiversity. People have always travelled to appreciate the geological wonders of this world, but it is only now that many people are giving it much more attention. Geotourism is creating a fresh niche in the tourism sector with fresh specificities and different contingencies that follow the general trends of tourism, but also has its own trends (Rodrigues and Carvalho 2009). Dowling (2009a) states that geotourism, as an emerging global phenomenon, is sustainable with initial focus on experiencing the Earth's geological features in ways that encourages environmental and cultural understanding, appreciation and conservation, and is locally beneficial. It promotes tourism to geosites and the conservation of geodiversity, and an understanding of Earth Sciences through appreciation and learning. This is achieved through independent visits to geological features, use of geotrails and viewpoints, guided tours, geo-activities and patronage of geosite visitor centres.

Geotourism complements scenic beauty with the revelation of how these geological features were formed (Robinson and Roots 2008). It has become a unique market segment in tourism centred on sustaining and enhancing the geological and geographical character of a place (Stokes et al. 2003). Dowling (2009a) views geotourism as having a number of interrelated components, all of which should be present for authentic geotourism to occur. There are five fundamental principles: 1. geotourism is geologically-based (that is, based on the Earth's heritage); 2. It is sustainable (i.e., economically viable, community enhancing and fosters geoconservation); 3. It is educational (achieved through geo-interpretation); 4. It is locally beneficial; and 5. It generates tourist satisfaction. The first three characteristics are considered to be essential for a product to be considered 'geotourism' while the last two characteristics are viewed as being desirable for all forms of tourism.

In relation to the concept of geotourism; sustainable (tourism) development is the main reason for the stimulation of geotourism. Mitchell (1989) documents that, from a geographical point of view, sustainable development can be traced to the time of Marsh when geographers started influencing the course of natural resource management in several ways. Hall and Lew (1998) supports Mitchell stating that geographers have been interested in the appropriate use of the physical environment by human-kind since the middle 19th century, and have also served to chart the history of environmental attitudes in Western and other societies. Mitchell (1989) identified some major contributions of geographers to the study of tourism with respect to environmentally, regionally, spatially, and evolutionarily. Indisputably, these four areas are of considerable importance to geographers and geologists. Uncertainties about the relationship between tourism and the physical and social environment, particularly with respect to such notions as carrying capacity, have been at the forefront of much geographical and geological study.

As Johnston (1991) recognised, academic life 'is not a closed system, but rather is open to the influences and commands of the wider society which encompasses it'; therefore the attention of geographers and geologists to the issues of sustainable tourism development through geotourism should come as no surprise. Geotourism is a holistic approach to sustainable tourism focusing on all definable points that create an authentic travel experience (Stokes et al. 2003). Pforr and Megerle (2006) have cited work by Buckley (2003) and Lang (2003) that defines geotourism as the intersection of nature-based tourism focusing on geo-objects and sustainable development. They see geotourism in the context not only of a new market segment but also as a 'normative direction contributing to geo-conservation and sustainable development'. Megerle and Megerle (2002) suggest that geotourism should be viewed as part of a holistic management approach to the broad field of geological and landscape history, including its interconnectedness with flora and fauna, the cultivated landscape, and present land use. They view sustainability and environmental education as integral parts.

Boley (2009) states that geotourism's mission is to preserve the geographical character of the destination which differentiates it from other forms of sustainable tourism. Instead of focusing on one specific dimension of the travel experience such as the environment, community or culture, geotourism encompasses various types of travel experiences into one distinctness that focuses on sustaining the geographical character of the destination. It is beneficial for both the tourist and local population because it provides tourists with an authentic experience while the destination's unique virtues are preserved. By accentuating the unique features of the travel destination, geotourism ideally should provide a tourism industry that protects the region's identity while providing an authentic travel experience.

It is best to view geotourism as a holistic form of sustainable tourism that incorporates themes from various types of sustainable tourism segments such as integrated rural tourism, cultural and heritage tourism and community-based tourism. The desire to experience pristine natural areas without negatively impacting on them is borrowed from ecotourism. The desire to experience unique cultural heritage is adapted from culture (Boley 2009). Robinson (2009) points out that geotourism is an ecologically sustainable tourism that explains the scenery in terms of how geological processes formed the patterns that can be observed in landforms in a plethora of landscapes such as mountains, deserts and islands, and in the rock outcrops that can be observed in coastal cliffs, creeks, road cuttings, lookouts, quarries, mine sites, and through walks in national parks. As most of these are erosional sites, none need to be ecologically challenged. It should be added here that the potential impact of increasing world tourism is immense, and this should preclude, or at least severely restrict, its involvement with wilderness areas.

Global tourism must be ecologically sustainable, and shifting the emphasis from other forms of sustainable tourism like ecotourism to geotourism represents a positive step towards more sustainable global tourism. National Geographical Centre for Sustainable Destinations documents that geotourism is sustainable tourism energised. It sustains, but it can also enhance by means of restorative and constructive forms of tourism that fit the nature of the destination. Tourist revenue can help to restore historic districts, for instance, and support local crafts. It can help to preserve and develop local cuisines, based on distinctively local ingredients supplied by local farmers. It can help to retain traditional cultural celebrations and performing arts that would otherwise disappear. It can help to beautify unattractive places and enrich poor places. It does those things best when focused on the distinctiveness of a place, avoiding the destructive pitfalls of undifferentiated global mass tourism.

Geotourism development at the local and regional levels must be developed within the context of sustainable local, national and international tourism development. At the local, regional and national levels, development policies, plans and programs, laws and regulations, and marketing, all influence sustainable tourism development. The three main principles of sustainable development which can also be applied to regional geotourism development planning are its concentration on ecological, social and economic issues (Dowling 2009a). Dowling goes on to stress that geotourism will only be sustainable where there are benefits for the host community, and these may be social and/or cultural, and environmental and will not necessarily be confined to economic benefits.

2.2 The Geotourism Charter

The National Geographical Society has developed a geotourism charter based on 11 principles (National Geographic 2010).

Integrity of place: Enhance geographical character by developing and improving it in ways distinctive to the locale, reflective of its natural and cultural heritage, so as to encourage market differentiation and cultural pride.

International codes: Adhere to the principles embodied in the World Tourism Organization's Global Code of Ethics for Tourism and the Principles of the Cultural Tourism Charter established by the International Council on Monuments and Sites (ICOMOS).

Market selectivity: Encourage growth in tourism market segments most likely to appreciate, respect, and disseminate information about the distinctive assets of the locale.

Tourist satisfaction: Ensure that satisfied, excited geotourists bring new vacation stories home and send friends off to experience the same thing, thus providing continuing demand for the destination.

Community involvement: Base tourism on community resources to the extent possible, encouraging local small businesses and civic groups to build partnerships to promote and provide a distinctive, honest visitor experience and market their locales effectively. Help businesses develop approaches to tourism that build on the area's nature, history and culture, including food and drink, artisanry, performance arts, etc.

Community benefit: Encourage micro- to medium-size enterprises and tourism business strategies that emphasize economic and social benefits to involved communities, especially poverty alleviation, with clear communication of the destination stewardship policies required to maintain those benefits.

Protection and enhancement of destination appeal: Encourage businesses to sustain natural habitats, heritage sites, aesthetic appeal, and local culture. Prevent degradation by keeping volumes of tourists within maximum acceptable limits. Seek business models that can operate profitably within those limits. Use persuasion, incentives, and legal enforcement as needed.

Land use: Anticipate development pressures and apply techniques to prevent undesired overdevelopment and degradation. Contain resort and vacation-home sprawl, especially on coasts and islands, so as to retain a diversity of natural and scenic environments and ensure continued resident access to waterfronts. Encourage major self-contained tourism attractions, such as large-scale theme parks and convention centres unrelated to character of place, to be sited in needier locations with no significant ecological, scenic, or cultural assets.

Planning: Recognize and respect immediate economic needs without sacrificing long-term character and the geotourism potential of the destination. Where tourism attracts immigration of workers, develop new communities that themselves constitute a destination enhancement. Strive to diversify the economy and limit population influx to sustainable levels. Adopt public strategies for mitigating practices that are incompatible with geotourism and damaging to the image of the destination.

Interactive interpretation: Engage both visitors and hosts in learning about the place. Encourage residents to show off the natural and cultural heritage of their communities, so that tourists gain a richer experience, and residents develop pride in their locales.

Evaluation: Establish an evaluation process to be conducted on a regular basis by an independent panel representing all stakeholder interests, and publicize evaluation results.

2.3 Geoparks Concept and Sustainable Development

Allied to the growth of geotourism is the development of geoparks. A geopark is an area with a geological heritage of significance, with a coherent and strong management structure and where a sustainable economic development strategy is in place. The philosophy behind the concept of geoparks' was first introduced at the Digne Convention in 1991 as a means to protect and promote geological heritage and sustainable local development through a global network of territories containing geology of outstanding value (Jones 2008a, b). In 2000, representatives from four European territories met together to address regional economic development through the protection of geological heritage and the promotion of geotourism. The result of this meeting was the creation of the European Geoparks Network (EGN). In 2004, at the first international conference on geoparks held in Beijing China, the 17 existing European geoparks joined with eight new Chinese national geoparks to form a Global Network of National Geoparks under the auspices of UNESCO. But it is important to note that geoparks are neither a UNESCO program nor a UNESCO initiative. Today, the idea of geoparks is spreading rapidly around the world in all continents, with Africa launching its Geoparks Network (AGN) in 2009 (Errami 2009; Errami et al. 2012). Progress has not always been easy, however, and finding funding to develop the initiative and secure the future of individual geoparks remains a significant challenge. The geoparks concept highlights the potential for interaction between socio economic development, cultural development, and conservation of the natural environment (Zouros and McKeever 2009). A geopark must have a management plan to foster sustainable socio-economic development predominantly based on geotourism. It must also demonstrate methods for preservation and promotion of geological heritage and provide opportunities for studying geology and other natural sciences. In order to be established as a geopark, it should be initiated together by local authorities, communities, and private enterprises. It has the potential to be part of a global network which demonstrates and shares good practices for preservation of Earth heritage and its involvement in strategies for sustainable development, (Geopark Iskar-Panega 2010). Geoparks address the need for the effective management of important geological sites and for the sustainable economic development of rural areas through the development of geotourism, thus enhancing the value of their Earth heritage, landscapes and geological formations.

A geopark must contain geologically or geomorphologically important locations of interest to a wider community. These locations can be important for their scientific value, rarity, aesthetic, or educational attributes. Geoparks not only benefit from being geologically interesting locations, but also from their various ecological, archaeological, historical and cultural qualities or attributes. Geoparks are run by local communities who can recognise and wish to confirm their geological, historical and cultural heritage, mostly through the activities of geotourism. According to Lochaber Geopark (2011), geoparks are not just about rocks—they are also about people, and helping communities to understand their Earth heritage, and to benefit from it. The significant aspect of geoparks is that they are driven by local communities who want to celebrate their Earth heritage and thereby achieve sustainable development of their area through "geotourism".

Geoparks have been established to enhance employment opportunities for the local population and to foster economic benefits for them, usually through the development of a sustainable tourism. These Earth heritage sites are part of an integrated concept of protection, education and sustainable development.

3 Geotourism and Geoparks as Africa's Contemporary Prospects for Sustainable Rural Development and Poverty Alleviation

3.1 Africa's Natural History Richness for Tourism

Africa is one of the fortunate continents blessed with abundant, undisturbed natural resources useful for tourism. Africa is an unusual tourist destination in the world as its attractions and its indigenous people are quite different from those of the rest of the world. Africa is the parallel universe, a continent where—according to popular perception and the tourist brochures—history has halted, and people live as in time immemorial, following their age-old traditions. Their thatched villages are set in a borderless expanse of bush where wild animals, normally only seen elsewhere in zoos, roam in the wild—it is a land of pristine wilderness.

Africa is a 'wild and unspoilt' landscape and, therefore, there is no doubt that the continent has much unexploited geotourism potential that can contribute to sustainable rural development and poverty alleviation. From the White Desert in Egypt, to the Blue Niles Falls in Ethiopia and over to the Victoria Falls (the Smoke that Thunders) in Zambia to the table mountains in South Africa, the list of geotourism potential in Africa is endless.

In the wake of sustainable development and globalisation, many nations, especially in Africa, are in a hurry to formulate, redefine and implement policies that are sustainable. To reduce environmental, social and economic costs and increase benefits, many international aid agencies and donor governments have recognised the positive impact tourism can bring to a country by creating economic opportunities and contributing to the general quality of life of local communities (Ngwira and Musinguzi 2011).

Thus, tourism has become one of the fastest developing industries in Africa and currently one of the continent's major economic development opportunities, as evidenced by its 6 % growth rate for the last decade. Africa receives 4.8 % of all tourist arrivals in the world, and 3.3 % of the receipts and, although it is not at the heart of the global tourist market, this modest proportion of the world's number one industry is still important for the continent. Global tourist dynamics depend on the situation in the developed world, but less on the situation in financial markets. Despite the fact that tourists' choice of international destination is often inconsistent and fleeting, a clear pattern has emerged for Africa: just one third of tourists go to the Maghreb countries, over a third to Southern Africa, almost a quarter to East Africa, and the remainder are spread over the rest of the continent, but mainly West Africa.

Though still crippled with persistent poverty, disease, war and political instability, in terms of tourism, Africa has witnessed tremendous growth. Ashley and Mitchell (2005) note that whilst Africa contributes little to global tourism figures, tourism contributes significantly to African economies. By 2003, tourism accounted for over 11 % of total African exports and 20–30 % of exports for most countries that exceeded the modest threshold of half a million foreign visitors a year. In fact, tourism is disproportionately important to Africa compared to other continents. Africa accounts for just 1.6 % of World GNP but 4.1 % of all international arrivals.

While this growth and development of tourism in Africa may seem insignificant compared to other parts of the world (e.g., Europe and North America), it has been rapid in the last decade. According to the World Tourism Organisation, tourism growth in developing countries, mainly in Asia and Africa, has been very strong. Asia (+13 %) was the first region to recover and was the strongest growing region in 2010. International tourist arrivals into Asia reached a new record at 204 million last year, up from 181 million in 2009. Africa (+6 %, 49 million arrivals), the only region to show positive figures in 2009, maintained growth during 2010, benefiting from increasing economic dynamism and the hosting of events such as the FIFA World Cup in South Africa. Results returned to double digits in the Middle East (+14 %, 60 million arrivals) where tourist arrivals to almost all destinations grew by 10 % or more.

3.2 Sustainable Tourism Development and Poverty Alleviation

The United Nations World Tourism Organisation (UNWTO) has defined sustainable tourism as "Sustainable tourism development that meets the needs of present tourists and host regions while protecting and enhancing opportunities for the future". It is envisaged as leading to management of all resources in such a way that economic, social and aesthetic needs can be fulfilled while maintaining cultural integrity, essential ecological processes, biological diversity, and life support systems (World Tourism Organisation 1998a).

According to Inskeep (1991), the goals of sustainable tourism are: to develop a greater awareness and understanding of the significant contributions that tourism can make to the environment, people, and the economy; to promote equity in development; to improve the quality of life of the host community; to provide a high quality of experience for the visitor; and to maintain the quality of the environment on which the foregoing goals depend. Butler (1993) states that the element of change in tourism is a crucial factor since sustainable development "implies some measure of stability and performance, at least in the very long-term view, and this does not blend with a highly dynamic and consistently changing phenomenon such as tourism". According to McIntyre et al. (1993), achieving sustainable tourism development "requires a vision which encompasses a larger time and space context than that traditionally used in community planning and decision making". The demands for sustainable tourism development to be developed irrespective of whether other, interrelated, segments are to be sustainable or is inappropriate and contradictory (Hall and Lew 1998). Notwithstanding this apparent discrepancy, various authors have recognized different forms of sustainability in the context of tourism. Hall and Lew (1998) suggests that there are at least four ways in which to elucidate tourism in relation to sustainable development. Coccossis describes these as linking to economic sustainability, ecological sustainability, long-term viability of tourism and the acknowledgment of tourism as a part of the overall strategy for sustainable development.

In terms of poverty alleviation; traditionally, the impact of tourism has been measured in relation to its contribution to Gross National Product (GNP) and employment created. Every so often, tourism's overall impact on the economy is estimated by looking at the effect of tourism expenditures through direct, indirect and induced spending using a multiplier effect approach. Tourism growth is most often measured through increases in international arrivals, length of stay, bed occupancy, tourism expenditures, and the value of tourism spending. However, none of these measures provide any means of determining the scale of the impact on the poor or even the trends which result from overall growth or decline on the poor. While in the literature there are references to the importance of tourism in the Least Developed Countries (LDCs), developing countries, and rural and marginalized areas, there is very little consideration of the impact of tourism on the poor (Walter et al. 2004).

The reasoning behind tourism development as a means of alleviating poverty in developing countries has been contended in general terms with a focus on economic modernization and economic growth. The supposition has been that any tourism development will eventually benefit the poor through the "trickle down" effect. There can be no doubt that tourism development does employ those who are economically disadvantaged, but there is a growing body of evidence that indicates that tourism development enriches others also. Walter et al. (2004) state that tourism development enriches international companies, expatriate workers and the local elite, while generating low-paying and low-status employment for the poor local communities. Additionally, poorly planned and managed tourism can destroy ecological systems, raise the cost of living for local people and damage social and cultural traditions and lifestyles. Those engaged in tourism development have generally not sought to demonstrate the impacts of tourism on poverty reduction—the focus has been on macro-economic impact and its potential to bring economic growth to poor and marginalized individuals and communities, rather than on measuring and demonstrating specific impacts on poverty.

Ashley and Mitchell (2005) show that recent analysis suggests tourism has reasonable credentials in favour of the poor. Tourism is labour-intensive compared to other non-agricultural sectors, has high female employment ratios, and is not necessarily import-intensive. The sector has low barriers to entry, encompassing a range of enterprises from the micro- to the multi-national and providing opportunities for downstream economic linkages in the local economy. Those who suffer from competition for water, land, and coast are likely to be the poor, but the poor also gain from opportunities for unskilled and semi-skilled employment and infrastructure development. But this good news does not justify complacency. There is increasing evidence (Ashley and Mitchell 2005) that actions at the level of the corporate and government can sharpen the benefits for the poor from tourism. A growing body of microeconomic evidence suggests that companies themselves can boost their local impact by doing business differently. They can develop stronger economic linkages, either by adapting their supply chain, or by stimulus to local tourism service-providers and cultural products. There is a range of partnership models for local people to engage with tourism businesses, often utilising their land or resource rights.

Garraway (2007) argued that there are a number of issues that must be considered in addressing poverty alleviation through tourism. Key amongst these are: partnership development between government, non-government, private and international bodies; empowering the poor and creating access to opportunities in the industry; reducing leakages and improving linkages with other sectors and monitoring the economic impact of the industry.

3.3 Opportunities Presented by Geotourism and Geoparks

Geotourism has emerged as an opportunity for sustainable rural development and poverty alleviation. It has immense potential to help in the global fight against poverty. Studies carried out so far on geotourism and the geopark concepts concluded that there is a great opportunity for geotourism to contribute to the alleviation of poverty (Dowling 2009b; Farsani et al. 2009; Piranha et al. 2009). Farsani et al. (2010) state that one of the main strategic objectives of a geopark is to stimulate economic activity and sustainable development.

A geopark serves to foster socio-economic development that is culturally and environmentally sustainable. This has a direct impact on the area involved by improving living conditions and the rural environment. Geotourism development also represents a partnership between government, local people and private sectors, local businesses, outdoor companies, tour agencies, restaurants, and accommodation facilities, among others. This partnership is welcomed because it makes good economic sense and can benefit all partners (Dowling 2009a).

Through the creation of Kanawinka Geopark, the first geopark in Australia, a number of local enterprise and small business have been established, as well as training programmes and new jobs by generating new sources of revenue, and at the same time, protecting the geo-resources (Dowling 2009a). The geopark has also fostered an education regime which includes a number of tools and activities which communicate geoscientific knowledge and environmental concepts to the public and the local community.

The Lesvos Petrified Forest European Geopark, is another example that is attracting 90,000 visitors annually and employing 35 local people directly, and with hundreds of new jobs having been created indirectly. The geopark is now the island's main visitor attraction and is an excellent example of how the holistic approach to conservation used in geoparks can be successful from the perspective of the local community.

Since geoparks and geotourism are opportunities for rural development, they reduce the rate of unemployment and migration through engaging local communities in geopark activities. Regarding this, geopark authorities have adopted some positive policies toward stimulating locals' participation for local economic prosperity and preservation of natural resources (Farsani et al. 2010).

Debatably, whilst there is a growing amount of research and understanding on the supply side of geotourism and geoparks, there is relatively little known about the demand for these products.

4 Conclusion

The literature review has shown that the concepts of geotourism and geoparks are relatively new, but presents essential credentials for poverty alleviation and sustainable development in developing countries. However, without in-depth understanding of role that each type of tourism such as geotourism can play in poverty alleviation and sustainable tourism development, the efforts of developing 'pro-poor' tourism in developing countries will be fruitless. Therefore, there is a need for further research and investigation into the role of geotourism and geoparks in sustainable development in Africa.

Since geotourism and geoparks are opportunities for rural development, they offer prospects for reducing poverty through engaging local communities in geopark activities. In line with this, geotourism practitioners and geopark authorities have to adopt some positive policies toward stimulating participation of the local population for local economic prosperity, poverty alleviation and sustainable development. This new vision of geotourism and geoparks presents an opportunity for developing nations, especially in Africa, by creating, new products related to the geoheritage called geo-products and geo-menus in local restaurant, new recreational activities (geo-tours, museums, etc.) and new jobs for local communities. It is worth mentioning that these recreational activities that are related to topography and geology, in some ways, are educational too.

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Geology: From Antiquity to Modern Day Geoheritage and Geoconservation, with Britain as a Case Study

La géologie: de l'Antiquité à nos jours Le géopatrimoine et la géoconservation, cas de la Grande-Bretagne

الجيولوجيا: من العصور القديمة إلى العصر الحديثالجيوتراث والجيوحماية، بريطانيا نموذجا للدراسة

M. Brocx and V. Semeniuk

Abstract

This paper outlines the long history of investigations and writings in regard to the geology, i.e., in the increasing level of awareness of the geological phenomena and the properties of geological materials resulting in different uses and hence different values being assigned to stone, minerals and metals, and crystals. This history spans from antiquity to the secular scientific endeavours that led to founding principles in geology, and the development of its discipline and sub-disciplines. The post-industrialisation events in Britain led to the world's first geosite inventory-based on geoconservation needs. While the beginnings of curiosity in geology date back to the beginning of civilisation, interest in what is now termed *geoheritage*, in modern times, largely derives from Britain. As such, with its classic sites, reference sites, and type locations, many of which are global standards for stratigraphy, and sites illustrating geological principles, Britain provides a case study of the history and development of geoconservation.

Résumé

Ce travail donne un aperçu sur la longue histoire des investigations et des écrits liés à la géologie. Cette dernière a évolué avec la croissante prise de conscience des phénomènes géologiques et des propriétés des matériaux géologiques résultant de différentes utilisations et donc des valeurs différentes ont été affectées à la pierre, les minéraux et les métaux, et des cristaux. Cette histoire s'étend de l'Antiquité aux efforts scientifiques laïques qui ont conduit aux principes fondateurs de la géologie, le développement de ses discipline et sous-disciplines. Les événements post-industrialisation en Grande-Bretagne ont conduit au premier inventaire mondial des géosites basé sur un besoin de géoconservation. Alors que le commencement de l'intérêt à la géologie remonte au début de la civilisation, l'intérêt au géopatrimoine revient surtout à la Grande-Bretagne. Avec ses sites classiques, ses sites de référence, ses sites

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illustrant les principes géologiques et ses localités type dont beaucoup sont des standards stratigraphiques internationaux, la Grande-Bretagne offre un cas d'étude de l'histoire et du développement de géopatrimoine et de la géoconservation.

ملخص

يقدم هذا العمل نظرة عامة حول التاريخ الطويل للتحريات والكتابات المرتبطة بالجيولوجيا. هذه الأخيرة تطورت مع الوعي المتزايد بالظواهر الجيولوجية وخصائص المواد الجيولوجية الناتجة عن الاستخدامات المختلفة، وبالتالي فإن قيما مختلفة أعطيت للحجر، المعادن والفلزات والبلورات. هذا التاريخ يمتد من العصور القديمة إلى الجهود العلمية العلمانية التي وضعت المبادئ التأسيسية لعلم الجيولوجيا، وطورت تخصصاتها الأساسية والفرعية. وقد أدت أحداث ما بعد التصنيع ببريطانيا إلى أول جرد عالمي للجيومواقع ينبني على الحاجة إلى جيومحافظة. في حين أن الاهتمام بالجيولوجيا يرجع إلى بداية الحضارة، فان الاهتمام بالجيوتراث خلال السنوات الأخيرة يعود خصوصا إلى بريطانيا. فبمواقعها الكلاسيكية، ومواقعها المرجعية، ومواقعها التي توضح المبادئ الجيولوجية، والمواقع النموذجية حيث العديد منها هي معايير دولية لعلم الطبقات، فبريطانيا تقدم نموذجا لتاريخ وتطور الجيوتراث والجيومحافظة.

Keywords

History • Britain • Geoheritage • Geoconservation • Geoparks

Mots-clés

Histoire • Grande-Bretagne • Géopatrimoine • Géoconservation • Géoparcs

الكلمات الرئيسية

تاريخ • بريطانيا • جيوتراث • جيومحافظة • جيومتنزهات

1 Introduction

The philosophy underpinning much of this paper derives from the adages of Aristotle (384 BC–*ca* 322 BC) "*He who sees things grow from the beginning will have the best view of them*", and Santayana (1863–1952) "*Those who cannot remember the past are condemned to repeat it*" (or commonly paraphrased as: "*Those who cannot learn from history are doomed to repeat it*"). Cuvier contended that practitioners must familiarise themselves with history to accelerate progress by preventing duplication of effort (Laudan 1993). In keeping with this stream of thought, the history of geology, geoheritage, and geoconservation is important to demonstrate what progress has occurred in the scientific journey to establish the importance of geoheritage, and hence inventory-based geoconservation and the establishment of Geoparks.

Globally, geoconservation has assumed increasing importance because it has been recognised that Earth systems are linked to the ongoing history of human development, providing the resources for development, and a sense of place, with aesthetic, historical, cultural, and religious values. In addition, Earth systems are the foundation of all ecological processes and part of the heritage of our sciences (Torfason 2001). Once destroyed, the *geoarchive* of the Earth is lost to future generations with a loss of already discovered information *and,* importantly, *as yet-to-be-discovered information*. Beyond practical aspects, geological features can have intrinsic worth.

In more recent years, the systematic conservation and incorporation of assessment and management of geosites of heritage significance into the world agenda have attracted a much wider appreciation as to their importance. In general, the term 'geoheritage' is assigned to features of geology that offer information or insights into the formation or evolution of the Earth, or into the history of science, or that can be used for research, teaching, or reference (Brocx 2008). It includes igneous, metamorphic, sedimentary, stratigraphic, structural, geochemical, mineralogic, palaeontologic, geomorphic, pedologic, and hydrologic attributes, at all scales (Brocx and Semeniuk 2007). However, with few exceptions, it was only after the destruction, or potential destruction, of sites of geoheritage significance that a need for a formal process for geoconservation was recognised.

With over 200 years of history of geological enquiry, Britain is replete with "standard" geological sites, classic sites illustrating geological principles, and a history of geological exploitation, geological controversy, and geoconservation. Beginning with the inauguration of the Geological Society of London in 1807, there has been a growing number of naturalists, geologists, geoheritage practitioners, geological interest groups, and government and non-government organisations that have recognised the importance for planning and management and of having a systematic method for identifying and conserving sites of geoheritage significance. This recognition has led to the advancement of geoconservation methods, and the development of categories such as Sites of Special Scientific Interest (SSSI), and assessment of site significance (local, regional, national, international) requiring different levels of protection. In addition, there is now community involvement in protecting sites of geoheritage significance, and local to large-scale geotourism based on geoheritage. As a result, Britain provides an interesting history in geoconservation in its national endeavour and stands as a case study for geoheritage practitioners (Brocx 2008).

While the objective of this paper is to highlight nodal points in the history of the development of the science of geology, leading to an appreciation of geoheritage, geoconservation, and geoparks, it is beyond the scope of this paper to acknowledge all the outstanding contributions of individual philosophers and geologists everywhere. This would be the subject of a book involving years of research.

Although the meanings of the terms "history" and "geology" have changed over time, nonetheless there has been a coherent tradition in the development of the science of Geology, where each generation of philosophers and "scientists" cite previous works and those of historians of science. However, it should be noted that these "histories" have led to (but are not equivalent to) today's standard literature reviews in assessing the state of the art of any geological and other scientific subject matter. Scientists clearly saw the writing of history as an important task (Laudan 1993).

The history outlined in this paper traverses the development of civilisation and initial utilitarian use of natural resources to the Renaissance and the Industrial Revolution (the latter transforming much of Britain from farming communities to mining and factory-based endeavours with workers living in towns and cities; Brown (1988), to the coining of terms such as "geology" and "scientist", to the intellectual revolutions in Earth dogma in the various disciplines and sub-disciplines of the geological sciences, to modern-day inventory-based geoconservation. The authors hope that the historical events outlined in this paper will be the stimulus for further publications expanding on the body of work herein.

The objectives of this paper are three-fold. Firstly, it outlines a brief history of geological endeavours, geological awareness, geoheritage and geoconservation from the beginning of civilisation to the present, showing a long-term and evolving awareness of the importance of geology to human cultures, and secondly, it outlines the history of geoconservation specifically using Britain as an example (a) showing how the awareness of the cultural importance of geoheritage increased over time, viz., from early curiosity, to the ad hoc conservation of fossil sites in the 1800s, to a more systematic inventory-based conservation of sites of scientific interest in the 1900s, to heritage theme-based geoconservation of sites of special scientific interest as well as cultural and aesthetic sites in the late 1900s and early 2000s in a whole-of-government planning and management endeavour; (b) how culturally-important sites of geoheritage significance were separated from intrinsically important (scientific) sites of geoheritage, from reference sites and teaching sites, which are important matters in the arena of geoheritage; and (c) how pragmatically and sociopolitically Britain tackled the issues of geoheritage and geoconservation, culminating in inventory-based classification and selection of sites of geoheritage significance, and the enactment of the CRoW Act (*Countryside and Rights of Way Act 2000*) that ensured important geological sites were protected regardless of land tenure. These latter aspects of geoheritage and geoconservation and how they unfolded historically are important issues in that they provide a case study for a global approach to geoconservation, as each country has its own part in the story of the "memory of the Earth". And finally, this paper highlights nodal points that have been instrumental in progressing geoconservation globally.

The names for Great Britain, England, the British Isles and the United Kingdom are often used interchangeably, however, "Great Britain", often shortened to "Britain", is a single island (comprising England, Scotland and Wales), located in the northwest of continental Europe and east of Ireland. The British Isles encompass Great Britain, the island of Ireland, and several other smaller islands, such as the Isle of Man; the United Kingdom, often shortened to the UK, is a country that includes England, Scotland, Wales, and Northern Ireland the official name of which is "United Kingdom of Great Britain and Northern Ireland". These names are *not* used interchangeably in this paper; however, this may not be the case in some of the works cited. Also, in this paper we refer to Great Britain simply as Britain.

2 A Brief History of Geological Endeavours, Geoheritage and Geoconservation

Traditionally, the history of geology, geoheritage, geoconservation, and geoparks is a journey that is presented in the literature as either beginning in the late 17th century (as a precursor to the curiosity and explosion of scientific discoveries made in the 18th and 19th centuries, during the Industrial Revolution by major "geological personalities" such as Brongniart and Cuvier from France, de la Beche, Hutton, Lyell, Murchison, Sedgwick, Smith from the Britain, and Steno from Denmark and Werner from Germany) or, alternatively, beginning at the time of the Ancient Greeks.

Adams (1938) cites Georgius Agricola (1494–1555), a German scholar and scientist, often referred to in the literature as "the Father of Mineralogy", as having conducted an exhaustive review of the entire body of Greek literature up until 334 BC. He concluded that of the 27 Greek philosophers who are recorded as having made geological observations, there were only a few contributions of any importance made to geological science. He named Thales of Miletus (*ca* 636–546 BC), Anaximander of Miletus (615–547 BC), Pythagoras of Samos (540–510 BC), Xenophanes of Colophon (540–510 BC), Herodotus of Halicarnassus (480-*ca* 420 BC), Aristotle of Stagira (384–322 BC), and Strabo (64-–23 BC) as the main Ancient Greek contributors to the geological sciences.

Other notable contributors in antiquity to the science of geology include Xanthus of Sardis, Turkey (*ca* 480 BC), who drew attention to the occurrence of fossil shells in Armenia, Phrygia, and Lydia, which were nowhere near the sea. He concluded that formerly these localities had been the bed of an ocean, and that the limits of the dry land and the ocean were constantly undergoing change. Another contributor, Theophrastus of Eresus on Lesbos (370–287 BC), in his treatise *On Stones*, classified rocks and gems based on their behaviour when heated, further grouping minerals by common properties, including hardness.

The record of mining and the use and trade of the products of the Earth for building, personal use, or economic value predates the record both of intellectual enquiry giving rise to philosophical theories on the origins of geological features based on observing geological phenomena, and of science-based reasoning. Aitchison (1960) records 7 metals as being the metals of antiquity, viz., gold (*ca*) 6000 BC, copper (*ca*) 4200 BC, silver (*ca*) 4000 BC, lead (*ca*) 3500 BC, tin (*ca*) 1750 BC, iron smelte, (*ca*) 1500 BC, and mercury (ca) 750 BC. The discovery in 1982 of the world's oldest surviving geological map, drawn during the reign of Ramesses IV (1151–1145 BC) of Egypt, is a measure of the geological knowledge of the day. It is recorded as having been produced as an aid for locating bekhen-stone (a grayish-green chloritic sandstone and siltstone) in the region of Wadi Hammamat. Now housed in the Egyptian Museum in Turin, Italy, this map (41 cm × 282 cm in size) accurately illustrates the topography and geology of Wadi Hammamat in the mountains of the central Eastern Desert of Egypt, and the distribution of sedimentary and igneous/metamorphic rocks (shown as black and pink hills, respectively). This ancient map also shows the gold-working settlement at Bir Umm Fawakhir, the gold-bearing quartz veins on the adjacent mountain, the famous bekhen-stone quarry, the lithologically diverse wadi gravels, and various cultural features. Hieratic texts on the map comment on the occurrence of gold in the area and the quarrying of bekhen-stone (Harrell and Brown 1992).

Further, using ancient literary sources dating back to 2600 BC, Sevillano-López and González (2011) identified well-established ancient overland and maritime commercial mining and mineral trade routes crossing to the extremes of the continent between the Roman and Chinese Empires (Fig. 1). They established that minerals were important products that were traded along "The Silk Road", and that this trade carried implications in relation to the cultural and economic values of minerals, links to associated technologies, diplomatic relationships that existed between different cultures, and their social and economic development. In Japan for example, with limited metal ore of its own, the possession of metal "status goods" factored in the increasing social stratification occurring during the Yayoi Perion (*ca* 400 BC–*ca* 250 AD; Henshall 2012). Furthermore, the natural minerals and metals were traded and were classified according to whether they were considered to be prestige goods, i.e., valuable (such as gold, silver, gems, glass and asbestos) or common utilitarian goods (such as iron, copper, lead and tin) according to their social uses (Sevillano-López and González 2011).

The creation of "Parks" also was a feature of ancient times, and the creation of Parks has been recorded from antiquity to the present (Allsen 2006). For instance, Isidore, Bishop of Seville (*ca* 560–636) and Diodorus Siculus (1st Century) credit the famous Rock of Behistan (Bisotun) (Fig. 2) as being the place that the legendary Queen Semiramis created a royal park (Rawlinson 2005).

Notably, the Rock of Behistan (Bisotun), in the Iranian Province of Kermanshah, was inscribed as a World Heritage site in 2006. Today, Bisotun is to cuneiform what the Rosetta Stone is to Egyptian hieroglyphs. Composed in three languages (Persian, Susian, and Babylonian cuneiform), royal engravers chiselled the lineage and conquests of Darius (Darayavush 1), King of Kings, the King of Persia and some 23 Provinces, in thirteen columns in the smooth vertical surface and then, above the five tall columns of Persian writing, artists carved a delicate panel with a life-sized figure of the king in relief, standing on the chest of Gaumata, and receiving the submission of the nine rebel "upstarts" who had once challenged his right to the throne, with the engravings in relief and associated inscriptions covering an area about 20 m by 10 m (Thompson 1937; Zolfagharia et al. 2005; Saliba 2011).

During the Dark Ages in Europe, the intellectual pursuits in the study of nature are to be found in publications from China and the Middle East. In the Middle East, medieval Persian polymaths include Abū Rayhān Muhammad ibn Ahmad Bīrūnī (Al-Biruni; 973–1048 AD), Ibn Sina (Latinised as Avicenna; 981–1037) and the Ikhwan al-Safa (translated as either the "Brethren of Purity" or the "Brethren of Sincerity", an anonymous group of scholars). Meyerhoff (1931) describes Al-Biruni as perhaps the most prominent

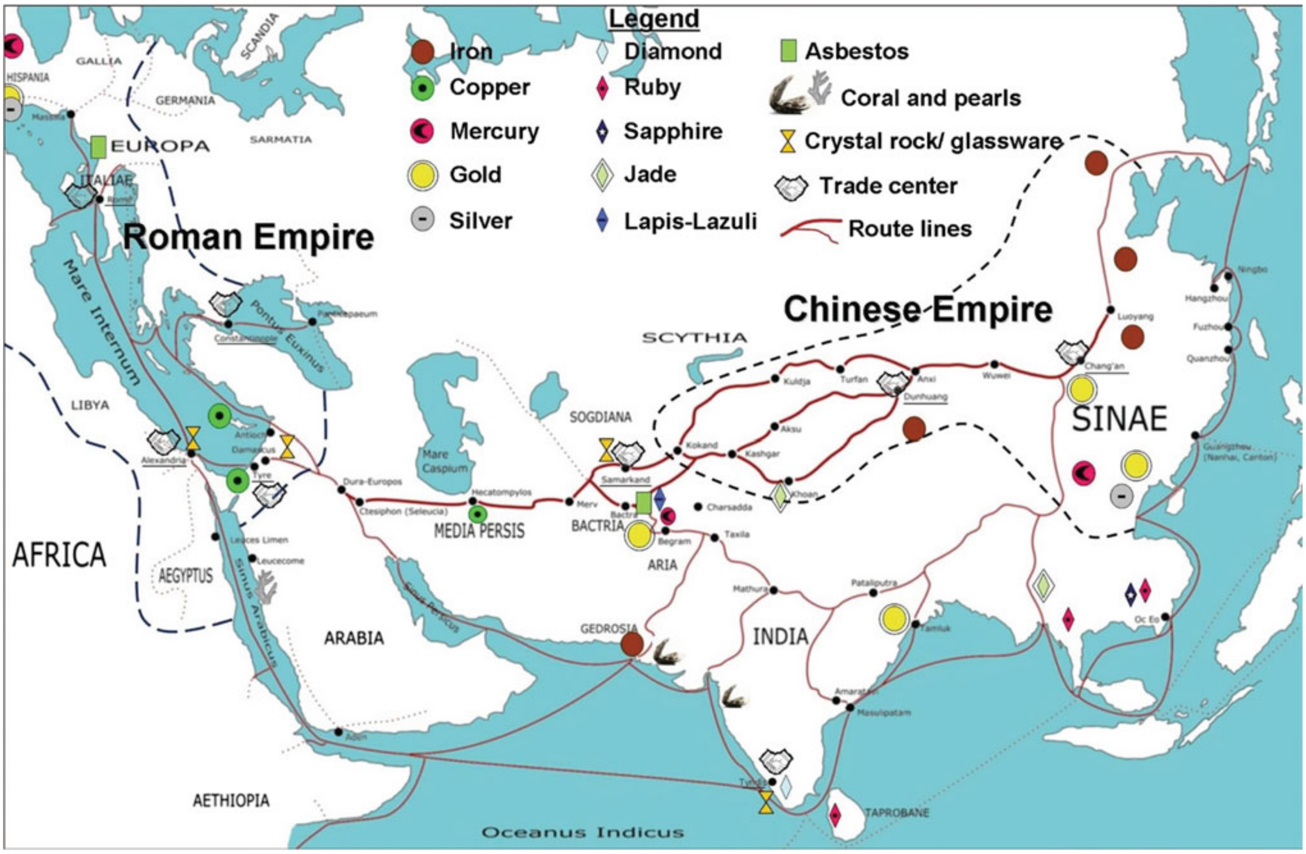

Fig. 1 Sevillano-López and González (2011)

Fig. 2 Sketch of Mount Behistun, or rock of Behistun (Rawlinson 2005)

figure in the phalanx of those universally learned Muslim scholars who characterize the Golden Age of Islamic Science (Said 1989; Saliba 2011). His scientific contributions in so many diverse fields earned him the title “al-Ustadh”, the Master or Professor *par excellence*. Al Biruni was of the view that, whatever the subject, one should use every available source in its original form, investigate the available work with objective scrutiny, and carry out research through direct observation and experimentation (Said 1989).

Kitab al-Jamahir (*Precious Stones*), written by Al Biruni, and translated and published by Said (1989), is described as including “the most complete medieval text of mineralogy, with descriptions of minerals and metals from all over the Asiatic and European continents”. Avicenna’s book, entitled “*Kitab al-Shifa*” (the Book of Cure, Healing or Remedy from Ignorance), includes six chapters on geology titled “Formation of mountains, the advantages of mountains in the formation of clouds; Sources of water; Origin of earthquakes; Formation of minerals; and the diversity of Earth’s terrain”. The anonymous authors of Rasa’il Ikhwan al-Safa have produced one of the most complete Medieval encyclopedias (52 volumes) of sciences, antecedent by at least two centuries to the best known in the Latin world dating back to the 13th century. These works deal with mineralogy, geology and gemmology and the correspondence established between the celestial and sub-lunar worlds, i.e., between the stars and minerals. It is a collection of epistles, the Arabic title of which is Rasâ’il Ikhwân al-Safâ’ wa Khullân al-Wafâ’(Epistles of the Pure Brethren and the Sincere

Friends), and consists of extremely heterogeneous materials, reworked to represent the whole educational training intended for the elite (Anon 2012).

Without the benefit of previous works on the study of Chinese contributions to the science of geology, in either Chinese or Western language, Needham (1959), in collaboration with Wang Ling, Trinity College, Cambridge University, undertook a "rough approximation" of the history of the development of geological principles and mineralogy. From the Chinese literature, Needham (1959) discovered that the Chinese were well versed in the principles of geology as early as the 1–6th Centuries, and that the mineralogical sections of books such as Hai Yao Pen Tshao (Li Xun; said to be of Persian heritage, in *ca* 900s) was in advance of Aristotelian ideas, and gave rise to several works of importance in Western languages. These include works by Fernand du Saussay de Mély (1851–1935).

Shen Kuo (1031–1095) was one of the first naturalists to have formulated a theory of geomorphology (pre-Agricola) and to understand concepts that, when stated by Nicholas Steno (1638–1686), and James Hutton in (1727–1796), as principles of science, became part of the foundations of the science of Geology. Shen Kuo also formulated a theory of gradual climate change after his observation of ancient petrified bamboos found in a preserved state underground near Yanzhou (modern Yan'an), in the dry northern climate of Shaanxi province (Asimov and Bosworth 1998).

Building on earlier work, the treatise on minerals by Mei Pia (the *Shi Yao Erh Ya*, the dictionary of minerals and drugs; *ca* 818 AD) lists 335 synonyms of 62 chemical substances, and predates scientific books devoted to stones and minerals during the Sung dynasty 969–1126 AD.

Historically, the Renaissance, and the Scientific Revolution, i.e., 14th–17th Century in Europe, is the next period when notable contributions to the science of Geology were recorded. In this period, modern Geology is recorded as beginning with Georg Baur, better known by the Latinised version of his name, Georgius Agricola (Germany, 1494–1555). Agricola is best known for his 12-volume publication *De Re Metallica* (published posthumously—Agricola 1556) and his contribution to mining and metallurgy, however, he is also known for *De Ortu et Causis Subterraneorum* (5 pioneering works on physical geology; *De Natura Eorum quae Effluunt ex Terra;* 4 works dealing with subterranean waters and gases; *De Natura Fossilium*; 10 works on the first systematic mineralogy; *De Veteribus et Novis Metallis*; two works dealing largely with the history of metals and topographical mineralogy; *Rerum metallicorum interpretatio*, and a dictionary of Latin and German mineralogical and metallurgical terms; Hoover and Hoover (1950). Other pioneering figures contributing to the foundations of the geological science, during this period, include Leonardo da Vinci (1452–1519), Ulisse Aldrovandi (1522–1605), Luigi Ferdinando Marsili (1658–1730), Abbé Anton Lazzaro Moro (1687–1740), and Antonio Vallisnieri (1661–1730) in Italy, Conrad Gesner (1516–1565) in Switzerland known for *De omni rerum fossilium genre* of 1565, Edward Lhuyd (Luidius; 1603–1709) and Robert Hooke (1635–1703) in the United Kingdom, and the Dane, Niels Stensen, better known as Nicolaus Steno (and Latinized to Nicolaus Stenonis or Nicolaus Stenonius (1638–1686)—known for *Dissertationis Prodromus* of *circa* 1669, which introduced concepts such as folded strata, faulting, volcanic intrusions and eroded forms).

[While the Latin term *geologie* was referred to in relation to "Earthly" sciences in *The Philobiblon* by Richard D'aungerville de bury (England, Bishop of Durham; 1287–1345) in 1345 (Brenčič 2011), Ulisse Aldrovandi, a pioneer of ichnology, is credited as having first defined the modern term and meaning of 'geology' in 1603 (Vai and Cavazza 2006)].

Following the period of the Antiquities and the Renaissance, there was a third wave of geological interest, i.e., during the Industrial Revolution, when the principles of Modern Geology were founded with contributions, for example, from Andrea Cespalpino (1519–1603) known for "*De metallicis libri tres*" of 1596), Ferrante Imperator (1550–1625) known for "*Dell'Historia Naturale*" of 1599 and Giovanni Arduino (1714–1795), often referred to as the "Father of Italian Geology" in Italy, Peter Simon Pallas (1741–1811), Abraham Gottlob Werner (1749–1817), and Leopold von Buch (1774–1852) in Germany, Johann Scheuchzer (1672–1733), Horace Benedicte de Saussure (1740–1799) and Jean-André de Luc (1727–1817) in Switzerland, Carl Von Linné, better known as Carl Linneus (1707–1778), Johan Wallerius (1709–1785), Axel Cronstedt (1722–1765) and Jöns Jacob Berzelius (1779–1848) in Sweden, John Woodward (1665–1728, William Smith (1769–1839), Charles Lyell (1797–1875) and James Hutton (1726–1797) in the United Kingdom, Georges Cuvier (1769–1832) and Jaques Valmont de Bomare (1731–1807), known for "Mineralogie, ou nouvelle exposition du regne minéral. Ouvrage dans lequel on a tâché de ranger dans l'ordre le plus naturel les individus de ce Regne & où l'on expose leurs propriétés & usages méchaniques; avec un dictionnaire nomenclateur et des tables synoptiques" in 1762, Jean-Baptiste Louis Romé de l'Isle (1736–1790), René Just Haüy (1743–1822, and Alexandre Brongniart (1770–1847) in France, and Andreas Kordellas (1836–1909) in Greece (Zittel 1901; Vai 2009; Needham 1959).

The period from circa 1700 to 1900, encapsulating the Age of Enlightenment (or the Age of Reason) and the Industrial Revolution, stands as the most important period for the discipline of Geology, because it marks the beginning of the geological sciences in academia, and both international and national initiatives for collaboration. For example, in 1860, a young Italian scientist, Giovanni Capellini (1833–1922), was appointed to the first Italian Chair of Geology in the University of Bologna. As a mapping geologist, palaeontologist and archaeologist, Cappellini considered that academic progress and social benefit of the "new geology" was highly dependent on international stratigraphical and litho-technical correlation through exchange of knowledge and experience, and on adequate standardisation of language techniques and procedures of the new discipline and related professional curricula. Cappellini is credited with having first expressed the idea of the International Geological Congress (IGC; in 1874), and was elected Vice-President of the first IGC held in Paris in 1878 (Ellenberger 1978; Vai 2003). For a more exhaustive list of numerous contributors to the history of the geological sciences from antiquity to the 18th or early 19th century, Zittell (1901) cites a number of primary sources for the history of geology including those undertaken by the English polymath, William Whewell (1794–1866), the Italian naturalist, mineralogist, and geologist, Giovanni Battista Brocchi (or Giambattista, 1772–1826), the Scottish geologist, Sir Charles Lyell (1797–1875), the German, Christian Keferstein (1784–1866; *Geschichte und litteratur der geognosie; ein versuch*) and the 8 volumes "*Histoire des progrès de la géologie de 1834 à 1859*" by French geologist and palaeontologist, Étienne Jules Adolphe Desmier de Saint-Simon, Vicomte d'Archiac 1802–1868) and essays by Sir Archibald Geikie (1835–1924). Adams (1938) and Laudan (1987) also provide useful references and sources for the history of the geological sciences.

3 Milestones in the History of Geoconservation in Britain

While there have been notable contributions to the geological science from philosophers, polymaths, naturalists, clerics, and geologists world-wide, from the time of the Antiquities to the 19th Century, as detailed above, since the 20th Century, Britain in many respects has been the pioneer in concepts and the application of inventory-based methods dealing with Geoheritage and leading to Geoconservation. As such, a case study in terms of the history of Geoheritage and Geoconservation, and identifying the need to systematically conserve sites of geoheritage significance through inventory-based geoconservation stands as a global model. This history spans from the 1700s to the present and can be divided into five main phases that largely describe the evolution of the thinking, processes and outcomes associated with geoconservation from geoscientific perspectives and actions. However, it must be stressed that a number of other activities are embedded in this history. For example, there were also legislative developments and government and non-government bodies that facilitated and promoted geoconservation. Also, while there are five phases conceptually and temporally different in terms of activities and outcomes, there is some degree of temporal overlap. For instance, the period of early discovery and the focus on fossils (Phase I) extends into the period when systematic work was undertaken to identify type sections, classic sites, and internationally significant sites (Phase II).

The history of geoconservation in Britain from different perspectives, such as the contributions of individuals and community groups, or in terms of chronology, or the developing relationship of the geosciences to environment and planning, can be found in various contributions in Burek and Prosser (2008).

3.1 Phase I (1700s–1800s)

This was an era of geological observation leading to scientific enquiry that included exploring the principles of geology, and the collection of fossils, minerals, and rocks. Natural historians, such as John Ray, were developing plant classification systems, and geologists such as Lyell, Sedgwick, Murchison, and Hutton were developing theories of natural geological evolution, and putting together "snapshots" in time of Earth history. Although there was no formal concept of geoheritage or systematic geoconservation, geoconservation emerged as a practice by individuals who collaborated to organise geological audits, and to establish various institutions where fossils, and mineral and rock collections and a library could be housed and preserved. During this phase, the world's first Geological Society, the Geological Society of London, was inaugurated (1807). Soon after its foundation, this Society established a library and began to accumulate a collection of minerals, rocks and fossils which were later housed in the Natural Museum of London in 1911. The first recorded protected sites are those that were of paleontological significance—for example, the Wadsley Fossil Forest in Sheffield, South Yorkshire discovered in 1872 (Prosser et al. 2006), and Fossil Grove in Glasgow in Scotland conserved in 1887 (Doyle et al. 1994).

3.2 Phase II (Mid-1800s–1970s)

This period marks the early development of inventories, with the identification of type sections, classic sites that illustrated geological principles, and internationally significant sites, because British geologists recognised that many locations in their country were significant as reference sites, and scientifically important sites. This phase progressed on two fronts: in the recognition of type sections, and classic sites; and in the recognition of regionally important sites such as the

Devonian series at Devon (documented through ad hoc regional geological surveys, which began in 1832, when Henry Thomas de la Beche, then Vice-President of the Geological Society, was employed to undertake a geological survey of Devon, effectively the first recorded geological survey). The results of the work of de la Beche contributed to the "Great Devonian Controversy" (Hallam 1989). The success of the survey also led to formation of the Geological Ordinance Survey (Fig. 3).

The region of Devon contains important fossil sites and classic coastal geomorphologic features and rock formations spanning the interval of the middle Palaeozoic Era to the middle Mesozoic Era (*ca* 260 Ma of the Earth's history) that have contributed to the study of Earth Sciences for over 300 years. The results of the survey brought a deeper understanding of the geological systems of the region in terms of stratigraphy, lithology, biostratigraphy and geochronology, and an appreciation that there was a need to preserve locations, cliffs, and reference sites as standards, and as research areas. Parallel to the establishment of the Geological Society of London and the founding of British Geological Survey (1835; to facilitate scientific discovery and information for resource-based exploitation), a movement to promote geoconservation was created. Organisations such as the Geologists' Association and the National Trust were founded to promote the importance of geology in environmental fields, giving guidance on the protection and management of geological sites, and funding geological research and conservation projects, as guardians against unbridled development and industrialisation (Snodin 1978). In addition, it was recognised by organisations such as the Society for the Protection of Nature Reserves that there was a need for a more systematic approach to geoconservation. However, up until and including this phase, conservation initiatives were not undertaken on a systematic basis, and there was no legal framework to ensure conservation or management of sites for which protection was sought. This history is outlined below in terms of the major events in the preservation of special sites, and in the generic preservation of sites of significance, and provides a chronology of the socio-political unfolding of geoconservation at this time in Britain.

In 1835, the Geological Ordnance Survey (now named the British Geological Survey) was established. The Geological Society strongly supported the establishment of such a survey, with Lyell referring, in his Presidential Address, to the Society in 1836 as follows "… *to the great advantages which must accrue from such an undertaking, not only as calculated to promote geological science, which would alone be a sufficient object, but also as a work of great practical utility, bearing on agriculture, mining, road-making, the formation of canals and rail-roads, and other branches of national industry*" (Lyell 1836).

The British Geological Survey today is the largest component body of the Natural Environment Research Council. It carries out geological surveys of Britain and Northern Ireland and of the surrounding continental shelf, and is custodian of extensive data collections of records collated over the last 160 years. It also maintains working national collections of fossils, rocks and mineral specimens and major libraries, which also house collections of geological photographs (which are accessible to the public), and publishes memoirs, reports, regional guides and maps, together with a wide range of popular publications on places of geological interest throughout the Country.

The next significant event was the publication of the *Geological Survey Act* on 31 July 1845, providing the Geological Ordinance Survey with a legal framework designed to facilitate the completion of a geological survey of Great Britain and Ireland. To promote the importance of geology in environmental fields, the Geologists' Association was founded in 1858 to provide guidance on the protection and management of geological sites, and to fund geological research and conservation projects. In 1887, the first practical steps in the formal (ad hoc) conservation of sites of geoheritage significance in the world were taken, with the conservation of geological monuments such as the fossil tree stumps of Carboniferous age in parks by the local Government in Glasgow (Doyle et al. 1994).

Natural Trusts and Preservation Societies were founded at different stages and places in the period 1895–1949. For instance, in 1895, the National Trust (England, Wales, and Northern Ireland) was founded out of concerns in relation to the impact of uncontrolled development and industrialisation.

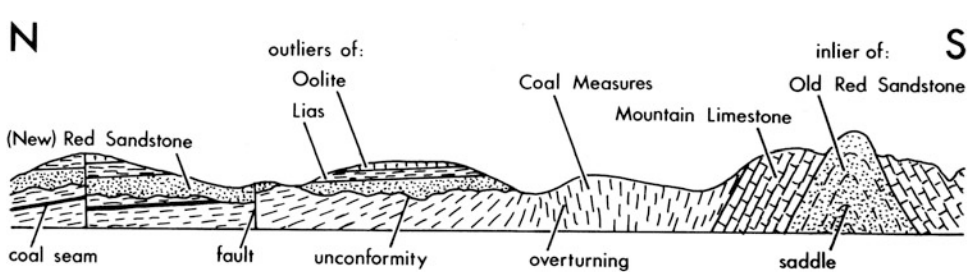

Fig. 3 de la Beche's 1830 cross-section through the Bristol coalfields to the Mendip Hills (from Hallam 1989)

It was set up to act as a guardian for the nation in the acquisition and protection of threatened coastlines, countryside and buildings. Its guardianship encompasses over 248,000 ha of countryside in England, Wales and Northern Ireland, and nearly 1,000 km of coastline. In 1912, the Society for the Protection of Nature Reserves (now the Royal Society for Nature Protection) was formed in recognition of the need for a formal conservation agency for Natural Heritage. The Society began the process of establishing a framework for a more systematic approach for identifying sites that merited conservation. In 1931, the National Trust for Scotland was founded, describing itself as "the conservation charity that protects and promotes Scotland's natural and cultural heritage for present and future generations to enjoy". In 1943, the Society for the Protection of Nature Reserves, Wildlife Conservation Special Committee (England and Wales) was founded to examine ways in which government could further support the national nature protection effort. Their report, *Conservation of Nature in England and Wales* (Cmd 7122, 1947), laid the foundation of nature conservation with a twin approach: (1) scientific activity; and (2) aesthetic and recreational activity. Also, in 1943, the Nature Reserves Investigation Committee (NRIC), with a geological sub-committee, was founded. Consequently, some 390 Earth heritage sites had been identified as being worthy of protection for scientific interest. This and other reports undertaken by the NRIC contributed towards shaping post-war government policy on geoconservation (Mason and Stanley 2001).

In 1949, in England, the Nature Conservancy was created by Royal Charter under the *National Parks and Access to the Countryside Act 1949*. This Act empowered the Conservancy to establish National Nature Reserves for the purpose of nature conservation. This included conservation of geological and geomorphological features. National parks, for the first time, could be created.

Thus the period between 1832 and 1964 saw a proliferation of reserves and nature protection agencies, leading to the conservation of many sites for their geoheritage values.

3.3 Phase III (1970s–1990s)

This phase saw the recognition and the development of methods and selection criteria for inventory-based classification and conservation, the foundation of organisations (both government and non-government) to carry out the task, the enactment of legislation to give proclaimed sites legal protection, and the involvement of community groups in order to select, conserve, and manage sites of scientific, and of cultural heritage.

The Nature Conservancy Council (NCC) was created under the *Nature Conservancy Council Act 1973* (the Nature Conservancy was abolished). The NCC was a statutory body, financed by and responsible to the Department of the Environment, contributing to the development of Sites for Scientific Research Series and the National Nature Reserve Series (Ellis et al. 1996). This was another step in recognising that geoheritage extended beyond purely "hard rock" geology to include geomorphology. Presumably driven by the wave of nature conservation initiatives being undertaken at a pan-European scale (notably since the Council of Europe's Conservation Year in 1970; Brocx 2008), the NCC, for the first time, formalised principles that underpinned geoconservation. The Council identified land or water containing plants, animals, geological features or landforms of special interest based on the following two main principles:

1. a prime duty to future generations to preserve our heritage so that it may become theirs. This premise encompasses the scientist's argument that we should maintain the means to seek knowledge in the future; and
2. that conservation has direct and immediate benefits for humanity—the health of the natural world is inextricably linked with our own well-being and its resources underpin every aspect of our way of life.

In 1974, the Geological Curators' Group (of the Geological Society of London) was founded to encourage a wider appreciation of sites of regional significance (Doyle et al. 1994). In 1977, the National Scheme for Geological Site Documentation was established with a Geological Conservation Review (GCR) unit to provide an audit of nationally-important Earth geological Sites of Special Scientific Interest (SSSI). Selected sites were formally designated as SSSI for conservation and management (Fig. 4). Completed in 1988, the review led to the publication of 45 volumes of detailed site reports.

In the context of an audit of sites of geoheritage significance, the GCR process has been a major advance in conservation of features of the Earth Sciences and there is no equivalent worldwide. It became the basis of conservation in future years using a three-stage process, i.e, 1. audit and site selection; 2. site designation through a statutory or non-statutory framework; and 3. site safeguard for management and protection (Prosser et al. 2006), thus identifying sites of geoheritage significance to be conserved for research, education and training, and related "geological leisure" such as recreational and aesthetic appreciation (Wimbledon et al. 1995). This procedure became the foundation of a systematic selection process for geoconservation that was exported from Britain to the rest of the World.

Prior to the GCR, never had so many of the Earth scientists (over 200) been directly involved in collaborating on conservation issues, illustrating the depth and extent that the professional geoscientists were interested in geoconservation. Organisations such as the Geological Society, Geologists' Association, and the Paleontological Association also

Fig. 4 Examples of nationally-important earth geological sites of special scientific interest in Britain. **a** Unconformity at Siccar Point, Scotland (Hutton 1788, 1795); **b** Mylonite along the Moine Thrust, Scotland (Lapworth 1885); **c** Old Red Sandstone stratigraphy toward St. Johns Head, Orkney Islands, Scotland (Barclay et al. 2005); **d** Purbeck fossil forest (Isle of Purbeck east of Lulworth Cove on the in Dorset, England) (Buckland and de la Beche 1836)

becoming involved in the conservation debate. The National Scheme for Geological Site Documentation (NSGSD) was founded in 1977, and assumed a complementary role to the GCR. The NSGSD was organised on a county basis and promoted the establishment of local geological records centres, usually operated by museum-based geological curators supported by volunteer field workers. By 1990, some 18,000 sites had been documented in 55 record centres across Britain (Mason and Stanley 2001).

By 1979, the Shropshire Wildlife Trust became the first (of 47) County Wildlife Trusts to systematically identify and protect natural history sites, including geological and geomorphological sites. It is currently supported by some 10,500 members.

The year 1981 saw the enactment of the *Wildlife and Countryside Act 1981*, which improved the previous structure for the effective conservation of Sites of Special Scientific Interest, and consolidated the importance of the conservation of sites of geoheritage significance in Scotland.

In 1987, the GeoConservation Commission was formed to provide a forum to promote the conservation of Earth Heritage, and to work towards ensuring that sites of geoheritage significance are conserved and maintained for future generations for investigation, education, and enjoyment. Also in 1987, the British Institute for Geological Conservation was founded to accommodate the views of the diverse geological interest groups. This institute was a new, independent body whose sole concern was geological site conservation (Cleal 1994).

One of the last major achievements of the Nature Conservancy Council, before it was subdivided, came in 1990 with the publication of *A handbook of Earth science conservation techniques* and *Earth science conservation in Great Britain—A strategy*, the latter publication providing guidelines to direct the efforts and enthusiasm of geoheritage interest groups towards active conservation in the Earth sciences. Following a consultation process, this approach and strategy represents a consensus of views from people who utilise, or research, or own, or develop Earth Heritage sites. Justification for the conservation of Earth Heritage sites lay primarily in four aims and six objectives.

The four aims of the Nature Conservancy Council strategy are:

- a commitment to the conservation of our natural heritage, whether it is wildlife, habitat, landform, or geological feature,

- a need to allow research for the advancement of science, industry and the understanding of natural processes and their effects on people,
- a need for naturally occurring Earth heritage sites to train Earth scientists and to provide teaching facilities for schools, and
- a need to maintain naturally occurring Earth heritage sites as part of our natural landscape, and in doing so aid greater awareness of natural beauty and natural systems.

The six objectives of the Nature Conservancy Council strategy are:

1. maintaining the SSSI network,
2. extending the Regionally Important Geological/Geomorphologic Sites,
3. developing new conservation techniques,
4. improving the documentation of sites,
5. increasing public awareness, and
6. developing international links.

In addition, the strategy identifies the government and non-government bodies most able to take an active role in managing the ongoing conservation objectives for a particular site, and provides the framework for fostering the effectiveness of local groups in the conservation of sites not afforded legal protection, i.e., that are of great interest and local importance which do not meet selection criteria but which are worthy of protection from damage and loss (Doyle et al. 1994). The strategy effectively became the guidebook to geoconservation in Britain.

3.4 Phase IV (Mid-1990s–2006)

The fourth phase was the refining of legislation, the revision of the classification and site selection, and development of management plans for sites at all levels of "geoheritage significance", i.e., from international to local significance within a whole-of-government and integrated framework. In addition, geoheritage values were extended to include intrinsic and cultural values.

In 1991, the Nature Conservancy Council became responsible for the natural heritage in England only, and was renamed English Nature. It reviewed the whole approach to wildlife and geoconservation, and developed a new integrated approach to conservation and land management—the "Natural Areas approach". In this approach, the assessment, conservation and planning process recognises that there is a link between the underlying geology and soils, and the expression of natural vegetation types and fauna, as well as the intrinsic values of geoheritage (Duff 1994). Further, in 1991, the Joint Nature Conservation Committee (JNCC) was formed by enactment of the *Environmental Protection Act 1990* and the *Natural Heritage (Scotland) Act 1991*. The Nature Conservancy Council was abolished and effectively split into three separate country-based organisations, i.e., English Nature, Scottish Natural Heritage, and Countryside Council for Wales. The JNCC became the forum through which the three conservation agencies in England, Scotland and Wales delivered their statutory responsibilities for the British Isles.

Finally, 1991 also saw the heritage values of sites of geoheritage significance and the importance of conserving them under the GCR summarised under six themes (Ellis et al. 1996). These themes were selected according to defined methods with principles of site selection, and site selection criteria, thus providing for the first time globally, a set of geoheritage themes, methods and criteria that should be considered in selecting sites of significance for conservation and land management (Tables 1 and 2), with detailed examples within the theme of Stratigraphy presented in Table 3.

While the list in Table 2 captures the large majority of sites that would have geoheritage significance in British Isles, in fact, it can also be applied globally.

In the period 1991–1992, Nature Conservancy Council/English Nature produced a series of educational leaflets on

Table 1 Geological conservation review—themes for heritage values

International significance of earth heritage sites	International standards where the relative age of rocks all over the world can be compared
	Reference sites where rocks, minerals and fossils were first described
Exceptional earth heritage sites	Where a feature is exceptionally well preserved
Earth science research	Geoheritage as a resource for present and future research into the geological past. Where sites can be visited and revisited to test old and new theories as new research techniques and new ideas are developed
Environmental forecasting	Geoheritage as a resource for studying past earth processes and to predict how they will operate in the future
Earth heritage sites in education and training	Geoheritage as a resource for training geologists in the principles of geology and landscape processes
Earth heritage as a cultural and ecological resource	Rocks, landforms and soils form the basis for landscapes and varied scenery that are highly valued by communities and the tourism industry, one of the most important economic sectors in United Kingdom

Table 2 Examples in Britain lists for systematic inventory-based surveys (theme-based recognition of geodiversity)

1. Places where a geologic feature, rock type, type specimen first recognised and described (type localities)
2. Historically significant sites where original contributions to understanding of geologic processes/principles were inspired
3. Textbook examples of geological features and processes
4. Palaeontological sites that contain scientifically significant stages of biological evolution
5. Features created by wind, water, ice, weathering and mass wasting
6. Caves and karst topography
7. Hot springs, artesian springs and aquifers
8. Geologic features that offer classic research or educational opportunities
9. Outstanding examples of significant stages in the earth's evolutionary history
10. Variety of related and significant geologic features in a small area; even though any one feature may not be worthy of special recognition, the combination of related features in proximity may be unique and significant
11. Mines and mining districts that have geological or historical significance
12. Geological curiosities such as meteorites, non-volcanic craters etc.
13. Unique or uncommon rock or mineral sites
14. Geological features, formations and landscapes that have exceptional natural beauty with existing or potential recreational uses; and
15. Rock and mineral specimen collection sites with intense recreational use or widespread educational value, or the potential for such recreational or educational use

Earth heritage conservation principles, including *Conserving Our Heritage of Rocks, Fossils And Landforms*; *Fossil Collecting and Conservation*; *Regionally Important Geological/Geomorphological Sites*; and the series "*Earth Science Conservation for…*" (*Landfill Managers*; *Farmers and Landowners*; *the Mineral Extraction Industry*; *Quarry and Pit Managers*; *District Planners*; and *Wildlife Trusts*).

In 1993, in keeping with Objective 6 of the 1990 *Earth Science Conservation in Great Britain—A Strategy*, the JNCC, Geological Society of London and the Geological Society, sponsored the Malvern International Conference on Geological and Landscape Conservation. One of the major items discussed at this Conference was the idea that geoheritage conservation on an international scale might be facilitated by an international convention. The Malvern Conference was also a milestone in developing international initiatives in inventory-based geoconservation on a country-by-country basis (Brocx 2008).

In January 1994 the first issue of the *Earth Heritage* was published. *Earth Heritage* is a free magazine produced twice a year to stimulate interest in a broad range of geological and landscape conservation issues. By 1994, *Planning Policy Guidance 9: Nature Conservation* was put in place, providing the first recognition of Regionally Important Geological Sites (RIGS) and, in 1995, the Environment Agency, the Scottish Environment Protection Agency (SEPA), and the National Park Authority were established under *The Environment Act 1995* (England and Wales). The Act created and set new standards for environmental management "*to protect or enhance the environment, taken as a whole*". The role of urban geology in Earth Heritage Conservation was also addressed (Bennett and Doyle 1996).

In 1999, the UK Regionally Important Geological Sites (UKRIGS) Geoconservation Association was founded to represent the growing RIGS movement and its independent, regional and county-sized RIGS groups across the United Kingdom. UKRIGS' vision is to be "*an outstanding champion of the geological and geomorphological heritage of the British Isles*". It works with other organisations and agencies to conserve surviving Earth Science heritage at local, regional, national and intra-national levels (Prosser et al. 2006).

The year 2001 was important because the *Countryside and Rights of Way Act 2000* (CRoW) was enacted (England and Wales). In terms of conserving and managing Sites of Special Scientific Interest, it is said to be the most significant piece of legislation in 20 years (Prosser and Hughes 2001). The *Act* aims to continue to achieve a secure and well-managed geological SSSI through partnership and co-operation, but with stronger powers, which can be used where conflicting issues with landowners and developers cannot be resolved through negotiation. There is an emphasis on supporting owners and occupiers of SSSI in the positive management of their land to benefit Geology and wildlife, rather than the fundamentally negative approach of paying money out to prevent new operations that could damage the sites. However, where appropriate management cannot be secured by agreement, the new legislation has the power to impose enforceable conditions (*op. cit.*). The *Act* requires all government agencies to conserve and enhance SSSI, and provide greater powers for conservation agencies to gain entry to investigate offences, and to monitor their status.

The year 2001 also saw a number of other programmes, agreements; orders and actions come into place. Under the

Table 3 Type examples of the earth heritage theme of stratigraphy under the geological conservation review

Stratigraphic categories
Pre-Phanerozoic
Late Proterozoic red beds (Torridonian), NW Scotland
Archaean/Proterozoic, Lewisian (Scourian and Laxfordian), NW Scotland
Phanerozoic
Cambrian type area, North Wales, southwest Wales
Ordovician (Arenig, Llanvirn, Llandeilo and Caradoc) type area Wales
Lower Silurian (Llandovery, Wenlock Ludlow) stratotypes
Permian-Triassic red bed sequence of Devon coast
Upper Cretaceous Chalk stratigraphy, Kent and Sussex
Phanerozoic Quaternary
Thames terrace stratigraphy, Pleistocene gravels/interglacial
Cromerian interglacials, Norfolk
Palaeontological categories
"Precambrian" Charnian faunas of the East Midlands
Early Devonian petrified flora and 'insects', Rhynie
Mississippian fish, first reptiles southern Scotland and the Midland
Late Triassic fissure faunas/floras, including first mammals world-wide
Early Jurassic marine reptiles and insects, Lyme Regis and Yorkshire
Palaeoenvironmental categories
Late Triassic desert wadi fills, South Wales
Early Cretaceous alluvial plain deposits and biota, Isle of Wright
Sites with igneous and metamorphic geology
Tertiary lavas and intrusions, Inner Hebrides
Igneous rocks of the Lewisian complex
Mineralogical, economic categories
Stratiform deposits within the Dalradian rocks, Grampian Highlands
Cambrian-Ordovician sedimentary exhalative Fe–Mn ores, North Wales
Magmatic segregations associated with Caledonian intrusive rocks
Hematite deposits of Cumbria, South Wales and the Forest of Dean
Historic, for development of geological science
Hutton (1795) angular unconformities, southern Scotland
Hutton's magmatic origin of granite (Glen Tilt)
First described pre-Tertiary mammals, Middle Jurassic of England

Global Geosites Programme, in consultation with the wider geological community in Britain, a "frameworks list" (a category-based inventory), has been completed with proposed sites for conservation designated as sites of international significance (Cleal 2001). These sites are considered to represent world-class examples of geoheritage significance. Some of the categories and sites are listed as examples in Table 4. Agreement was reached by the JNCC, the Inter-agency Earth Heritage Working Party and Chief Scientists to update the entire GCR Site Series according to scientific principles, on a 10–15 year cycle (Weighell and Ellis 2001). In addition, the first World Heritage Site in England to be inscribed on account of its geology was established at the Dorset and East Devon Coast.

During the period 2002–2003, the concept of Local Geodiversity Action Plans (LGAP) was developed by English Nature. LGAPs integrate the delivery of both national and local geological conservation objectives through developing partnerships and plans aimed at conserving, managing and promoting sites of geoheritage significance on a local basis (Burek and Potter 2003). LGAPs provide a context for the broad range of activities associated with geological conservation, and provide a process and framework for the delivery of geoconservation that previously did not exist (Prosser et al. 2006). In May 2003, the Geology Trusts (formerly the Western Association of RIGS Groups) was launched in England and Wales. This new county-based organisation works in a similar way to its wildlife equivalent. It currently comprises six of the leading county-based Geoconservation and Earth Heritage Trusts: Gloucestershire, Herefordshire and Worcestershire, Oxfordshire, Shropshire, Warwickshire and Wiltshire.

In 2003, under the European Geoparks initiative, the Declaration of European Geoparks for the Abberly Hills, Malvern Hills, and the North Pennines marked a new approach to geological conservation in Britain on a wider scale.

The year 2004 saw the *Nature Conservation (Scotland) Act* enacted, revising and strengthening the law concerning SSSI. This new Act addressed many of the recognised shortcomings of the *Wildlife & Countryside Act 1981* (as amended). The listing and proclamation of SSSI notified under the *Wildlife and Countryside Act* continued under the new Act. In addition, the Earth Science Conservation Classification, developed by the Nature Conservancy in 1990, was revised. In contrast to the original classification which had 11 site types and two main categories, the revised classification has 16 different site types in three main categories:

1. exposure or extensive (E)—geological features that are relatively extensive below the surface;
2. integrity (I)—sites are geomorphological and are characterised by the need for holistic management; and
3. finite (F)—sites contain geological features that are limited in extent so that removal of material may cause depletion of the resource.

The revised classification has been agreed to by all of the British Isles statutory conservation agencies (Prosser et al. 2006).

Table 4 World-class examples of sites of geoheritage significance in Britain

Category	Geological Era, Period, or Epoch	Location
Stratigraphic	Precambrian (Pre-Phanerozoic)	Late Proterozoic red beds (Torridonian), NW Scotland
		Archaean/Proterozoic, Lewisian (Scourian and Laxfordian), NW Scotland
	Phanerozoic (lower Palaeozoic to upper Mesozoic)	Cambrian type area, North Wales, southwest Wales
		Ordovician (Arenig, Llanvirn, Llandeilo and Caradoc) type area, Wales
		Lower Silurian (Llandovery, Wenlock Ludlow) stratotypes, SW Scotland
		Permian-Triassic red bed sequence of Devon coast, England
		Upper Cretaceous Chalk stratigraphy, Kent and Sussex, England
	Quaternary	Thames terrace stratigraphy, Pleistocene gravels/interglacial, River Thames, England
		Cromerian interglacials, Norfolk, England
Palaeoenvironmental	Mesozoic	Late Triassic desert wadi fills, South Wales
		Early Cretaceous alluvial plain deposits and biota, Isle of Wight, Wales
Palaeontological	Precambrian, Palaeozoic to Mesozoic	"Precambrian" Charnian faunas of the East Midlands, England
		Early Devonian petrified flora and 'insects', Rhynie, Aberdeenshire, Scotland
		Mississippian fish, first reptiles, southern Scotland and the Midlands, England
		Late Triassic fissure fauna/flora, including first mammals world-wide
		Early Jurassic marine reptiles and insects, Lyme Regis, Wales and Yorkshire, England
Sites with igneous and metamorphic geology	Precambrian and Tertiary	Tertiary lavas and intrusions, Inner Hebrides, Scotland
		Igneous rocks of the Lewisian Complex, NW Scotland
Mineralogical, economic	Precambrian, lower to upper Palaeozoic	Stratiform deposits within the Dalradian rocks, Grampian Highlands, Scotland
		Cambrian-Ordovician sedimentary exhalative Fe–Mn ores, North Wales
		Magmatic segregations associated with Caledonian intrusions, various locations in the UK
		Haematite deposits of Cumbria, South Wales, and the Forest of Dean, England
Historic, for development of geological science	Silurian to Devonian; Mesozoic	Hutton (1788, 1795) angular unconformities, southern Scotland
		Hutton's magmatic origin of granite (Glen Tilt), Scotland
		First-described pre-Tertiary mammals, Middle Jurassic of England
Global stratotype section and points (GSSPs)	Callovian/Oxfordian boundary interval base of Jurassic	Ham Cliff near Redcliff Point, Weymouth, Dorset, England (Page et al. 2008), and St Audries Bay, West Somerset coast, West Somerset, England (Page et al. 2009)

An important milestone at the national level in 2004 was formal recognition and promotion of the linkage between geodiversity and biodiversity (English Nature 2004). The Natural Areas concept developed by English Nature in the 1990s, as a strategic landscape-scale approach to nature conservation, placed geodiversity at its core by defining innumerable terrestrial areas based on rocks, soils and landforms (English Nature 1998). This was consolidated by the Office of the Deputy Prime Minister in 2005–2006 (ODPM 2005, 2006) in publishing guidelines for planning for biodiversity and geological conservation. Geodiversity was recognised as contributing to landscape conservation, and was integrated into the planning system through the Landscape Character Types concept, placing human settlement and land-use patterns into their context of rock types, soils and landforms (Stace and Larwood 2006).

3.5 Phase V (2005-Present)

This phase involves building on the recognition that geodiversity underpins biodiversity, the development of holistic management strategies by linking geodiversity to biodiversity and geodiversity to land-use planning, and the use of geoheritage areas for geotrails and geotourism. While there were earlier activities that began linking geodiversity to biodiversity and using geological precepts in planning (Devon Biodiversity Partnership 1998, 2005; English Nature

1998), Phase V commenced in earnest around 2005; it is still ongoing, and overlaps with the latter stage of Phase IV.

The formal linking of geodiversity to biodiversity provided a process by which geologists with a focus on geoheritage and geoconservation engaged with biologists/ecologists with their focus on biodiversity and bio-conservation. This provided the community of biologists/ecologists with an understanding that, to design and maintain a robust ecosystem conservation plan, there needed to be a foundation of geosciences. It also provided decision-makers with a platform to understanding the importance of geodiversity because of its conceptual similarity to biodiversity which, by that stage, had been entrenched in the conservation arena.

The year 2005 saw the publication of the *Planning Policy Statement 9: Biodiversity and Geological Conservation*. This policy represented a major step forward in achieving greater recognition for geological conservation in the planning system in England. In particular, it makes a number of important statements about the need for planning to deliver geological conservation across the whole landscape, not just protected sites.

In October 2006, English Nature produced an important publication: *Geological conservation—a guide to good practice: working towards Natural England for people, places and nature*. The environment activities of the Rural Development Service and the Countryside Agency's Landscape, Access and Recreation division merged in a single body called *Natural England*. Natural England is an organization that can deliver geological conservation as part of whole-of-natural-environment management. It brings together geology, geomorphology, soils, habitats, landscapes, and public access and recreation. This approach supports the delivery of sustainable environmental management (Stace and Larwood 2006), and geological conservation now is an integral part of English conservation and land management. In England, there are approximately 1,240 SSSI with a notified geological interest.

In 2006, English Nature, the Countryside Agency and Department for Environment, Food and Rural Affairs' Rural Development Service jointly published '*Natural Foundations: geodiversity for people, places and nature*' as major a step towards an integrated approach to environmental conservation, management and enhancement, by linking biodiversity, landscape and human life (Stace and Larwood 2006).

Over the period 2005–2013, numerous other works linked geodiversity to biodiversity in Britain. These included Jonasson et al. (2005) who used the link between geodiversity to biodiversity in the European mountains with case studies from Sweden, Scotland and the Czech Republic, Gordon and Barron (2012) who emphasised the value of geodiversity and geoconservation in developing a more strategic approach to ecosystem management, and Gray et al. (2013) who emphasised the contribution of geoscience in delivering integrated environmental management.

The development of holistic management strategies by linking geodiversity to biodiversity and to land-use planning was pursued over this period by Gordon and Leys (2001), Page et al. (2005) and Page (2008).

The focused use of geoheritage areas and geosites for geotrails and geotourism also has been one of the most recent activities during Phase V and came about as an outgrowth of the recognition of the value of these sites to science, education and tourism. This activity was also linked in parallel to the developing concept of geoparks where the geological features of a region were recognised as locations for geoconservation and local economic sustainable development based on the sites of geoconservation (Eder and Patzac 1999). In Britain, key areas that were used for geotrails and geotourism included the Jurassic Coast World Heritage Site in Dorset and East Devon, the Dinosaur Coast of North Yorkshire and the Aberlady and Malvern Hills Geopark are actively promoting geotourism (Rawson and Wright 1992; Welton 2004; Badman et al. 2003; Earth Heritage Trust 2008).

4 Geoparks—A Brief History

Globally, there are three geoparks initiatives, viz. (1) National Geoparks; (2) Global Geoparks; and (3) European Geoparks. National Geoparks have been in existence for the longest period as geological conservation areas or regions. The Global Geoparks and the European Geoparks are more recent endeavours.

National Geoparks are areas designated by individual countries for their geoheritage values. In fact, many may not be termed geoparks, but conserved either under Category III of IUCN conservation categories and criteria, and effectively function as geoparks in that the National Heritage site, or National Conservation of the site is based on its geological values. In this context, there either had been no application for a given National Geoparks in an individual country to be part of an international network, or they do not meet the criteria, or there has been a choice not to be affiliated to global networks. However, all three initiatives can be seen to share a common aim to protect geodiversity, promote geoheritage, and to support sustainable economic development.

The European Geoparks Network (EGN) was initially created in 2000 as an experimental tool to promote geological heritage in Europe, originally consisting of four territories (France, Germany, Greece and Spain). With an annually-expanding programme, the EGN has now 44 Geoparks (including cross boundary sites) in Austria, Romania, Italy, Portugal, Slovenia, Hungary, Spain, the British Isles, Norway, Iceland, Croatia, Finland, and Poland.

In April 2000, the EGN was placed under the auspices of UNESCO and, in 2004, in Madonie, Italy, the "Madonie Declaration" was signed.

Global Geoparks are defined as a territory encompassing one or more sites of scientific importance, not only for geological reasons but also by virtue of its archaeological, ecological or cultural value. The Global Geoparks Network (GGN), established in 2004 is an annually-expanding programme that currently (2013) has 100 geoparks across 29 countries, of which 28 geoparks are in China. The GGN is a "quality label", without specific legal effect beyond the commitment to protect the sites under the applicable local, regional or national laws.

Africa has only one national geopark which is in Morocco (Mgoun Geopark). Further, most of the other African countries *do not have legislation to protect their sites of geoheritage significance* (Errami et al. 2013). In order not to lag behind in the endeavour of geoconservation, in 2009, the African Association of Women in Geosciences created the African Geoparks Network (AGN) to promote the concept of geoparks in Africa and to conceptualise how African geoparks can be achieved (Errami et al. 2012).

5 Key Progress in Geoconservation Globally

As outlined earlier in this paper, there has been emphasis on Britain as a model for the history of geoheritage and the development of geoconservation, as it shows the most complete record of the phases of geological awareness and pursuit of geoconservation. Other countries show incomplete or only partial stages of this type of history (Brocx 2008).

The key milestones in the history of geoconservation, globally, either in the conservation of a geological site, or an important event, or some other conservation-oriented activity, strategy, or concept, are summarised below:

- The Baumannshole Cave in Germany was the subject of a nature conservation decree by Duke Rudolf August in 1668 (Erikstad 2008);
- Foundation of the Geological Society of London (1807);
- Natural monuments first used as a term by Humboldt 1819 (Wiedenbein 1994);
- Crystal Palace Park, SE London, the first geological theme park (1853);
- The importance of (geological) monuments is proffered as sites where the Earth's geological history can be deciphered (Lyell 1872);
- *The Antiquities Act, USA (1906)*, which is arguably one of the most important Acts in protecting natural areas of all time;
- *National Parks and Access to Countryside Act, Great Britain (1949)*;
- Sites of Regionally Important Sites—RIGS (1980s);
- ProGEO, and the geosites programme (1990);
- ProGEO working groups (1996);
- Declaration of the Rights of the Memory of the Earth (in Digne in 1991; Anon 1993);
- The Malvern Conference (1993);
- European Geoparks Network (2000);
- Global Geoparks Network (2004);
- Council of Europe Working Group on the Geological Heritage (2002);
- IUCN Resolution Geoheritage (2008);
- The Journal *Geoheritage* (2009);
- Asia-Pacific Geoparks Network (2009);
- African Geoparks Network (2009);
- IUCN Resolution Geoheritage WCC-2012-Res-048-EN: "Valuing and conserving geoheritage within the IUCN Programme 2013–2016".

6 Conclusions

While there was an interest in Geology, rocks, fossils, geological mapping, minerals, geohistorical interpretations, and other matters geological, in various regions in the Antiquities and during the Renaissance, using the terminology of the model of Britain, much of the activity did not proceed past what could be termed "Pre- Phase I", where the history of geoheritage/geoconservation in Britain is considered to have progressed to near-completion and provides the best model of the unfolding of the history of Geology, leading to the concept of geoheritage and geoconservation in time, and their use in landscape and land-use planning, conservation of biodiversity, and the establishment of geoparks.

Britain, a country rich in geoheritage sites, thus plays a key role in the history of modern-day geoconservation. Its history reveals that, with advances in the geosciences, and a growing awareness of the importance of geology and geoheritage, geoconservation emerged and became incorporated into environmental legislation, and planning and management at all government levels. Geoheritage is a fundamental tenet of conservation in that it addresses scientific importance, and geoconservation addresses the importance of geology and geoheritage and the link between geodiversity and biodiversity and cultural needs. Geoheritage also provides a sense of place, spatially, evolutionarily, and temporally. Doyle et al. (1994) noted the importance of geoheritage for modern society, and for future generations.

The unfolding history of geoconservation in Britain is seen to follow two strands. The first led to systematic inventory-based geoconservation. The ad hoc conservation of sites during the pioneering days of scientific discovery in the 1800s led to early audits to provide an inventory of sites of geological significance in the mid-1900s, and then to the systematic inventory-based site assessment and selection of SSSI and heritage themes resulting from the ongoing Geological Conservation Review, beginning in 1977. The second strand began in the 1900s, overlapping in time, and running parallel to the first. There was recognition of the need to identify and conserve sites of geoheritage significance, and the development of methods and site selection criteria, which resulted in the development of legislation, conservation-friendly policies, practices, action plans, and active voluntary local community-based geoconservation groups.

In terms of its historical development in Britain, the pattern of geoconservation that is of relevance to understanding the historical unfolding of events is summarised in Table 5. An understanding of these events can assist to circumventing problems and perhaps avoiding similar destruction of significant sites in countries that are in the early stages of developing a framework for their inventory of geological, geoheritage and geoconservation sites. The important aspect to arise from this historical review is that, in time, with knowledge and a growing awareness of the importance of geoheritage, geoconservation as a cultural process emerges in Western Industrialised countries, and thereafter there is a sustained effort to identify, conserve and manage sites of geoheritage significance.

Table 5 Summary of important milestones in geoconservation in the Britain

1807	The geological society of London founded
1832	1st geological survey conducted at Devon
1835	The geological ordnance survey founded
1887	1st practical steps by local government in geoconservation of a fossil site
1945	1st inventory of sites of scientific interest
1977	Geological conservation review established
	The national scheme for geological site documentation
1987	The geoconservation commission was founded
	The British institute for geological conservation founded
1990	Publication—*Earth science conservation in Great Britain—a strategy*
1991	1st educational material earth heritage conservation principles
1993	1st international conference on geoconservation
1994	1st recognition RIGS in planning policy
2001	CRoW Act: 1st time land ownership not an impediment to geoconservation
	1st world heritage site in the British Isles based on geological values
2003	The concept of local geodiversity action plans developed
	Geology trusts formed
	1st European geopark established in the British Isles
2004	1990 earth science conservation classification under review
2005	Planning policy statement 9: biodiversity and geological conservation
2006	Earth science conservation classification revised
	Publication of *Geological conservation a guide to good practice: working towards natural England for people, places and nature*

There have been more significant milestones and progressive movements towards systematic geoconservation in Britain than in other nation states (Brocx 2008). With its relatively small land area and dense population, there are many demands on the land that may conflict with site conservation. Whilst it is recognised that it is impractical to conserve every rock exposure, it has been considered essential to conserve sites making a unique contribution to Britain's Earth Heritage (Weighell and Ellis 2001). Interestingly, the completion of the GCR publication series and the planned database for updating and disseminating Earth Heritage information goes beyond its shores to the inventory-based ProGEO programmes, and is a major milestone in the development of Earth Heritage conservation in both Britain and internationally (Brocx 2008).

Since the creation of the GGN, there has been an extensive use of geodiversity and geoheritage for social and economic development, and the promotion of Geoconservation. The creation of the African Geoparks Network in 2009 came about as a contribution of the African Association of Women in Geosciences to promote the geopark concept on the African continent and the role that it could play in geoconservation for the well-being of African societies.

From this historical account it can be seen that since antiquity, i.e., early civilizations, to modern society, different values have been placed on geological phenomena. This ranges from valuing precious stones and metals based on economic exploitation and utilitarian use to academic pursuits, the identification and conservation of sites of scientific interest, valuing geoheritage, and geotourism. Emerging from the war, famine and plagues of the middle ages, in Europe, the Age of Enlightenment overlapped with the Industrial Revolution, with the development of the discipline of Geology and Geoheritage, and associated academic pursuits far behind the development of techniques for mapping mining and metallurgical extraction of metals and minerals. While Britain stands as a case study for Western Society, China has its own independent history of developing the geological sciences, and is a world leader in establishing National and global Geoparks.

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Part II

History of Geoheritage, Geoparks and Geotourism: Case Studies

Geosites, Sites of Special Scientific Interest, and Potential Geoparks in the Anti-Atlas (Morocco)

Géosites, Sites Géologiques d'Intérêt Scientifique Spécial et potentiels géoparcs dans l'Anti-Atlas (Maroc)

الجيومواقع، المواقع الجيولوجية ذات الأهمية العلمية الخاصة والجيومتنزهات ذات المؤهلات بالأطلس الصغير (المغرب)

E. Errami, M. Brocx, V. Semeniuk, and N. Ennih

Abstract

An inventory of the geoheritage features of the Anti-Atlas region has been performed to promote geoheritage and geoconservation in Morocco. This latter is best achieved after assigning heritage values to these features and identifying geosites, specific areas of special value or interest (Geological Sites of Special Scientific Interest, or SSSI) that usually are of International significance, or by viewing sites as integrated geological ensembles with significant geology that needs to be protected as an ensemble (Geoparks). Sites that could function as geosites, SSSI and/or as geoparks have a special significance for research, education and geotourism. The Anti-Atlas geology reflects its tectono-metamorphic and magmatic evolution from the Proterozoic to Mesozoic with plate collision, subduction and obduction witnesses, Mesozoic stratigraphic sequences, fossil-bearing strata, and arid zone landforms. Sites that could function as SSSI include pre-Pan-African doleritic dykes, the Bou Azzer and Siroua Ophiolites, the Pan-African diamictites, the Major Anti-Atlas Fault, the Late Neoproterozoic stromatolites, the unconformity between the late Neoproterozoic Ouarzazate volcanic Supergroup and Cambrian Tata Group, the contact between Taghdout Group and the Zenaga Eburnian (Palaeoproterozoic) formations, the contacts between three Pan-African Groups, viz., Saghro Group—Mgouna Group—Ouarzazate Group, the Ediacaran Iknioun granodiorite and the Devonian Kess Kess carbonate mounds. Sites that could function as geoparks include: the Zenaga inliers, the Neoproterozoic passive margin (Taghdout Group), and the Jurassic Foum-Zguid dyke traversing various formations. The Anti-Atlas region also hosts numerous internationally important fossil localities that could function as SSSI, e.g., the large Cambrian trilobite (Paradoxides), Ordovician trilobites (Asaphus) as death assemblages, Silurian and lower-most Devonian Orthoceras-rich black limestones, Frasnian plants

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from the Drâa Valley and ammonite-rich limestones. The geological areas that host these SSSI could function as geoparks.

Résumé

Un inventaire des caractéristiques géologiques de la région de l’Anti-Atlas a été entrepris pour promouvoir le géopatrimoine et la géoconservation au Maroc. Cette dernière est mieux assurée après l’attribution des valeurs géopatrimoinales à ces caractéristiques et l’identification des sites de valeurs ou d’intérêts particuliers (Sites géologiques d’Intérêt Scientifique Spécial, ou SISS) ou en considérant les sites comme un ensemble géologique intégré qui a besoin d’être protégé dans le cadre de géoparcs. Les géosites qui peuvent fonctionner comme SISS et/ou géoparcs ont une importance particulière pour la recherche, l’éducation et le géotourisme.La géologie de l’Anti-Atlas reflète son évolution tectono-métamorphique et magmatique durant le Protérozoïque et le Mésozoïque avec différents témoins de subduction, d’obduction, des séquences stratigraphiques, des niveaux fossilifères et des paysages des zones arides. Les sites, qui pourraient fonctionner comme SISS sont les dykes doléritiques pré-panafricains, les complexes ophiolitiques de Bou Azzer et de Siroua, les diamictites panafricaines, l’accident majeur de l’Anti-Atlas, les stromatolites Néoprotérozoïques, la discordance entre les formations volcaniques Néoprotérozoïque et les formations cambriennes, le contact entre le Groupe de Taghdout et les formations Eburnéennes (paléoprotérozoïque) de Zenaga, les contacts entre les trois groupes panafricains (Groupe Saghro—Groupe Mgouna—Groupe Ouarzazate), la granodiorite Ediacarienne d’Iknioun et les monts carbonatés Dévonien du Kess Kess. Les sites qui pourraient servir de géoparcs sont les boutonnières de Zenaga, la série Néoprotérozoïque de marge passive (Groupe de Taghdout), et le dyke Jurassique de Foum Zguid. L’Anti-Atlas contient aussi de nombreux sites fossilifères d’importance internationale qui pourrait fonctionner comme SISS tels que les trilobites géant du Cambrien (Paradoxides); les trilobites de l’Ordovicien (Asaphus) comme assemblages fossilifères, les calcaires noirs à Orthocères du Silurien et du Dévonien inférieur, les plantes frasniennes de la vallée du Drâa et les calcaires riches en ammonites. Les régions géologiques qui abritent ces SISS peuvent fonctionner comme geoparcs.

ملخص

لقد تم القيام بجرد للخصائص الجيولوجية لمنطقة الأطلس الصغير لتعزيز الجيوتراث والجيومحافظة بالمغرب. هذه الأخيرة أضحت مؤكدة بشكل أفضل بعد منح قيم جيوتراثية لهذه الخصائص وتحديد المواقع ذات قيمة أو أهمية خاصة) مواقع جيولوجية ذات أهمية علمية خاصة) أو تقييم المواقع كوحدة جيولوجية مدمجة تحتاج إلى حماية في إطار الجيومنتزهات. الجيومواقع التي يمكن أن تكون بمثابة مواقع جيولوجية ذات أهمية علمية خاصة أو جيومنتزهات هي ذات أهمية خاصة للبحث، التربية والجوسياحة. تعكس جيولوجية الأطلس الصغير تطوره التكتوني التحولي والصهاري خلال الحقبين البروتروزويك و الميزوزويك مع مختلف دلائل الطمر، الطفو، تسلسل الطبقات الرسوبية، ومستويات أحفورية ومناظر مناطق جافة. المواقع التي يمكن أن تصنف بمثابة مواقع جيولوجية ذات أهمية علمية خاصة هي العروق الدوليريتية ما قبل البان إفريقي، و مجمعي أفيوليت بوعزار وسيروا،و الصخورالجليدية البان إفريقية، و الفالق الرئيسي للأطلس الصغير، والستروماتوليت النيوبرتيروزوية، والتماس بين الصخور البركانية النيوبرتيروزوية والصخور الكمبرية، و تنافر بين مجموعة تغدوث وصخور البروتيروزوي القديم لزناكة، و تنافرات بين المجموعات البان إفريقية الثلاثة، وكرانوديوريت إكنيون وقعيرة جبل كيسان الأوردوفيسي، وتلال كس كس الكلسية الديفونية. المواقع التي يمكن استخدامها كجيومنتزهات هي عروة زناكة، وسلسلة الهامش غير النشيط النيوبرتيروزوية (مجموعة تغدوث) ، والعرق الجوراسي لفم زكيد.ويحتوي الأطلس الصغير أيضا على عدد من المواقع الأحفورية ذات الأهمية الدولية علمية خاصة مثل ثلاثية الفصوص الكمبري، والكلس الأسود ذات الارثوسير السيلوري والديفوني الأدنى، والنباتات الفرسنية لوادي درعة والكلس الغني بالأمونيت يمكن للمناطق الجيولوجية التي تؤوي هذه المواقع الجيولوجية أن تعمل كجيومنتزهات.

Keywords

Morocco • Anti-Atlas • Geoheritage • Geosite/SSSI • Geoconservation • Geoparks

Mots-clés
Maroc • Anti-Atlas • Géopatrimoine • Géosite/SISS • Géoconservation • Géoparcs

الكلمات الرئيسية
المغرب • الأطلس الصغير • جيوتراث جيومواقع/مواقع جيولوجية ذات أهمية علمية خاصة • جيومحافظة • جيومنتزه

1 Introduction

The history of planet Earth since its formation ca 4.6 Ga ago is recorded in its rocks, fossils, minerals, landscapes, etc. This story can be read from large scale (e.g., the evolution of the Andes Mountain Chain), to medium scale (such as the historically important site at Siccar Point where Hutton first described and conceptualised the importance of unconformities; Hutton 1788), to fascinating aspects at the micro-scale (e.g., the story inherent in the zoning, corrosion, inclusions, fracturing-and-healing, and overgrowths of the Archaean zircons of Jack Hills, the oldest crystals on Earth; Wilde et al. 2001). The story of the Earth and its products are linked to the ongoing history of human development, providing natural resources, a sense of place, and have scientific, historical, cultural, aesthetic, and religious values. In addition, Earth systems are the foundation of all ecological processes, are part of the heritage of our sciences (Torfason 2001), and have been an inspiration and a framework to other sciences, such as astronomy, chemistry, evolutionary biology, archaeology, arts, etc.

Geology is the library of Earth and life histories. The conservation of representatives of its features across continents and regions ensures that the witnesses to this history are available for present and future generations. Thus geoconservation is an important endeavour to preserve scenically-and/or scientifically-important areas for a number of reasons. From environmental management considerations, it ensures that the Earth functions in an environmentally sustainable way to maintain ecosystems for the well-being of their inhabitants. Geoconservation ensures also that Earth history, as a field textbook, is preserved in critical areas to be examined by scholars, researchers, students, and the interested public. Geoconservation ensures that key areas are available for geotourism considerations. Destruction of in-field information deprives future researchers and students of the opportunity to test, learn on-site, revise, or extend information in the light of new technology or new concepts. However, as a result of the ongoing tension between resource exploitation and resource conservation, geoconservation brings with it the questions—what to preserve, and how much to preserve? To this objective, geoconservation practitioners worldwide have been working towards raising the consciousness of land managers, governments, scientists, and the public to the importance of geoheritage, and geoconservation, and towards developing strong criteria to ensure representative and adequate geoconservation of Earth.

Building on geoheritage from global reviews to local principles for conservation and planning (Brocx 2008), a "tool-kit", termed here the "Geoheritage Tool-kit" has been developed to address geological and geomorphological features that should be encompassed under the umbrella of geoheritage (Brocx and Semeniuk 2009, 2011). In a given area, geoheritage features of geoconservation significance can range from large- to small-scale, from international to local in significance, can encompass a wide range of geological/geomorphological features, and can occur in isolation, or in inter-related suites that should be viewed and preserved as an ensemble. The Geoheritage Tool-kit has been designed to systematically address and assess this diversity. This paper outlines the concepts underpinning the approach adopted to geoheritage and geoconservation, describes the Geoheritage Tool-kit as developed in Western Australia, and applies it to the Anti-Atlas in Morocco to identify sites and regions that may be targeted either as SSSI or as aspiring geoparks. This work aims also to contribute to enhance geoconservation and promote Moroccan geoheritage.

2 Scope, Scale, and Levels of Significance of Geoheritage Features, and Terms/Definitions

In terms of scope, since geoheritage and geoconservation are concerned with heritage and conservation of geological matters, then all components of geology should be part of geoheritage (Brocx and Semeniuk 2007). This includes the subsidiary disciplines of geology such as igneous, metamorphic and sedimentary geology, igneous, metamorphic and sedimentary petrology, stratigraphy, structural geology, mineralogy, palaeontology, geomorphology, pedology, hydrology, and surface processes such sedimentology. This list covers a large variety of processes and products but, in addition, it also traverses a wide range of scales, from global tectonics, mountain building, and landscape evolution, to local surface processes such as weathering, erosion and sedimentation and, at microscale, diagenesis, crystal defects and deformation, amongst others. This perspective definitively places many aspects of geology, perhaps previously not recognised as part of the spectrum of geoheritage (Brocx and Semeniuk 2007).

Sites of geoheritage significance can be assigned to one of four categories (Brocx 2008; Fig. 1). Scale is important to consider in geoheritage/geoconservation since features of significance can range from crystals, bedding planes and outcrops, to that of landscapes and phenomena at montane-scale. In many locations, sites are important because of crystal-sized features and crystal fabrics, and it is often at this scale that the story of Earth unfolds. At the next scale, features of geoheritage significance are represented by outcrops and bedding scale features. Important geological/geomorphological features continue to occur in increasing scale, up to the scale of mountain ranges, extensive landforms, and major drainage basins. Scales and levels of significance assigned to geoheritage are given in Figs. 2 and 3.

Geoconservation involves preservation of specific sites (special sites), or of geological ensembles. The former is where a significant geological feature occurs in isolation, or may have historical or cultural significance. The term SSSI (Bowen et al. 1996) refers to a small or isolated site that has special significance. The encompassing local geology of these features may not be significant nationally or regionally. In contrast, the term "geosite" is used to refer to a small location that has been identified as having geological attributes but has not been allocated special significance. In this paper, most of the identified geosites are, in fact, SSSI.

Geoconservation of geological ensembles involves preservation of areas that contain a range of significant geological features. Geological ensembles can be viewed as a suite of inter-related SSSI occurring in the same area.

Globally, a geopark is defined as a territory encompassing one or more sites of scientific importance, not only for geological reasons but also by virtue of its archaeological, ecological or cultural value. The European Geoparks Network, established in 2000 (Zouros 2000) defines a geopark as an area to conserve and valorise geological heritage through an integrated and sustainable development of their territories. The Asia Pacific Geoparks Network, founded in 2007, defined a geopark as a nationally-protected area containing a number of geological heritage sites of particular importance, rarity or aesthetic appeal. These Earth heritage sites are part of an integrated concept of protection, education and sustainable development. The African Geoparks Network created by the African Association of Women in Geosciences in 2009 (Errami et al. 2012a, b) defines a geopark as an area where geoheritage could be used as a tool to enhance human sustainable development. All these initiatives aim to protect geodiversity, promote geological heritage, and to support local sustainable economic development, thus involving

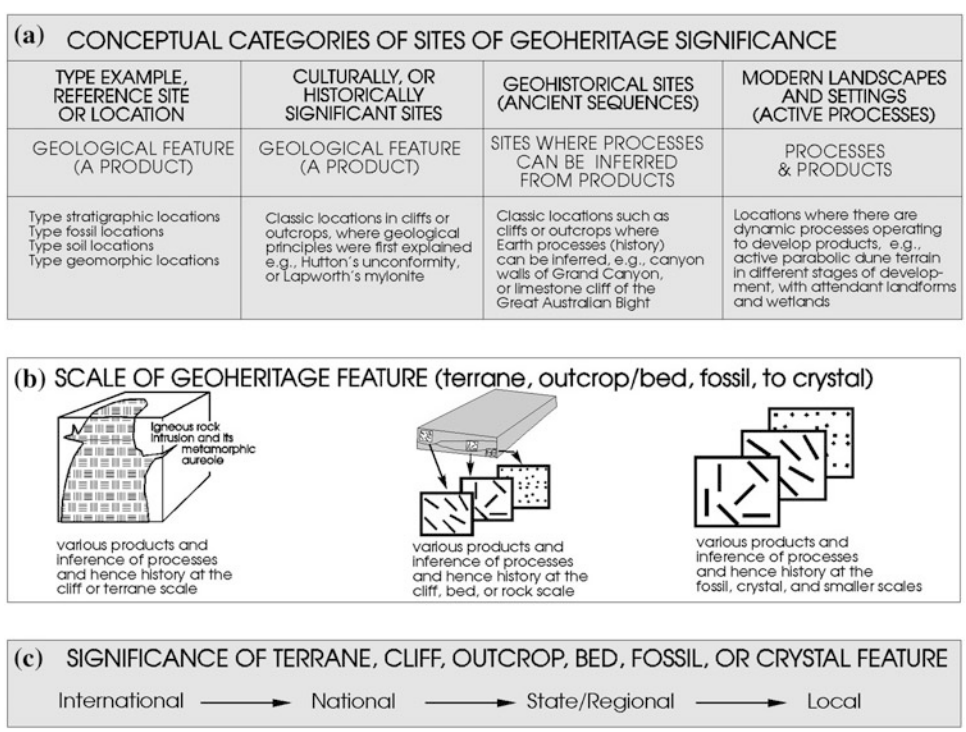

Fig. 1 The essentials of geoheritage (Brocx 2008). **a** The four categories of sites of geoheritage significance. **b** The use of scale. **c** Designating a level of significance

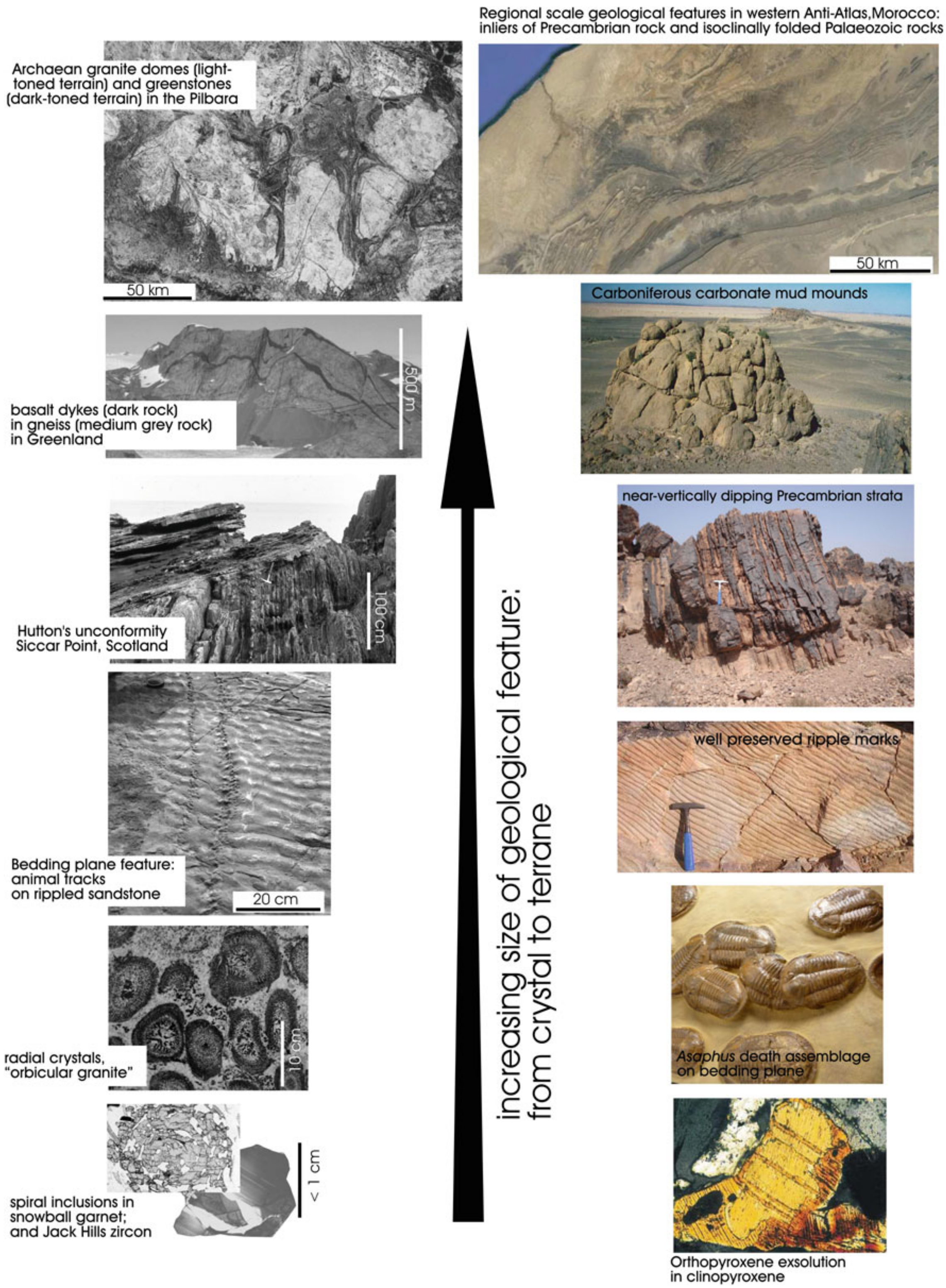

Fig. 2 Scales of geological phenomena from crystal size to montane terrains. The *left* hand side of the diagram shows the original range of features as illustrated by Brocx and Semeniuk (2007) and the *right* hand side shows examples of geological features from Morocco

community and commercial interests. We view geoparks as conservation, promotional valorization entities focused on geological and geomorphological attributes for local sustainable development. That is, to provide a comparative context and example, using a biological analogue, if a region can be conserved for its biological attributes and biodiversity,

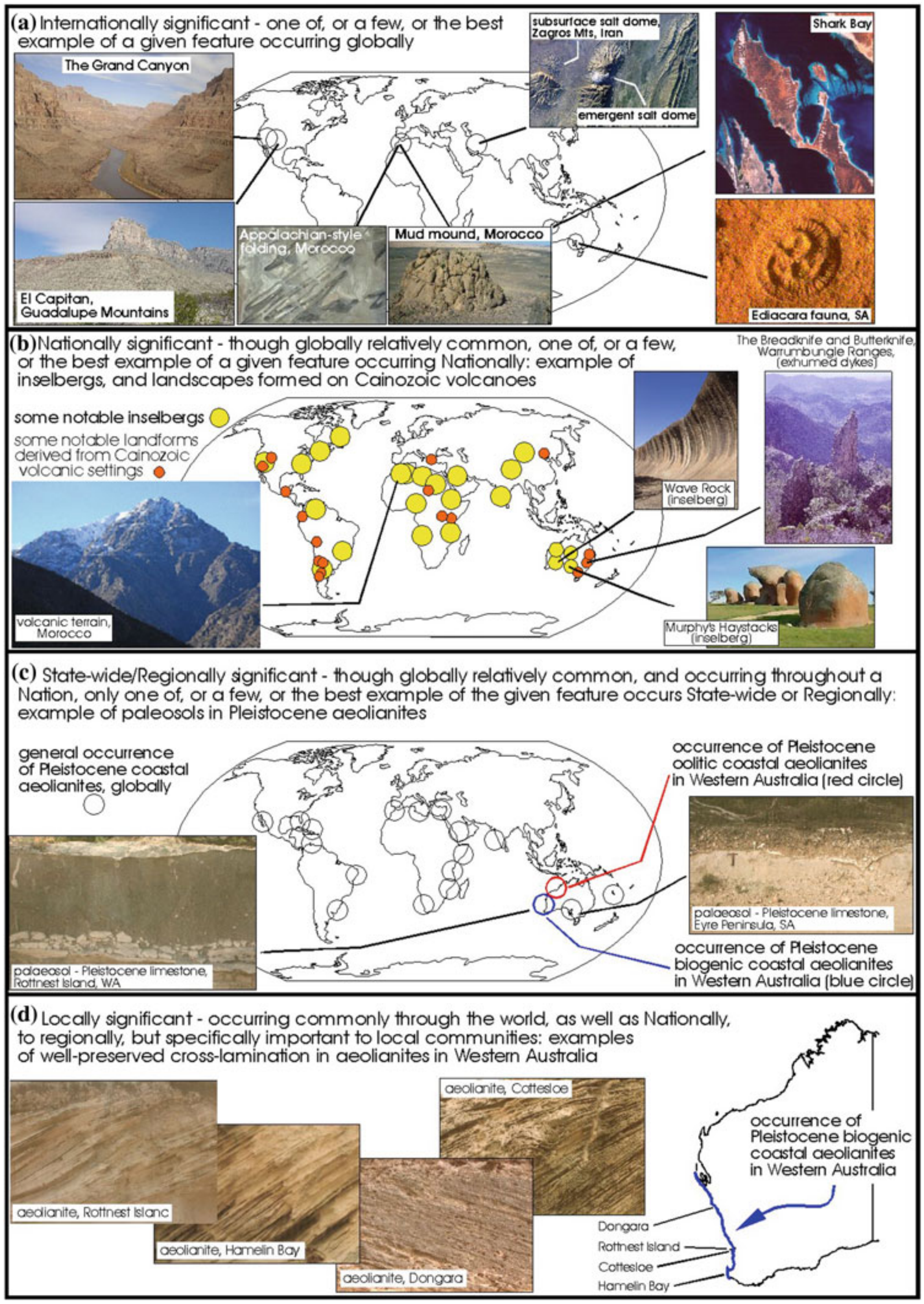

Fig. 3 Summary of criteria for assessment of level of significance, modified after Brocx and Semeniuk (2007), with added examples from Morocco for International and National significance (viz., the Appalachian-type folds, and carbonate mud mounds, and Cainozoic volcanic geology). Examples from Western Australia are used to illustrate State-wide/Regional, and Local significance

the same rationale can and should be applied to areas manifesting ensembles of inter-related significant geological and geomorphological features. The first can be considered to be worthy of conservation as a "biopark" and the second as a "geopark". Once protected in conservation parks, both can be utilised for local socio-economical sustainable development through ecotourism or geotourism (i.e., as "biotours" or as "geotours") and for Science and Education.

3 Identifying Sites of Geoheritage Significance by Defining Geological Regions and Developing an Inventory of Their Geological Essentials

There are a number of ways to identify sites of geoheritage significance. Numerous scientific works provide information as to how this has been achieved in many European countries, with the final outcome being a regional and/or a national inventory-based approach (Doyle et al. 1994; Wimbledon et al. 1995; Wimbledon 1996; De Wever et al. 2006; Brocx 2008; Garcia-Cortès and Carcavilla 2009; Lalanne and Egoroff 2012). In 2001–2002, ProGEO contributed to a number of important geoconservation initiatives that included the incorporation of a policy statement relating to the importance of geology and physical landscapes in the Pan-European Biological and Landscape Diversity Strategy, and an alliance with the International Union of the Geological Sciences (IUGS) and UNESCO for the purpose of compiling a European inventory for the geosites project (ProGEO 2002). Currently, many national and/or regional geosites inventories are in progress (Garcia-Cortès and Carcavilla 2009; Errami 2012c, Lalanne and Egoroff 2012; Errami et al. 2013a, b).

Our inventory-based approach aims to identify geological regions and their geological essentials or their fundamental geological features as a first step. Identifying the geological essentials provides an inventory of geological features characteristic of a given region that can be systematically assessed as to their significance in isolation or within an ensemble. It is important to note that not all aspects of geology of the Earth are necessarily present in any one region and, conversely, many geological regions may have unique or peculiar features. Further, many aspects of the geology of a region may be globally common but not necessarily of geoheritage significance. As such, there is a need to recognise the unique occurrence, rarity, or representativeness of some geological features and to apply some measure of significance. A geological region carries a distinctive Earth history and has a degree of geological consistency in terms of age, structural and tectonic history, and suite(s) of lithology.

The geological essentials of a region can be identified using a three-pronged approach to compile information or a database and to potentially identify sites of geoheritage significance. The first step is based on published literature. The second draws on the experience of geologists still practising in the field, providing information and personal insights about the geoheritage potential of an area. The third, after identifying gaps in information seeks to systematically obtain further information, if necessary, directly from the field. For all three approaches, there will be some degree of overlap in information and outcomes.

Identifying the various geological regions, and their characteristic, representative, unusual, or peculiar geological features, therefore, is the first stage of a systematic inventory-based approach to develop a database for sites of geoheritage significance according to the scope of geoheritage (i.e., all matters geological). This does not necessarily translate to just listing isolated sites of geoheritage significance, but also attempts to identify ensembles of features where they are inter-related. This is followed by identifying, within a given geological region, good examples, regardless of scale, of any special isolated features, or of inter-related ensembles of features. These features are assessed according to the significance criteria outlined above.

4 The Geoheritage Tool-Kit for Use in Identifying SSSI and Geological Ensembles

The Geoheritage Tool-kit provides the procedure to identify geological components across various geological sub-disciplines and at various scales, to assign geological sites to various conceptual categories of geoheritage, and to assess the levels of significance of the various geological features (Fig. 4) (Brocx and Semeniuk 2009, 2011). Once the inventory of components and their level of significance is compiled, and enough geological features have been ranked as being of significance, the last step is used to determine whether the area can be proposed for geoconservation at a regional, state, national/continental or international level for one or a few of its components, or for the integrated ensemble of its components. The area may be designated as a geosite, an SSSI or viewed as a geopark especially if it consists of a range of inter-related geological features that ranked highly in assessment of significance.

The Anti-Atlas provides a good example of the application of the principles of the Geoheritage Tool-kit as it consists of a wide diversity of geological features ranging from large to fine scale, crossing a wide variety of geological phenomena, and ranging in significance from International, National, Regional to Local.

5 The Geology of the Anti-Atlas Region

By its position at the North Western edge of the West African Craton (WAC) and at the junction between the African and European plates, and earlier at the triple-junction of the African, European, and American Plates, and its marginal history interfacing with the Tethys Sea, Morocco presents a varied and globally-important geology reflecting its successive geological settings. This provides a rich geological history largely unique globally, with a wide variety

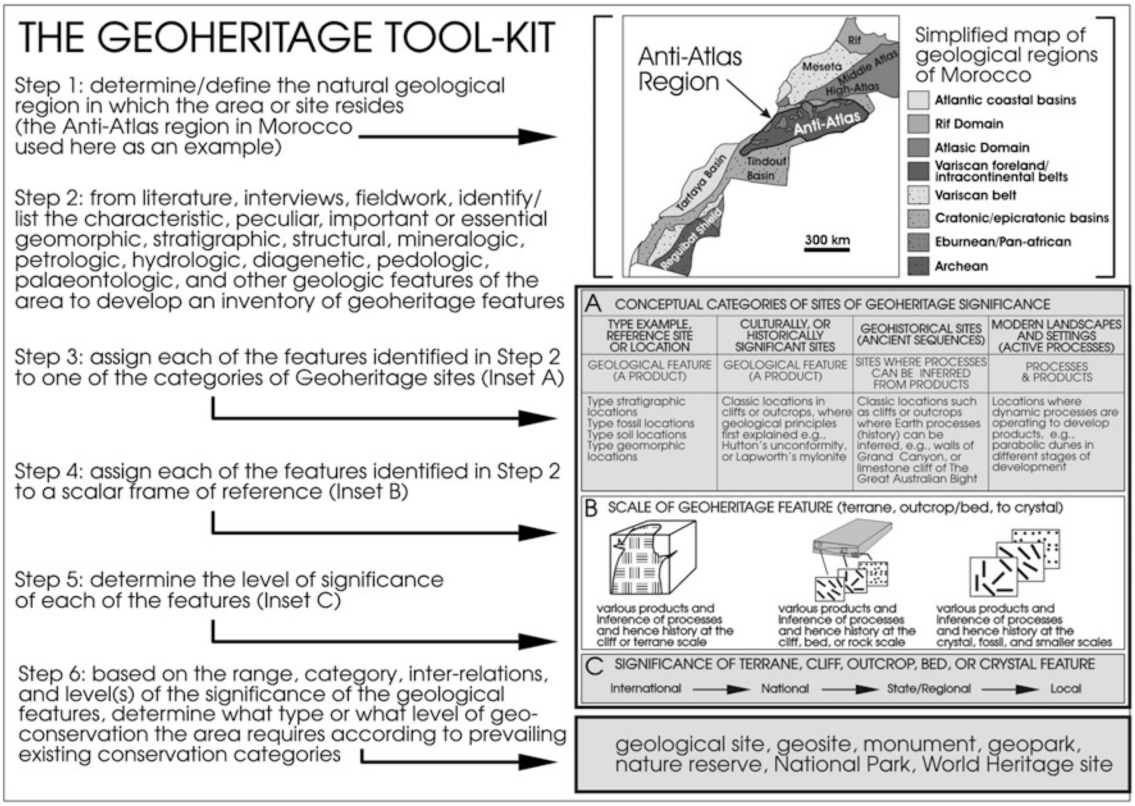

Fig. 4 The elements of the Geoheritage tool-kit showing the six steps in its application leading to assessment of types of geoconservation (modified after Brocx and Semeniuk 2011). The map in Step 1 shows the simplified geological regions of Morocco (after Michard et al. 2010) and the location of the Anti-Atlas

of geological features of various ages from Archaean to Quaternary, from large- to small-scale, and varying in significance from International to Local. The location of Morocco in semiarid to arid environment provides excellent exposures of many of these features.

Geology in the region strongly controls physiography. For example, where the folding is isoclinal, there is development of ridge-and-valley topography and linear ridges, and fold limbs develop linear ranges. Lithology plays a major part in the style of drainage and development of topography. Physiographically, the geological regions, their lithology, and the surrounding climate and earlier Quaternary climates have been and are the influences on developing the landforms. The major geological regions (whether folded and faulted rocks corresponding to tectonic belts, intrusive batholiths, or sedimentary basins) influence the development of the major physiographic regions, each with their own megascale geomorphic expression and relief. Thus the physiographic regions of the Rif, Meseta, High and Middle Atlas, Anti-Atlas, and Saharan Plateau largely correspond to the geological regions (Choubert 1963; Michard 1976; Piqué 1994; Chevalier et al. 2000; Gresse et al. 2000; Michard et al. 2008; Soulaimani and Burkhard 2008; Fig. 5).

The Anti-Atlas (AA) consists of a NE-SW-trending belt of discontinuous Palaeoproterozoic to Neoproterozoic inliers surrounded by Palaeozoic formations ranging in age from Cambrian to Carboniferous and are well exposed in large folded structures. These inliers from the SW to NE are Bas Drâa, Ifni, Kerdous, Tagragra d'Akka, Igherm, Sirwa, Iguerda, Zenaga, Bou Azzer, Saghro and Ougnat (see Fig. 5, and Thomas et al. 2004)

The AA is separated from the northern regions (Meseta and High Atlas) by a major north-east trending fault, the South Atlasic Fault which extends from the Atlantic Ocean to Gabès in Tunisia. It is classically subdivided into two main domains by the Anti-Atlas Major Fault (AAMF) (Leblanc and Lancelot 1980) and consists of variable stratigraphy, expressed in lithologically diverse formations (Leblanc and Lancelot 1980; Saquaque et al. 1989; De Kock et al. 2000; Thomas et al. 2002; Walsh et al. 2002; Inglis et al. 2004; Gasquet et al. 2005; Burkhard et al. 2006; D'Lemos et al. 2006; Raddi et al. 2007; Soulaimani and Burkhard 2008; El Hadi et al. 2011a). The Palaeoproterozoic and Neoproterozoic formations are affected by Eburnean and/or Pan-African orogenies, dated at circa 2 Ga and 700–600 Ma, respectively (Leblanc and Lancelot 1980;

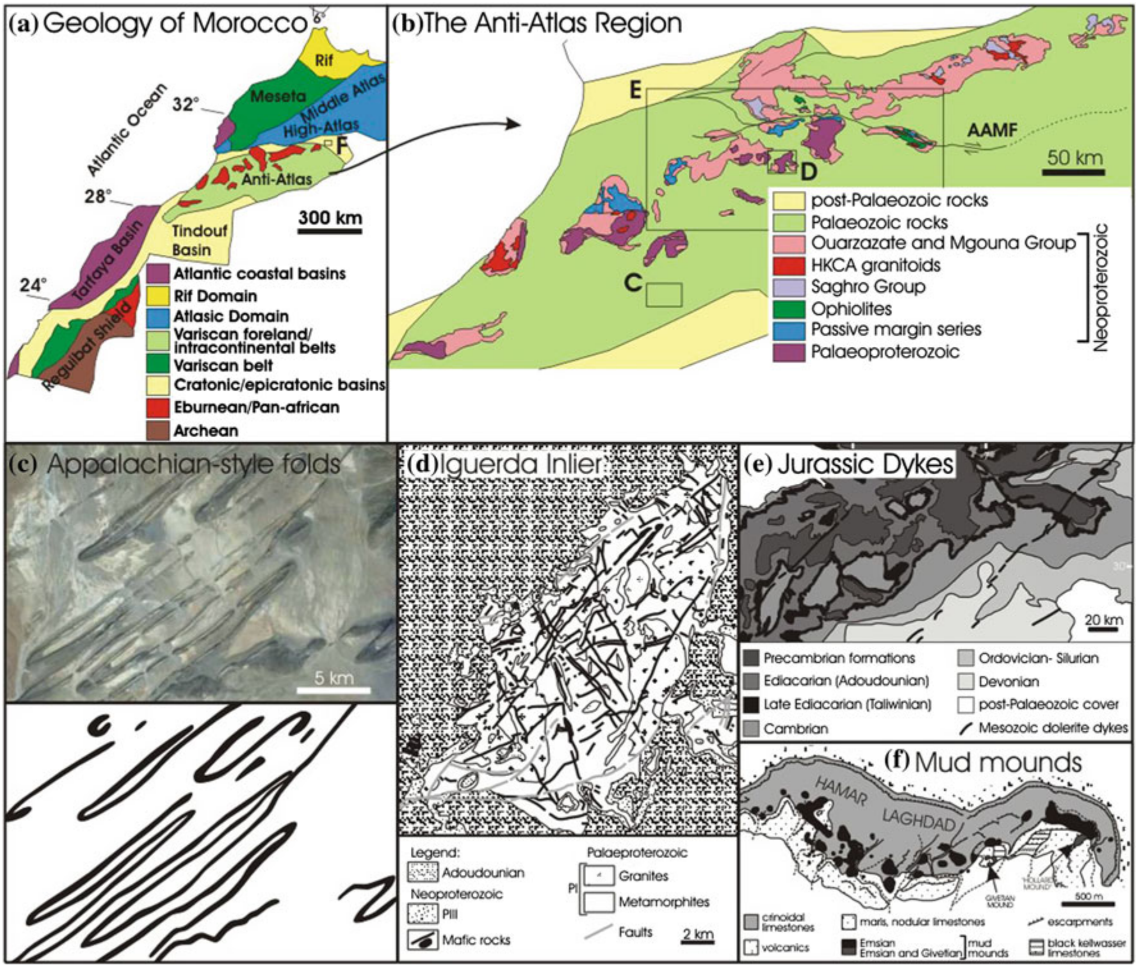

Fig. 5 **a** and **b** Simplified geological map of Morocco showing the location of the Anti-Atlas region. *Insets c–f* show some of the key features of geology of the Anti-Atlas region. **c** Map of the southern Anti-Atlas region showing Appalachian-style folds in Palaeozoic strata. **d** Detailed map of the Iguerda Inlier showing the Palaeoproterozoic inlier surrounded by Neoproterozoic and Adoudounian rocks (El Aouli and Amaouain 2010). **e** Central part of the Anti-Atlas region and the distribution of Jurassic dolerite dykes (after Touil et al. 2008). **f** Eastern Anti-Atlas region (see *Inset a* for location) showing distribution of mud mounds amid crinoidal limestone (Belka 1998)

Saquaque et al. 1989; Aït Malek et al. 1998; De Kock et al. 2000; Ennih et al. 2001b, Thomas et al. 2002, 2004; Walsh et al. 2002; Gasquet et al. 2005, 2008; D'Lemos et al. 2006). Structurally, the AA also exhibits spectacular Appalachian-style folds, ranging from open to isoclinal styles, and locally with dome-and-basin structures, varying in scale from 100 to 10 km (Helg et al. 2004; Burkhard et al. 2006). The Palaeozoic rocks commonly form dome structures around and over the Precambrian inliers.

The AA region is an important metallogenic province. Mineral occurrences are associated with faults, fractures, and igneous intrusions, ophiolites, and some with volcanic-hosted mineralisation. Several mining sites, exploited for a long time, are currently inactive while others are still active, with new mining areas being discovered. The Western Anti-Atlas hosts several gold occurrences such as Iwriren in Tagragra d'Akka inlier. In the Central Anti-Atlas, the Co–Ni–Ag–Au Bou Azzer mine, a most famous mine, has been exploited for over a century, and is still active; mineralization is hosted in serpentinites and podiform chromites (Gasquet et al. 2005). The Bleida mine, exploited for copper during the 1980s and 1990s, is currently inactive but an interesting gold concentration was discovered in fluvial sediments. The Eastern Anti-Atlas is well known for its Imiter Silver mine (Cheilletz et al. 2002). Many mining sites are internationally known for their splendid and diverse mineral deposits, with numerous specimens now in museum collections worldwide.

5.1 The Geoheritage Tool-Kit Applied to the AA to Identify Its Geological/Geoheritage Essentials and to Assess Their Significance

Morocco consists of a rich and diverse geology and geoheritage, however, an inventory in this regard is still in its early stages, despite few localized attempts by research groups from universities (El Hadi et al. 2011b; Errami 2012; Errami et al. 2013a). Numerous sites of outstanding geoheritage value are in need of preservation, e.g. specific palaeontological sites, notably those of the Palaeozoic of southeast Morocco, such as in the Erfoud and Tazarine areas, which are being over exploited either as ornamental rocks or as rare specimens sold for private collections (Errami et al. 2008; El Hadi et al. 2011b). These sites are at risk of serious deterioration.

The key geological features of the Anti-Atlas are listed in Table 1 and are important and distinctive to the region. We have not included in this list geological features such as Tertiary stratigraphy, Quaternary stratigraphy, arid-zone landforms and other geomorphology, and active, modern geological processes in the region, nor the wetlands. The focus has been on Precambrian and Palaeozoic geology involving their stratigraphy, stratigraphic relationships, tectonism, magmatism, metamorphism, structural geology, and the fossil and mineral content of the strata. Describing and assessing the geoheritage of the younger strata and landforms are beyond the scope of this work. Morocco has several type locations for lithostratigraphic sequences that areof National and or international importance.

Due to its tectonic setting, Morocco has a globally distinct and unique geology. Consequently, many of the mega-scale features of geology of the AA stand in contrast to other geological and tectonic settings. These include the extensive and well-preserved examples of plate-edge Precambrian rock sequences (e.g., ophiolites), thick and well-preserved sequences of Palaeozoic sedimentary sequences, and the tectonic relationships between Precambrian rocks and younger strata. This means that many of the mega-scale geological features of the Anti-Atlas are globally unique and significant.

At the medium and smaller scales, because of the well-preserved nature of the Palaeozoic strata in their tectonic setting and in their expression in the present arid climate setting, there is a plethora of biogenic and sedimentary features, such as Palaeozoic carbonate mounds (weathered out in relief) and biostromes, sedimentary (formational) contacts such as unconformities, sedimentary structures, and well-preserved fossils.

A description of the key aspects of these geoheritage features, in terms of their geology, their significance and their scale, whether they are a geological ensemble or an isolated feature, where the features is best developed for geoconservation as a geopark, geosite, or SSSI, and recommended area for geoconservation and what type of activity (strict geoconservation or geopark) is recommended is presented in Table 1. The key features of the geology of the AA listed in Table 1 are ordered with respect to their age. The grading of these essential geoheritage features with respect to International, National and Regional significance, and the rationale for that assessment of these geological features are also outlined in Table 1. Because of their variable size, the geological features, for purposes of geoheritage and geoconservation, will be assigned either to geosites, SSSI and/or to geoparks. Selected photos of geological features are shown in Figs. 5, 6, 7, 8, 9, 10 and 11. Some selected key features of the geology of the AA are described in text form below.

5.1.1 Corridor of Precambrian Inliers

The Anti-Atlas contains a N–E trending corridor of Precambrian inliers (Fig. 5b) surrounded by weakly-folded Palaeozoic strata. It is an unusual structural array, and the significance of this corridor is that it preserves a style of tectonics and folding existent in Palaeozoic times (and probably founded on ancestral Precambrian structures), and the contacts between Precambrian and Palaeozoic rocks, as well as their contrasting tectonic, metamorphic, and structural history.

5.1.2 The Zenaga and Iguerda Inliers

The Zenaga Inlier and Iguerda Inlier occur within the corridor of Precambrian inliers mentioned above and is a well-exposed part of the corridor (Figs. 5d and 6). They provide examples of the internal structure and lithology of Precambrian inliers and their relationship to surrounding Palaeozoic rocks. The Zenaga Inlier consists of granodiorites, syenogranites, and metamorphic rocks, with conjugate fractures and faults and mafic dykes oriented north-east, north-west, and east-west transecting the inlier (Ennih et al. 2001b). Zenaga is an example of a Palaeoproterozoic inlier that has been subjected to Eburnean and Pan-African orogenies and preserved didactic structural witnesses of both orogenies. The main part of the Iguerda Inlier is comprised of quartz diorites, granites, and metamorphic rocks, with conjugate fractures and faults and mafic dykes, oriented north-east, north-west, and east-west transecting the inlier (Fig. 5d; El Aouli and Amaouain 2010). There is a strong structural control of the mafic dykes by the fractures and faults. The margins of the inlier are sharply and discordantly truncated by the surrounding Palaeozoic rocks.

Table 1 Essential features of geoheritage that characterise the Anti-Atlas region; Categorising and grading of essential features of geoheritage significance in the AA; the rationale for the assessment and suggested allocation of the sites of geoheritage significance to geosites and SSSI, or geopark

Geological feature	Category of site (from Fig. 1)	Significance	Rationale	Geosite/SSSI, geopark
Corridor of Precambrian inliers	Geohistorical	International	The area hosting the corridor of Precambrian inliers is globally significant	As it involves an area of megascale size it would function as a mega-geopark or as numerous complementary geoparks (e.g., the Zenaga Inlier as a geopark)
Zenaga Inlier Iguerda Inlier	Geohistorical	International	Zenega Inlier and the Iguerda Inlier are of global significance. The Zenega Inlier is unique in the Anti-Atlas as it shows evidence of two orogenies (Eburnean and Pan-African). The main part of the Iguerda Inlier is comprised of quartz diorites, granites, and metamorphic rocks, with conjugate fractures and faults and mafic dykes (Fig. 5d)	The areas hosting Zenaga Inlier and the Iguerda Inlier and their immediately surrounding formations would function as geoparks
Neoproterozoic doleritic dykes (Zenaga, Central AA)	Geohistorical	International	The Palaeoproterozoic basement of Zenaga inlier is cross-cut by tholeiitic dykes that witness to the break-up of the WAC during the Pre Pan-African orogeny around 1,000–800 Ma, and are of International significance	The dyke swarms could also function as a SSSI. The inliers hosting these dyke swarms associated with the other geoheritage components could function as a mega-geopark or a series of complementary geoparks
Neoproterozoic Passive margin with its spectacular sedimentary features	Geohistorical	International	Well preserved Pre-Pan-African sedimentary features are not common globally and the hosting formations can play an important role in regional geological correlation. The whole sequence is internationally significant	The site could function as a SSSI or as could be integrated into a geopark that include the Zenaga inlier
Pan-African ophiolites of Bou Azzer and Siroua inliers, central AA)	Geohistorical	International	Viewed worldwide, Proterozoic ophiolites are globally relatively uncommon. Their occurrence and implications for Proterozoic plate-margin history also renders them globally significant	The Precambrian ophiolites are limited in size, and would function as separate SSSI. They could be also included in a thematic geopark that groups all the ophiolites of the central AA and associated phenomena
Major Anti-Atlas Fault (central AA)	Geohistorical	International	This major fault provides information on crustal tectonics that has a global significance	SSSI
Pan-African Diamictites (Bou-Azzer and Siroua inliers, central AA)	Geohistorical	International	The two Pan-African diamictites consist of mudstone with matrix-supported polymictic boulders and pebbles (Fig. 9a and b). They represent a Precambrian record of glacial conditions (Abati et al. 2010). Proterozoic glaciogene deposits are globally uncommon and of limited occurrence worldwide; as such, this deposit is globally significant	The areas hosting the Precambrian diamictites is limited in size and would function as a SSSI

(continued)

Table 1 (continued)

Geological feature	Category of site (from Fig. 1)	Significance	Rationale	Geosite/SSSI, geopark
Ediacarian Iknioun granodiorites	Geohistorical	National	The granodiorite is a particularly useful tectonic marker for the Ediacaran evolution of this part of the Anti-Atlas along the northern border of the WAC; thus the area is Nationally significant	The area hosting the contacts is limited in size and would function as a SSSI or could be included in a thematic magmatic geopark covering the eastern Saghro Inlier with its rich and varied magmatic rocks
Late Neoproterozoic stromatolites	Geohistorical	National	The late Neoproterozoic stromatolites (Fig. 8i), witness of the oldest life in Morocco (Lottaroli et al. 2009), crop out 25 km south of Ouarzazate on the road to Agdz. Proterozoic stromatolites are relatively common globally; as such, this deposit is Nationally significant	The area hosting the Precambrian stromatolites is limited in size and would function as a SSSI.
Contacts between three Pan-African Groups: Saghro, Mgouna and Ouarzazate Groups	Geohistorical	International	The contacts record the Pan-African geological history of the African crust superposition and orogenies with a variety of lithologies; this sequence is globally important	The area hosting these didactic contacts is limited in size and would function as a SSSI
Contacts between Palaeoproterozoic Zenaga complex, late Neoproterozoic Ouarzazate Supergroup and the Cambrian Tata Group	Geohistorical	National	The contact between the Palaeoproterozoic (Eburnean) Zenaga complex (ca 2 Ga), the Late Neoproterozoic Ouarzazate group volcano-clastic series (580-560 Ma) and the contact between the Ouarzazate Group and the Cambrian Tata Group are well exposed along the road to Bou-Azzer 5 km from Tazenakht village (Fig. 10). These contacts are lithologically distinct and is an interface of National significance	The area hosting the contacts would function as a SSSI
Appalachian type folding in western AA	Geohistorical	International	Appalachian-type folding is not common globally and, in a context of arid-zone weathering/erosion, the Appalachian-type folding in the Anti-Atlas is globally well-preserved; it is also distinct in folding style; as such, it is globally significant	Global Geopark
Large Cambrian trilobite *Paradoxides*	Geohistorical Cultural	International	The occurrence of this large trilobite in abundance is rare, and so this deposit assumes global significance	The area hosting the *Paradoxides* is limited in size and would function as a SSSI or could be included in the Alnif-Erfoud area to form a thematic geopark based on Palaeozoic fossils
Ordovician outcrop of Jbel Kissane	Geohistorical	National	Jbel Kissane is famous as it shows an impressive cliff of Ordovician sedimentary rock of sandstone, shale, and siltstone; it is nationally significant	Geosite
Large Ordovician trilobites (*Asaphus*) death assemblages	Geohistorical Cultural	International	The death assemblages of the large trilobite *Asaphus* occur in Ordovician shales (Fig. 2) in the eastern AA. The trilobite occurs in rippled sandstone in what appears to be a tidal sand deposit. Death assemblages of large trilobites are rare, and so this deposit assumes global significance	The area hosting the *Asaphus* is limited in size and would function as a geosite of SSSI included in the Alnif-Erfoud area in order to form a thematic geopark based on Palaeozoic fossils

(continued)

Table 1 (continued)

Geological feature	Category of site (from Fig. 1)	Significance	Rationale	Geosite/SSSI, geopark
Silurian and lowermost Devonian *Orthoceras*-rich limestones and ammonite-rich limestones	Geohistorical Cultural	International	These deposits are globally distinct and well known and of limited occurrence worldwide; as such, it is globally significant	Both areas hosting *Orthoceras* and goniatites are limited in size and would function as SSSI or could be included in the Alnif-Erfoud area to form a thematic geopark based on the varied Palaeozoic fossils
Early Devonian Kess Kess carbonate mounds	Geohistorical	International	The geology and setting of these unique carbonate mounds provide insight into Devonian ecology and submarine conditions render it a feature of global significance	The site could be considered as SSSI
Middle Devonian coral-stromatoporoid biostrome	Geohistorical	International	This site is one of a limited number of such biostromes and in this context it is globally important	The site and its surrounding stratigraphy would function as SSSI
Green eyes and red Devonian phacopid trilobite	Geohistorical	International	Colour preserved in fossils is rare, and so the occurrence of Devonian phacopid trilobite with green eyes and red colouration from the Hmar Lakhdad (Tafilalt) area, as described by Klug et al. (2009), is significant. Additionally, the eyes of the trilobite still show faceting. The occurrence of these fossils is of International significance	The area hosting the phacopid trilobite is limited in size and would function as a SSSI or could be included in the Alnif-Erfoud area in order to form a thematic geopark based on the varied Palaeozoic fossils
Frasnian plants from the Drâa Valley	Geohistorical	International	Devonian plants are rare globally and point to the early history of plant life on the planet. Thus, the Frasnian plants from the Drâa Valley occurring in marine shales are of global significance	The area hosting the Devonian plants is limited in size and would function as a SSSI
Well preserved shallow-water sedimentary features in Cambrian rocks	Geohistorical	National	Cambrian sedimentary structures are not common globally, and so these geological features, though limited in size and outcrop, and are localised, assume National significance	Geosite
Foum-Zguid Jurassic dyke	Geohistorical	International	Its geological setting renders the Foum-Zguid Jurassic dyke a feature of global significance	The area hosting Foum-Zguid dyke is megascale in size and would function as a geopark.

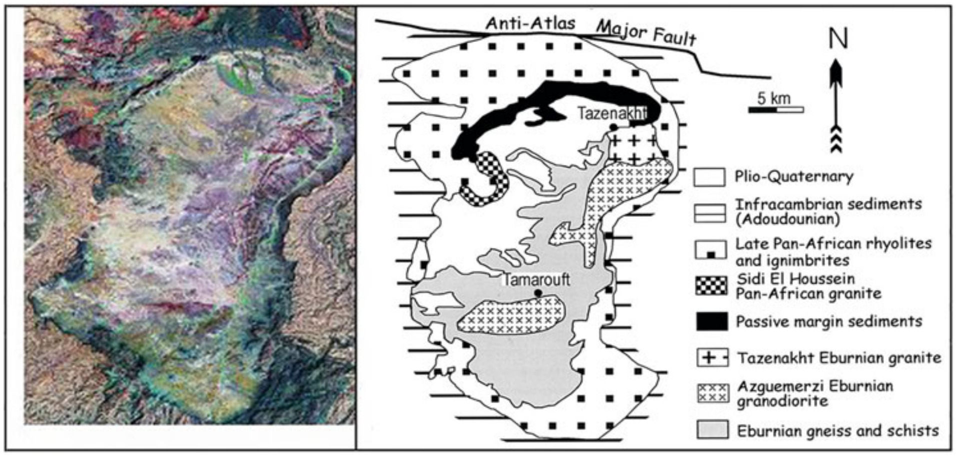

Fig. 6 Landsat TM image of the Zenaga Inlier showing the Palaeoproterozoic surrounded by the Neoproterozoic volcano-sedimentary rocks and Palaeozoic sediment cover (Ennih et al. 2001b)

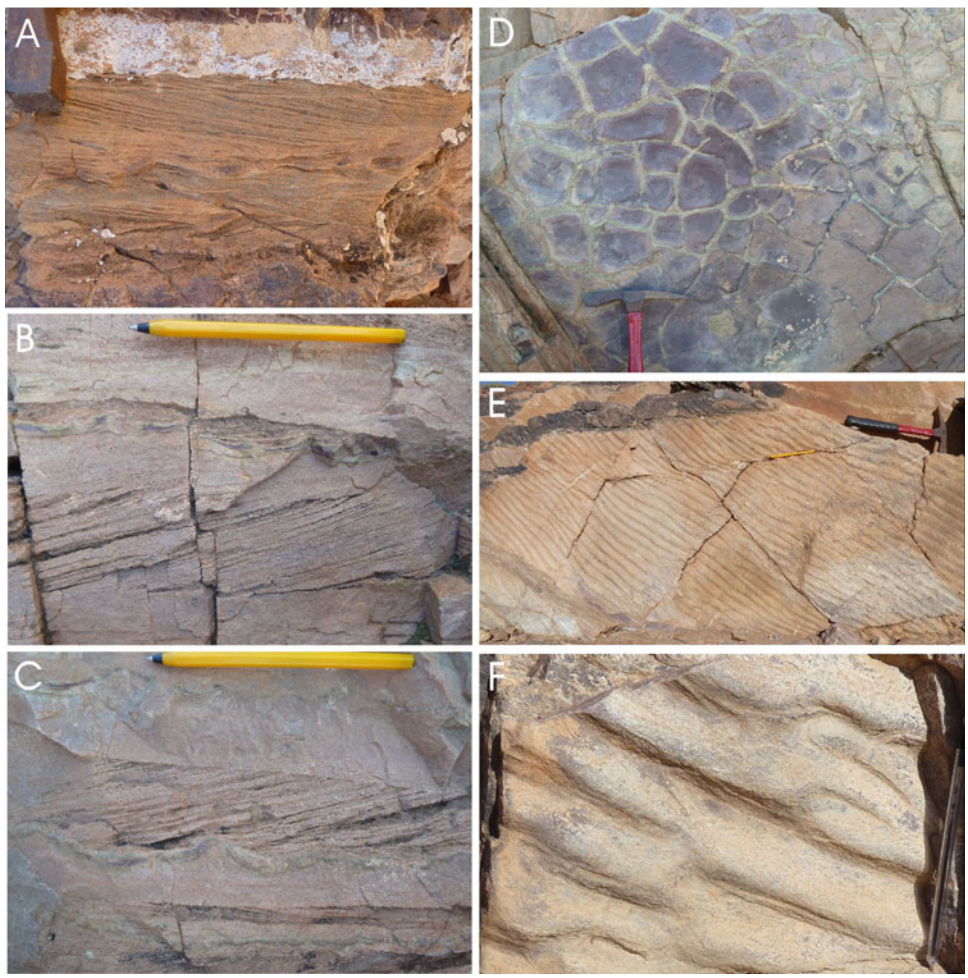

Fig. 7 Sedimentary structures of the Precambrian rocks of the Taghdout Group in the Anti-Atlas. **a** Complex of ripple-drift lamination, and ripple lamination in sandstone (**b**) and (**c**). Small scale ripple lamination, horizontal lamination, mud drapes, buried ripple bedforms, and larger-scale cross lamination. **d** Mud cracks exposed on a bedding surface—the cracks are filled with syndepositional sand. **e** Rippled sandstone. **f** Close-up of rippled sand showing asymmetric ripples

5.1.3 Neoproterozoic Doleritic Dykes (ca 1,000–800 Ma)—Witness of the Break-Up of the WAC During the Pre-pan African Orogeny

The Palaeoproterozoic basement of the Zenaga inlier is cross-cut by tholeiitic dyke swarms in N–S, NW-SE and NE-SW directions (Ennih et al. 2001a; Hafid et al. 2001). These dykes consist mainly of gabbro, dolerite and trachy-andesites. They often preserve their original texture and their primary mineralogy, in spite of a secondary hydrothermal alteration under greenschist facies (epidotization, hematitization) probably related to the Pan-African orogeny. The primary mineral assemblage consists of plagioclase, clinopyroxene (augite), very rare orthopyroxene, ilmenite, apatite,

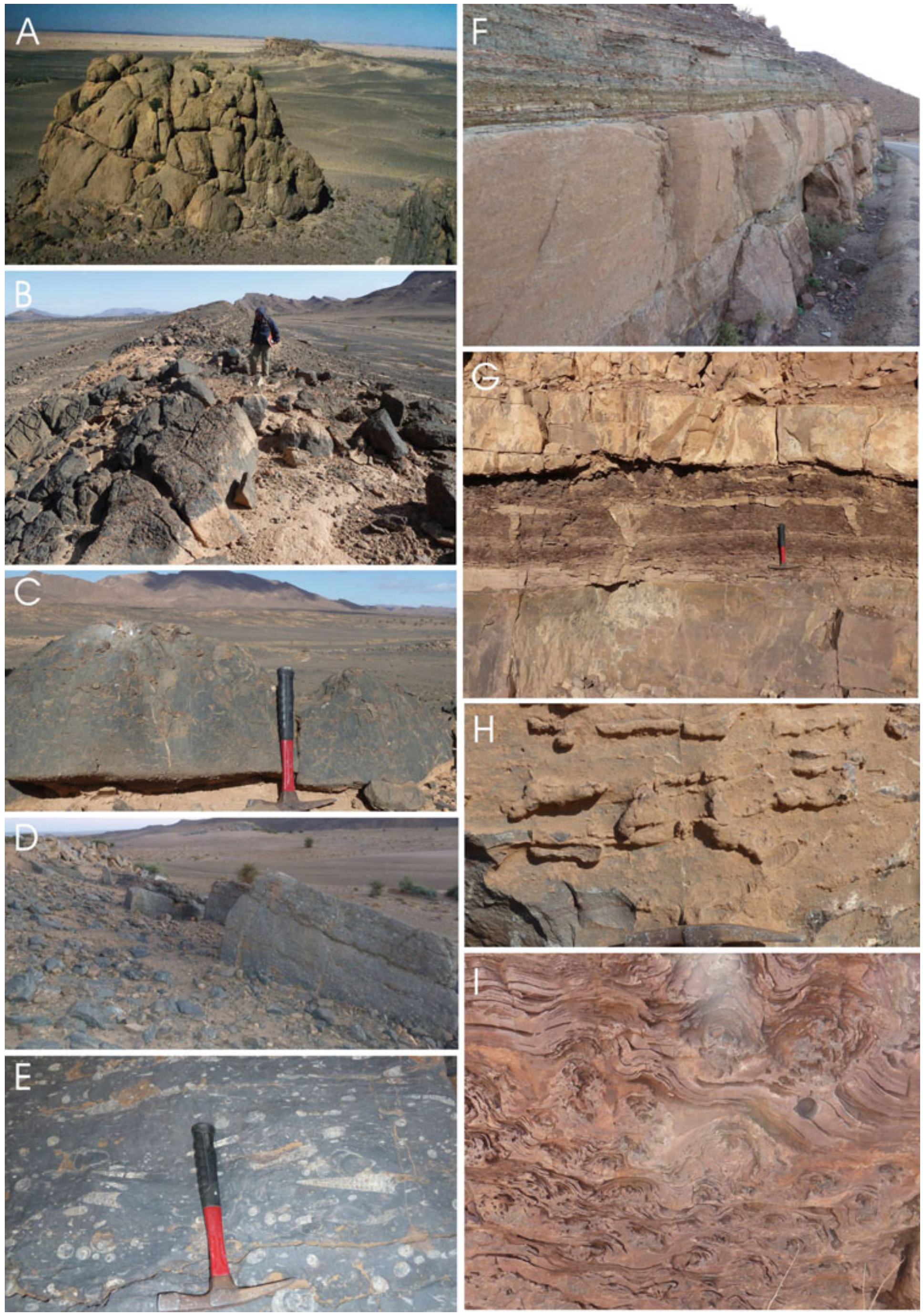

Fig. 8 Examples of stratigraphy and sedimentary features in strata of Proterozoic to Devonian age in the Anti-Atlas. **a** Kess Kess mud mound. **b** Hill-capping Devonian coral-stromatoporoid biostrome limestone. **c** Close-up of coral-stromatoporoid biostrome limestone. **d** Outcrop of Orthoceras-bearing limestone. **e** Close-up of *Orthoceras*-bearing limestone showing current-oriented *Orthoceras*. **f** Stratiform sheets of Cambrian sandstone and shale. **g** Sand dykes in Cambrian sandstone and shale sequence. **h** *Horizontal* and *vertical* burrows in Devonian Goniatite-bearing limestone. **i** Lamination in Proterozoic stromatolites (vertical section)

micropegmatite, hornblende and biotite. The secondary mineralogy includes albite, chlorite, actinolite, epidote, sphene, calcite and quartz. These doleritic dykes are occasionally deformed where they are intersected by mylonite. These basic rocks are also interbedded in the sedimentary passive margin series. Similar basic rocks were defined in the western Anti-Atlas inliers (Iguerda, Tagragra d'Akka, Bas Dràa, Ighrem and Kerdous) and are described as witness of the break-up of the WAC during the Pre-Pan-African orogeny around 1,000–800 Ma.

5.1.4 Neoproterozoic Passive Margin Series (Taghdout Group) with Its Well-Preserved Sedimentary Features (ca 800 Ma) and Its Pre-Pan-African Doleritic Sills

Neoproterozoic (ca 800 Ma) volcano-sedimentary sequences of the northern rifted margin of the WAC are exposed in the central and western Anti-Atlas inliers. The Zenaga Eburnian gneisses are overlain in their northern edge by Neoproterozoic quartzite and carbonate rocks with interbedded continental tholeiitic basaltic lavas. These sedimentary rocks are

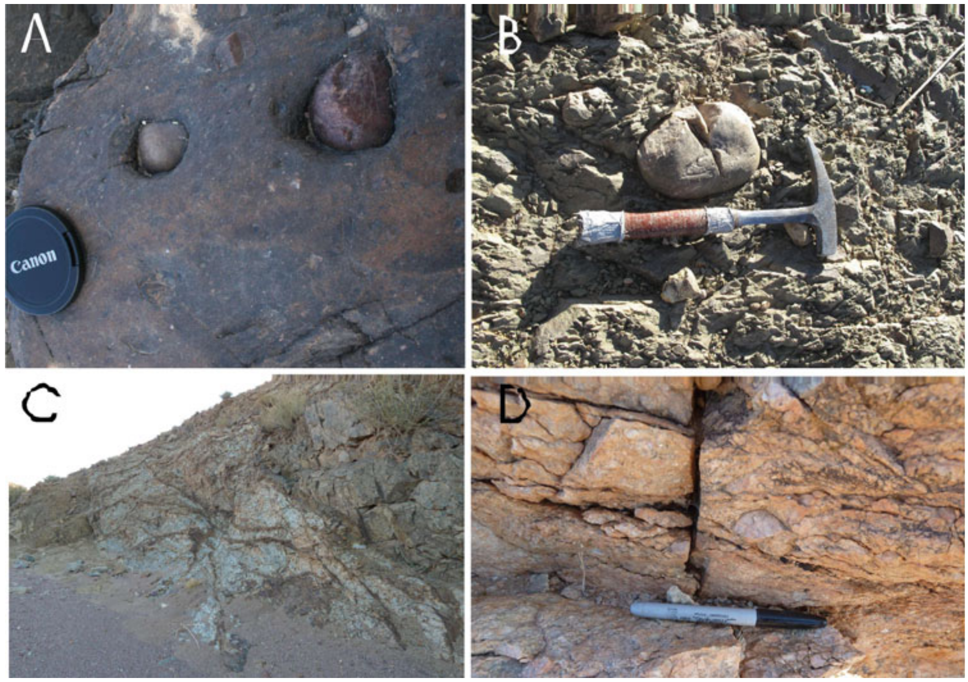

Fig. 9 **a** and **b** The diamictite from the Bou-Azzer inlier (**a**) and from the Siroua inlier (**b**). **c** and **d** Features of the Anti-Atlas major fault. **c** Shear zone with network of sigmoidal slip surfaces; the shear zone transects shales (which are splintered) and diamicitite. **d** Closeup of conglomerate within the shear zone with fracture surfaces and fragmented pebbles

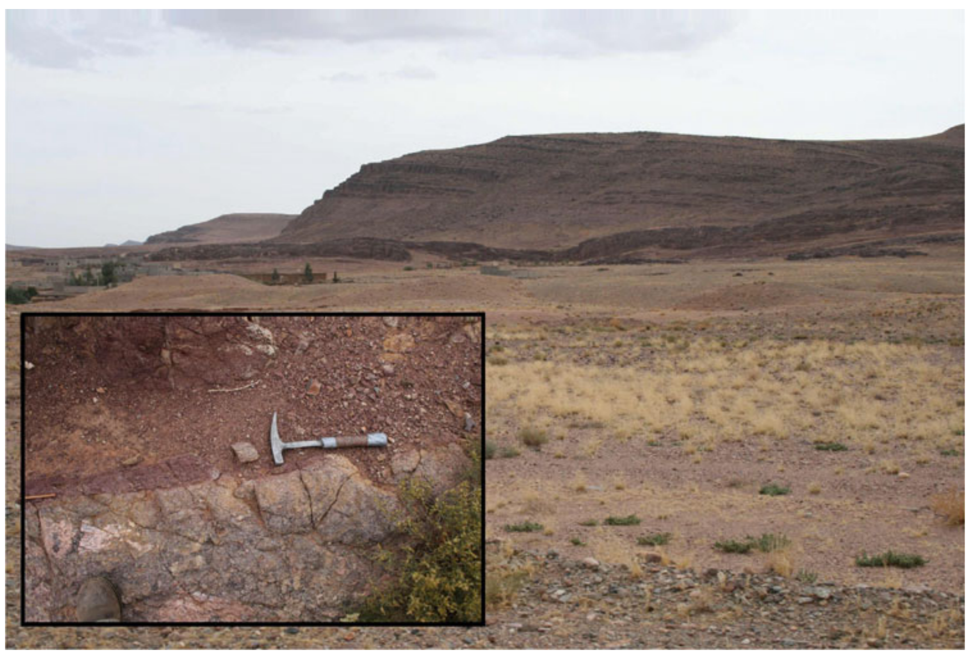

Fig. 10 Overview of contact between Palaeoproterozoic basement and Ouarzazate Group and the Tata Group. *Inset* shows contact marked by micro-conglomerates and thin layers of rhyolitic tuff

Fig. 11 Jbel Kissane showing well layered sequence of sedimentary rocks of Ordovician age

composed of limestones, jaspilites and quartzites where spectacular shallow-water sedimentary features (ripple marks, mud cracks, cross-bedding) are well preserved (e.g., at Jbel Mimount) (Fig. 7). The stromatolitic strata and cross beds, and occasional herring-bone cross-stratification indicate that this series was deposited in a shallow marine-tide and wave-agitated environment.

5.1.5 Bou Azzer Pan-African Ophiolite (Bou Azzer Inlier, Central AA)

The Bou-Azzer ophiolite, an old fragment of oceanic crust (697 ± 8 Ma; El Hadi et al. 2011a), is a witness of the Pan-African suture marking the boundary between the Palaeoproterozoic Eburnean basement forming the WAC in the south and the Neoproterozoic accreted arcs to the north. This ophiolite plays an important role in the geodynamic interpretations of the AA during the Pan-African orogeny that occurred between 650 and 580 Ma (Leblanc 1976, 1981; Bodinier et al. 1984; Saquaque et al. 1989; Hefferan et al. 2000; Admou et al. 2002; Gasquet et al. 2005; D'Lemos et al. 2006; El Hadi et al. 2011a; Ouanaimi and Soulaimani 2011). The ophiolite consists of serpentines (mainly harzburgites with chromite pods), gabbroic cumulates and gabbros, and limited sheeted dyke complexes. Only rare metasediments associated with volcanic layers are found on top of the oceanic complex (e.g., Ambed Co-bearing calcareous jaspers). The ophiolite sequence was obducted onto the WAC during a southward-dipping subduction (Leblanc and Lancelot 1980) or northward-dipping subduction (Saquaque et al. 1989). It hosts the famous Co–Ni–Ag–Au Bou Azzer mine.

The unusual character of this Neoproterozoic magmatic and tectonic geoheritage site, together with the excellent quality of the outcrops in a desertic landscape of ca 15 km length and 4 km width and the relatively easy access to the area, make this complex attractive from both a scientific, an educative and a geotouristic perspective (El Hadi et al. 2011b).

5.1.6 The Khzama Pan-African Ophiolite (Siroua Inlier, Central Anti-Atlas)

The well-preserved Pan-African dismembered Khzama ophiolitic complex, an old oceanic crust, forms a 4 km wide E-W-striking outcrop. Geochronological data give an age of 760 ± 1 Ma for Khzama plagiogranite that cross-cuts the ophiolite (Admou et al. 2002; Samson et al. 2004). The ophiolitic complex is partly bound by normal faults and is covered either by the Ouarzazate Group or by the Neogene Siroua volcanic rocks. The complex comprises mantle harzburgites, and a crustal sequence typical for oceanic ridges, including layered gabbros and sheeted dykes beneath the pillow basalts section. Only rare metasediments associated with volcanic layers are found on top of the oceanic complex (e.g., keratophyric tuffites and flows). It is composed of a succession of metamorphosed ultramafic rocks and minor acid volcanic and plutonic rocks (Schermerhorn et al. 1986; Wallbrecher 1988; El Boukhari et al. 1991, 1992; Admou and Soulaimani 2011). It consists of serpentine and talc schist, hornblendite and tremolite schist, amphibolites as well metamorphosed quartz keratophyre and plagiogranite. Khzama ophiolite is of tholeiitic affinities (El Boukhari et al. 1991, 1992). Schermerhorn et al. (1986) concluded that the ophiolite sea-floor spreading was in a fore-arc environment, also borne out by the high-Mg low-Ti boninitic nature of the ophiolite.

5.1.7 The Major Anti-Atlas Fault (Central Anti-Atlas)

The Anti-Atlas Major Fault, located south of the South Atlas Fault, is an important fault in Morocco (Fig. 9c, d), which provides information on crustal tectonics that has global significance. The fault is underlain by Bou-Azzer and Siroua ophiolitic complexes and has been viewed formerly as separating two geological domains in the Anti-Atlas, namely, the Pan-African domain 600–700 Ma in the North-East and the ∼2 Ga Eburnian domain in the South-West (Leblanc and Lancelot 1980; Saquaque et al. 1989). Recent studies by Ennih and Liégeois (2001), Gasquet et al. (2008), Errami et al. (2009) on the Zenaga and Saghro inliers suggest that the Eburnian and Pan-African materials occur throughout the Anti-Atlas region and that the entire Anti-Atlas is underlain by Eburnian crust, unconformably overlain by a lower Neoproterozoic passive margin. Allochthonous Pan-African ocean crustal slices were thrust onto the WAC passive margin sequence ∼685 Ma ago as a result of Pan-African accretionary tectonics.

5.1.8 Ediacaran Iknioun Granodiorite (Eastern Anti-Atlas)

The Ediacaran Iknioun amphibole-bearing granodiorites are intruded into the Saghro Group volcano-sedimentary formations and are intruded by the Iskn'Allah pink granite and covered by ignimbrite/rhyolite flows of Jbel Amalou'n Mansour. The area is providing didactic contacts between the main Ediacaran formations of Eastern Saghro, Saghro and Ouarzazate Groups (Errami et al. 2011) It hosts basic rock enclaves that point to a mixed origin for these granitoids (Errami et al. 2009). Iknioun granodiorite displays a regular pattern of magmatic lineations and foliations determined through the anisotropy of magnetic susceptibility (AMS) study. S-sigmoid features outlined by these lineations and top-to-the-SE movements in the adjacent country rocks show that the emplacement of this pluton was related to the E-W-trending dextral transpressive movements previously described in the Saghro inlier. Consequently, this pluton appears as a particularly useful tectonic marker for the Ediacaran evolution of this part of the Anti-Atlas which constituted the northern border of the WAC (Errami and Olivier 2012).

5.1.9 Imider Geosite: Contacts Between Three Pan-African Groups: The Saghro Group, Mgouna Group and Ouarzazate Group

This site, occurring in the eastern Saghro inlier, shows spectacular contacts between the three main Pan-African formations (Saghro Group, Mgouna Group and Ouarzazate Group). The Mgouna Group, which discordantly covers the volcano-sedimentary Saghro Group and the associated HKCA granodiorite, consists of a volcano-sedimentary sequence formed mainly by arkose, micro-conglomerates, sandstones, tuffs and pyroclastites (Chakir et al. 2007; Otmane et al. 2007). The conglomerates occupying the summit of hills in the area of outcrop marks the limit between Mgouna and Ouarzazate Groups. The Mgouna Group is covered discordantly by the Ouarzazate Group which consists mainly, in this part of the Anti-Atlas, of ignimbrite and rhyolite. The emplacement of these volcanic rocks and the basic dykes, which cross-cut all the Neoproterozoic formations, has occurred along sinistral faults during the late Pan-African Orogeny (Azizi et al. 1990; Otmane et al. 2007). This site gives an overview about the geological evolution of this part of the AA during the Neoproterozoic time (Errami et al. 2011).

5.1.10 Appalachian-Type Folding in the Western Anti-Atlas

The south-west of the AA manifests large-scale folding of the Appalachian style, best exposed in the southwest region in the vicinity of Guelmim-Es Smara (Fig. 5c). The Appalachian-type folding in this region extends over an area of 500 km long by 50 km wide. The rocks involved in the folding are Palaeozoic sequences, with the limbs of the folds moderately inclined, and fold axes generally oriented NE-SW. In the arid, vegetation-sparse setting of Morocco, the folds are well exposed. Helg et al. (2004) consider that this folding represents a special type of foreland fold belt with a striking absence of observable thrusts. In terms of folding and deformation style, they recognize four structural units with different wave lengths and amplitudes, corresponding to four distinct stratigraphic levels, separated by the thick incompetent units of the Middle Cambrian, Silurian, and Upper Devonian respectively. Helg et al. (2004) consider that the Anti-Atlas folded Palaeozoic rocks are similar in tectonic style to the Appalachian Valley and Ridge province.

Appalachian-type folding is not common globally. There are a limited number of locations where it is best developed, for instance, in the Appalachian Mountains of the USA, comprising Palaeozoic rocks such as clastic sedimentary rocks, dolomite and limestone, in the MacDonnell Ranges in central Australia, comprising Proterozoic rocks such as shale, dolomite and chert, in the Capricorn Ranges in the southern Pilbara region of Western Australia, comprising Proterozoic rocks such as shale, dolomite and chert, in the King Leopold Ranges in the south-western Kimberley of Western Australia, comprising Proterozoic rocks such as quartzite, other metasediment, shale, and ironstone, along the eastern margin of the Andes Mountains, and in the northern Sahara to southern Algeria region, comprising Proterozoic rocks. Not all Appalachian-type folding is comparable because, in the different regions, there are differences in rock types, ages, and styles of metamorphism. The limited range of Appalachian-type folding worldwide means that those of the Anti-Atlas are globally significant. Additionally, each region of Appalachian-type folding worldwide, though broadly similar, have details of smaller scale effects and lithological response that renders each region globally distinct and, as such, in this context, the Appalachian-type folding of the Anti-Atlas become further globally significant.

5.1.11 Large Cambrian Trilobite *Paradoxides*

Large *Paradoxides* occur in the middle Cambrian rippled sandstone such as in the Bardou Mountain area (Eastern AA). The trilobites are in various degrees of taphonomic preservation (from complete to disarticulated fossils). The local population considered, until the beginning of the 1970s, that collecting trilobites brought bad luck which actually resulted in their preservation and protection, until foreign tourists collecting these fossils changed this tradition.

5.1.12 Ordovician Outcrop at Jbel Kissane

The eastward view from Agdz on the Jbel Kissane is famous as it shows an impressive Ordovician sedimentary rock pile which consists of shale and sandstone of Arenig and Lianvirn age, sandstones of the 1st Bani (Llandeilian age) followed by the mudstone, shale and siltstone of the Ktaoua Formation (Caradocian age), and the sandstone of the 2nd Bani (Ashgillian age) in the summit (Fig. 11). Jbel Kissane forms the perched syncline core of the east-trending synclinorium which extends between Bou-Azzer and Saghro Precambrian antiforms.

5.1.13 Silurian and Lowermost Devonian Orthoceras-Rich and Ammonite-Rich Limestones

Upper Silurian black limestones containing current-oriented *Orthoceras* occur in the Eastern AA in the Serdrar Mountain locality (Fig. 8d, e). Locally, the limestones are linked to

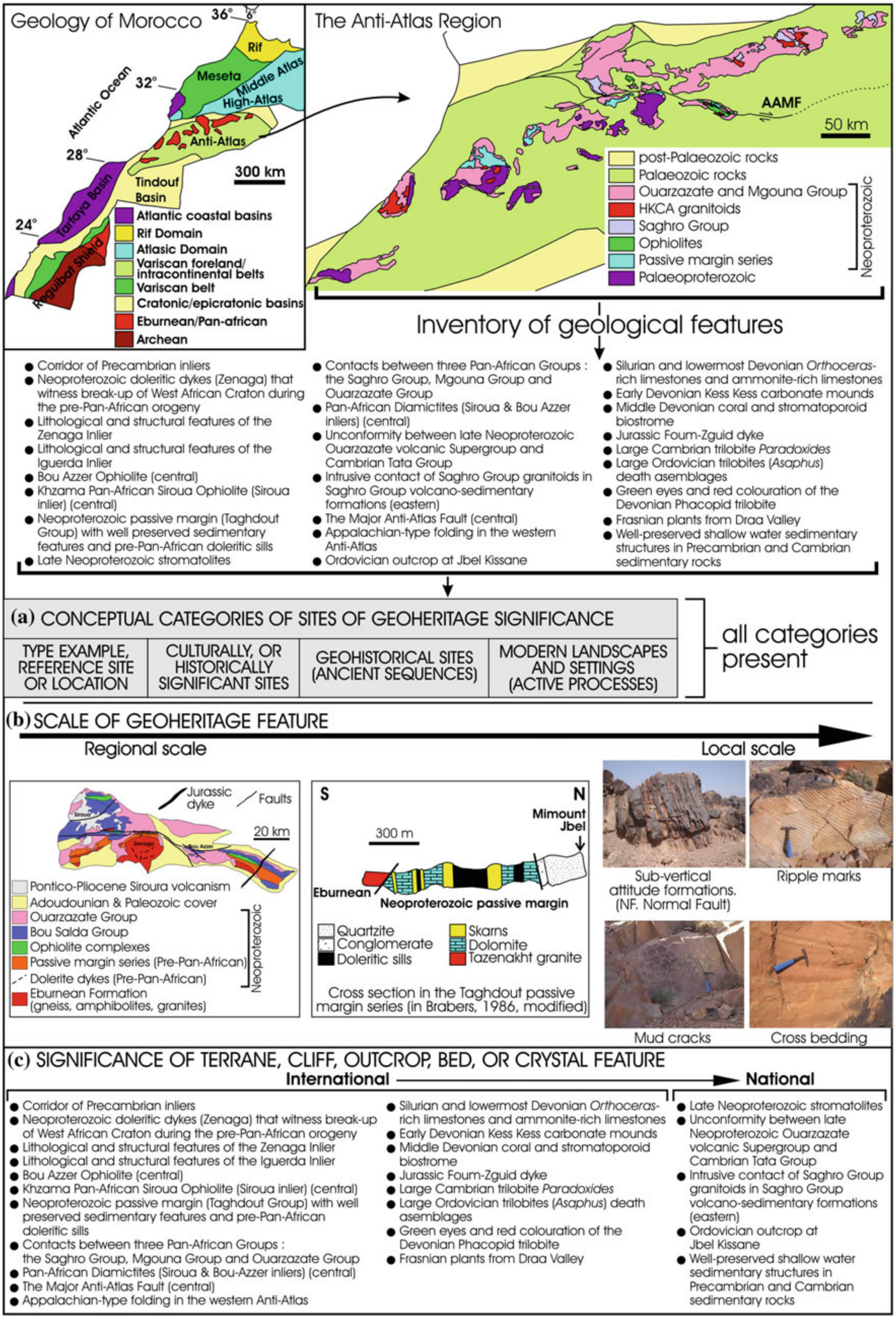

Fig. 12 The Geoheritage tool-kit of Fig. 4 applied to the Anti-Atlas. In *inset a*, categories of geoheritage applicable to this area are highlighted in grey (four categories of sites are present in various localities in the Anti-Atlas). In *inset b*, selected geological features that have geoheritage significance from the Anti-Atlas are illustrated, graded in decreasing scale from *left* to *right*. In *inset c*. all features listed in Table 1 are allocated to a level of significance

cultural legends, where the fossils are seen as "demon plates". The fossil-bearing limestones are internationally well-known as ornamental rock, and fossil-collecting localities. Nearby in the Ighes locality, there are Devonian goniatitic limestones that also contain current-oriented *Orthoceras* and lesser numbers of several species of goniatites. The limestones are skeletal lime wackestone, and some calcarenite, and are burrowed with horizontal and fine vertical burrows, some of which disrupt the current-oriented *Orthoceras*.

5.1.14 Early Devonian Kess Kess Carbonate Mounds

Early Devonian Kess Kess carbonate mounds have been described in the eastern Anti-Atlas by Wendt et al. (2001) and Steven et al. (2002) (Figs. 5f and 8a). They are submarine mounds comprised of skeletal wackestone and lime mudstone, with crinoids, sponges, and bryozoans. From their lithology and facies relationships, four types of mounds are recognised (Wendt et al. 2001): 1. Massive crinoidal wackestone or packstones without stromatactis; 2. Massive crinoidal wackestone or packstones with rare stromatactis; 3. Similar to (2), but allochthonous; and 4. biodetrital (skeletal) grainstone mounds. The mounds stand a few metres to some 30 m emergent above the sea floor, and appear to have been initiated above submarine hot water vents (Cavalazzi 2006).

5.1.15 Middle Devonian Coral and Stromatoporoid Biostrome

A well-preserved and extensive Middle Devonian coral-stromatoporoid biostrome, some 0.5 m thick, outcrops in the Eastern Anti-Atlas (Tamjout n'Ouihlane area) (Fig. 8b, c). The limestone is black lime mudstone with a coral-stromatoporoid skeletal frame, with hemispherical to platy *Favosites* and platy stromatoporoids. The outcrop in the Tamjout n'Ouihlane area shows a vertical and lateral variation in biofacies and lithofacies. Devonian coral and/or stromatoporoid biostromes occur throughout the globe, but are not common.

5.1.16 Well-Preserved Sedimentary Structures in Cambrian Sedimentary Rocks

In various locations throughout the Palaeozoic sequences in the AA, there are occurrences of well-preserved shallow water sedimentary structures. These include mud cracks, rippled sandstone, flaser bedding, wavey lamination, ripple-drift lamination, cross-bedded sandstone, and herringbone structures, and sandstone dykes cutting into a shale sequence, and tidal flat sediments with their array of tidal flat sedimentary structures in Cambrian Tata Group. A selection of these sedimentary features is illustrated in Figs. 7, 8f, g. Cambrian sedimentary structures are common globally, and assume National significance.

5.1.17 Foum-Zguid Jurassic Dyke

The Jurassic Foum-Zguid doleritic dyke, some 120 m wide and over 150 km long, occurs in the central part of the AA (Fig. 5e), and traverses a variety of Precambrian and Palaeozoic sequences (Ouanaimi and Soulaimani 2011). The dyke has been studied from the perspective of its lithology, its internal flow structures, structural relation to enclosing rocks, and metamorphism of the host rocks (Rahimi 1988, Silva et al. 2004, 2010).

5.2 Sites of Geoheritage Significance Allocated to Geosites, to SSSI or to a Geopark

As outlined above, the Geoheritage Tool-kit is used to determine whether an area can be proposed for geoconservation at a Regional, National or International level either as a geosite, a SSSI, or as a geopark. If a geological site is relatively small, and consists of geological features that are not extensive (e.g. a fossil site, sedimentary structures, etc.), depending on their significance, the area may be designated as a geosite (e.g., sedimentary features in Cambrian rocks), or a SSSI (e.g., the coloured phacopid trilobite). These would be small, isolated occurrences of a given important geological feature. In the Anti-Atlas, there are numerous sites that can be designated as geosites or SSSI (Table 1). The results of applying the Geoheritage Tool-kit to the Anti-Atlas are summarised in Fig. 12.

If there are a number of geological features in an area (e.g., the corridor of Precambrian inliers), or if an area manifests an integrated ensemble of geological features (e.g., Zenaga Inlier, Errami et al. 2013a), or if the geological feature is expressed over a large area (e.g., the Appalachian-style of folding), the geological feature(s) or the ensemble may qualify to be viewed as a geopark. The area may be proposed for geoconservation as a geopark especially if there is a range of inter-related geological features that all ranked highly in assessment of significance.

Given the range of inter-related geological features in the AA region, there is a need for geoconservation of individual features and for an integrated geoconservation system of these inter-related ensembles. Thus, in terms of geoconservation, addressing the various features of geoheritage value in different areas of the AA that individually rank from Regional, National to International significance, can be best achieved in many locations by viewing systems as geoparks. In this context, many areas should be viewed as Global geoparks, or African geoparks, or National and/or Regional geoparks. Table 1 lists areas and geological features that are fulfilling criteria for geoparks.

6 Conclusion

The preliminary inventory of sites of geoheritage significance of the AA geological region, using the Geoheritage Tool-kit approach, assigns a level of significance to geological features and, from there, they can be allocated to geosites, to Sites of Special Scientific Interest (SSSI) and/or to geoparks. The geology of the Anti-Atlas was used as a case study because it contains a wide variety of geological features ranging in size from regional scale to fine scale, and varying in significance from International to Regional. Thereafter, in the geoconservation of the identified geosites, SSSI, and potential geoparks, the next step is to inscribe these sites as formal geoconservation sites, and to integrate some of them into the cultural context of the region. For instance, the first interpretative panel of the Bou-Azzer inlier is in progress in collaboration with a local association. The next stage for geoconservation and geoheritage in the Anti-Atlas is to focus on each inlier to identify further sites of geoheritage significance (Errami et al. 2013a).

This paper has emphasised the unique geological setting of Morocco, and the global importance of many sites within the Anti-Atlas. In this context, given their importance, and the current commercial and tourist exploitation of numerous sites, it is clear that many geologically-important areas are in urgent need of protection. All fossiliferous sites are in this category. Adequate capacity building of the local communities and stakeholders will help to increase the awareness about the necessity for the protection and valorisation of their geoheritage.

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The Geoheritage of Kerdous Inlier (Western Anti-Atlas, Morocco): Pages of Earth History in an Outstanding Landscape

La géologie: de l'Antiquité à nos jours Le géopatrimoine et la géoconservation, cas de la Grande-Bretagne

جيوتراث عروة "كردوس" (غرب الأطلس الصغير- المغرب) : صفحات من تاريخ الأرض في مشهد طبيعي استثنائي

E. Druguet, A. Rahimi, J. Carreras, L.M. Castaño, and I. Sánchez-Sorribes

Abstract

The Kerdous massif (Anti-Atlas of Morocco) consists of outstanding geological features and landscapes, such as many fascinating erosion landforms. Moreover, the outcropping rocks in the area comprise a unique record of multiple processes in the Earth geological evolution. The first list, resulting of the preliminary inventory of the most relevant and representative geosites in the region includes four large zones of exceptional value. These are the granite landforms of Tafraoute (south of Tafraoute village), the Ameln valley (north of Tafraoute), the Aït-Mansour gorges (southeast of Tafraoute) and the Izerbi plain (south of the Kerdous inlier). Their features make the Kerdous area worthy of conservation as a natural-cultural site deserving a Global Geopark status. The protection of these geosites is compatible with their use as a cultural resource. Geoheritage-based tourism activities could be promoted under an appropriate management plan based on geoeducation and geoconservation.

Résumé

Le massif de Kerdous (Anti-Atlas, Maroc) est caractérisé par une importante géodiversité due à sa structure géologique complexe et aux reliefs et paysages exceptionnels qui lui sont associés. Dans cette région, un grand nombre de sites géomorphologiques et géologiques offrent un potentiel, très important et unique dans son genre au Maroc, pour des usages scientifiques, éducatifs et touristiques. La première liste résultant de l'inventaire préliminaire-des géosites les plus pertinents et les plus représentatifs de la région, inclut quatre grandes zones les plus remarquables. Il s'agit de Tafraout connue par ses curieuses et impressionnantes formes modelées dans le granite rose, la vallée d'Ameln et ses paysages pittoresques, les gorges d'Ait Mansour et la plaine d'Ait Ouafka-Izerbi. A ces paysages magnifiques, il faut ajouter d'autres patrimoines d'intérêt particulier du point de vue archéologique (gravures sur

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les rochers), architectural, écologique, historique et culturel. La protection de ces géosites est compatible avec leur utilisation comme une ressource culturelle. Les activités touristiques basées sur le géopatrimoine pourraient être promues dans la cadre d'un plan de gestion approprié basé sur l'éducation et la géoconservation.

ملخص

تتميز عروة `` كردوس"، المتواجدة بالأطلس الصغير – المغرب، بجيوتنوع هام وذلك راجع إلى بنيتها الجيولوجية المعقدة والتضاريس والمناظر الطبيعية الخلابة المرتبطة بها.في هذه المنطقة تمنح العديد من المواقع الجيومورفولوجية والجيولوجية مؤهلات هامة وفريدة من نوعها بالمغرب، لأغراض علمية، تربوية وسياحية. القائمة الأولى، الناتجة على الجرد الأوليلأهم الجيومواقع، مَكَّنَت من تسليط الضوء على أربعة مناطق الأكثر أهمية.يتعلق الأمر بـ `` تافراوت" المعروفة بجرانيتها الوردي المنحوث على أشكال مثيرة للإعجاب، وادي `` املن" ومناظره الطبيعية الخلابة، ومضيق `` آيت منصور" وسهل `` آيت وفقه- ازربيي". لهذه المناظر الطبيعية الخلابة ينبغي إضافة أنواع أخرى من التراث ذات أهمية خاصة من وجهة نظر أثرية (المنحوتات على الصخور)، هندسية، ايكولوجية، تاريخية وثقافية.إن المحافظة على هذه الجيومواقع تتلائم مع استخدامها كمورد ثقافي. ويمكن تعزيز الأنشطة السياحية التي تستند على الجيوتراث في سياق خطةِ تدبيرٍ مناسبةٍ تنبني على التربية والجيومحافظة.

Keywords

Anti-Atlas • Geotourism • Geoconservation • Geopark • Kerdous inlier • Tafraout

Mots-clés

Anti-Atlas • Boutonnière de kerdous • Géotourisme • Géoconservation • Géoparcs • Tafraout

الرئيسية الكلمات

الأطلس الصغير • عروة "كردوس" • جيوتراث • جيومحافظة • جيومنتزه • تافراوت

1 Introduction

Geoheritage is represented by all those geological elements of significant value to humans, including scientific research, education, aesthetics values and cultural developments (Dixon 1996; Sharples 2002). Thus, it can be represented either by minerals and fossils, or by geomorphological, stratigraphic, tectonic, magmatic, metamorphic, old mining sites or by any outstanding geological feature. The Global Geoparks Network supported by UNESCO aims to protect and develop territories which include particular geological heritage of international significance. The geological heritage of these Global Geoparks is being used to promote the sustainable development of the local communities who live there, and they are protected under local, regional or national legislation as appropriate.

Morocco is unanimously recognised for the richness and the diversity of its landscapes, largely due to its geological history. However, it was not until the last few years that an Association for the Protection of Moroccan Geological Heritage (APPGM) was created and that the outstanding geological heritage of Morocco has started to be promoted internationally. Examples of areas where and inventory and protection plan has been promoted are as the M'Goun Geoparc in the High Atlas mountains (El Khalki et al. 2009), the Ait Hajji geomorphosite in Central Morocco (Nahraoui et al. 2011) and the Bou Azzer area in the Anti-Atlas (El Hadi et al. 2011). Relevant to geoconservation of geoheritage in Morocco is the recent initiative of the African Geoparks Network (AGN) to promote African geoheritage and geoparks. This was stated in El Jadida Declaration (Errami et al. 2012) that come out from the First International Conference on African and Arabian Geopark held on November 2011 in El Jadida (Morocco), where the Moroccan geoheritage was widely promoted (Errami and Al-Aawah 2011). Besides this, the Ministry of Energy and Mines of Morocco has been working on a regulation and legislation project for the national geological heritage, in which different geozones are grouped into three main categories: sites of geological interest, geotopes and geoparks (El Hadi et al. 2011).

Among the zones in Morocco being of a particular interest from a geological and geomorphological point of view is that of the western Anti-Atlas Kerdous inlier. The present work aims to demonstrate the didactic, scientific, cultural and geotouristic values of the area. The valorisation and the promotion of these values will help to improve the leaving standards of local population and promote the Kerdous inlier as a main geotouristic destination. Based on that, an action plan is proposed which comprises the compilation of an inventory of the geological heritage and the diagnosis of the anthropic negative impacts that may threaten them, as well as identification of local development projects for its restoration, protection and cultural and economic development. Moreover, this contribution aims to persuade not only geologists, but decision makers that are responsible for land policies and management about the importance of this geological heritage, and to consider the potentiality of the Kerdous area to achieve the status of Geopark.

2 Geological Framework of the Kerdous Inlier

The NE-SW oriented Anti-Atlas belt is characterized by the presence of several large Precambrian erosional windows called inliers or "boutonnières" (Choubert 1963). These inliers form a complex assemblage of basement rocks (Paleoproterozoic, Neoproterozoic) rimmed by a cover of Lower Paleozoic rocks (Gasquet et al. 2008). The current configuration where the Precambrian rocks are outcropping within these inliers is due to the Alpine uplift of the Anti-Atlas (Choubert 1963; Cahen et al. 1984).

The Anti-Atlas marks the northern boundary of the Eburnian West African Craton (WAC) (Ennih and Liégeois 2001; Thomas et al. 2004) and is characterized by a local display of the effects of the Neoproterozoic Pan-African orogeny.

The Kerdous inlier, located at about 100 km SSE of Agadir and with Tafraoute as the main town on its eastern flank (Fig. 1a), is one of the largest Precambrian inliers of the Anti-Atlas belt. The area has been a subject of numerous scientific studies devoted specifically to its geology (Choubert and Faure-Muret 1972; Hassenforder 1987; Nachit et al. 1996; Malek et al. 1998; Thomas et al. 2004; Soulaimani and Piqué 2004; Gasquet et al. 2004; Pons et al. 2006; among others).

As most other inliers of the Anti-Atlas, the Kerdous inlier is formed by three main lithological units (Fig. 1b): (1) A Paleoproterozoic basement of crystalline metamorphic and magmatic rocks, traditionally designated in the literature as PI (Choubert 1963; Choubert and Faure-Muret 1983) or as Eburnean. The metamorphic rocks, predominantly of sedimentary origin (slates, phyllites, schists and migmatites) were

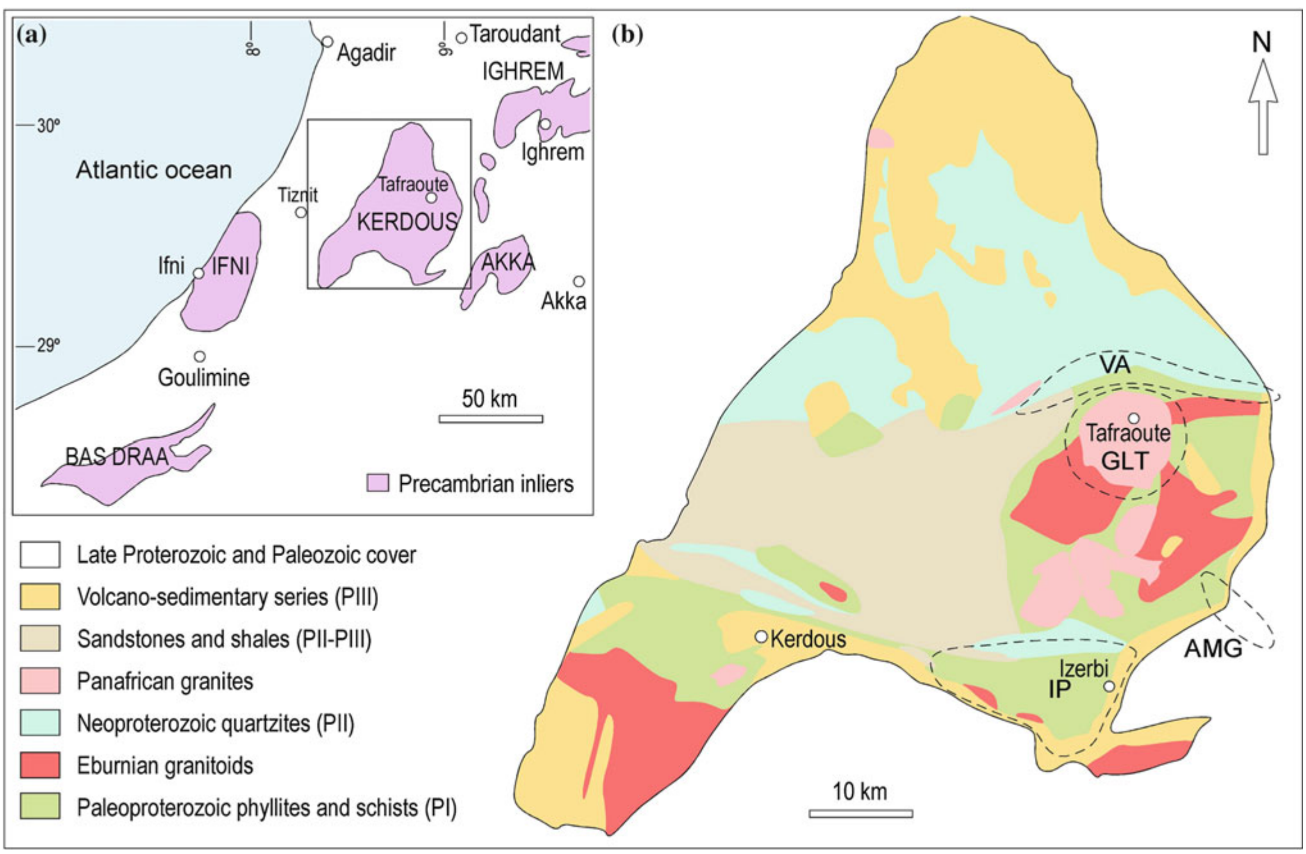

Fig. 1 Location (**a**) and schematic geological map (**b**) of the Kerdous inlier in the southern Anti-Atlas of Morocco, after Choubert (1963) and Hassenforder (1987). *VA* Valley of the Ameln; *GLT* granitic landforms of Tafraoute; *AMG* Aït-Mansour gorges; *IP* Izerbi plain

deformed and metamorphosed during the Eburnian Orogeny (~2.000 Ma) and the Eburnean magmatic rocks, mostly granitoids, are considered to be emplaced synchronically with this tectonometamorphic event (Charlot 1978).

(2) Several sedimentary (mainly quartzites) and volcanic sequences of lower to mid-Neoproterozoic age, which are locally affected by the Pan-African orogeny and intruded by Pan-African granitoids (known as PII, of ages ranging between 630 and 550 Ma, Gasquet et al. 2008). The Paleoproterozoic basement rocks were also heterogeneously affected by the Panafrican deformations (folds and shear zones) and metamorphism.

(3) An upper Neoproterozoic (known as PIII) to Paleozoic cover which unconformably overlies the earlier units (PI and PII). These cover rocks are disposed sub-horizontally, although they are locally affected by Variscan folds.

3 Sites of Significant Geoheritage Value in the Kerdous Region

The Kerdous massif includes outstanding landscapes which largely reflect a variety of geological components. Besides the contribution of the geology to the design of magnificent landscapes, the outcropping rocks in the area and their intrinsic characteristics comprise a unique record of multiple processes in the Earth geological evolution. Obviously because of the prevalence of basement rocks, most (if not all) existing peer-review international publications devoted to the Kerdous inlier are dealing with structural, igneous and metamorphic features and with their geodynamic aspects (see references in the previous section). These studies evidence that the area is of great local, national and international scientific interest.

As a precursory step in the compilation of a more complete and systematic inventory of the study area, we present here a first list of sites of geological and geomorphological interest. Four large zones (geozones) of exceptional value have been selected on the basis of their representativeness and the diversity of their geological configurations. Their locations and approximate boundaries are outlined in Fig. 1b. Each geozone may include several smaller spots or geotopes. These four geozones are described below.

3.1 Granite Landforms of Tafraoute, South of Tafraoute Village (GLT)

The arid and semi-arid landscapes, surrounding Tafraoute village (Fig. 1b), are characterized by magnificent landforms which are being developed on the Neoproterozoic granitic pluton of Tafraoute. Also known as the Tafraoute granites, these intrusive rocks represent the youngest rocks of the Pan-African episode (549 ± 6 Ma according to Pons et al. 2006). While the Tafraoute granites are relatively homogeneous from the petrologic point of view, their geomorphologic scope makes them more interesting and famous. Particularly remarkable are the forms that result from weathering along joints (Figs. 2a and 3c, d), dome-shaped inselbergs (Fig. 3a, b) and tafoni. These features resulted from wind and water weathering. Some of these natural sculptures have become part of the popular heritage, such as the "Chapeau de Napóleon" (Napoleon's Hat, Fig. 2b) or the Elephant. A proof of the relevance of this geozone is the science promotional video by Lüning and Geiger (2005) on the geology and geological history of Morocco, in which a section is dedicated to the Tafraoute granites. A photograph of "Napoleon's Hat" appears in the video front cover.

Also famous but controversial are the "Roches Peintes" (Painted Rocks or Blue Rocks), a group of granitic small hills and boulders located at 4 km south of Tafraoute village (Fig. 3). In 1984, the Belgian artist Jean Verame lead a project to spray these landforms with several tonnes of blue, red, violet and white paint (Fig. 3b). With time passing, the

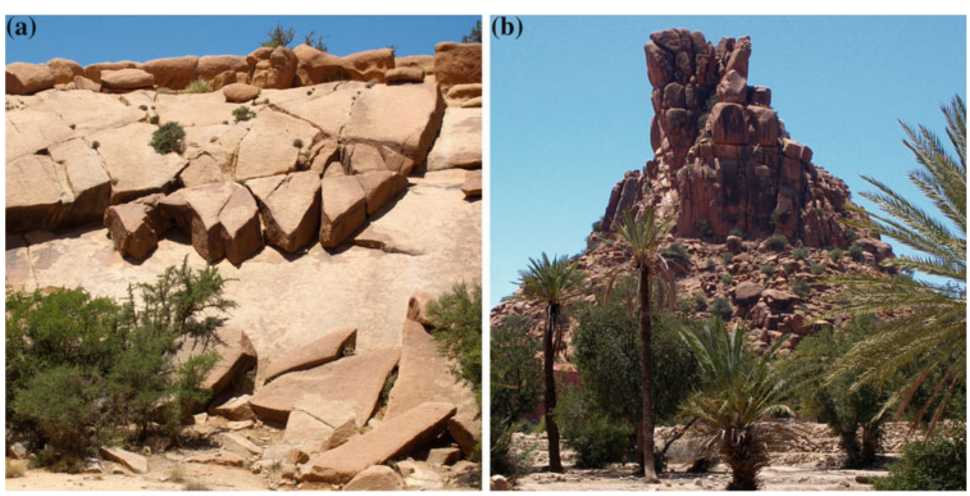

Fig. 2 Granite landforms. **a** Prismatic shapes resulting from erosion along the jointed Tafraoute granite. **b** The emblematic granitic figure "Chapeau de Napóleon" (Napoleon's hat) in the village of Aguerd Oudad, 2 km south of Tafraoute

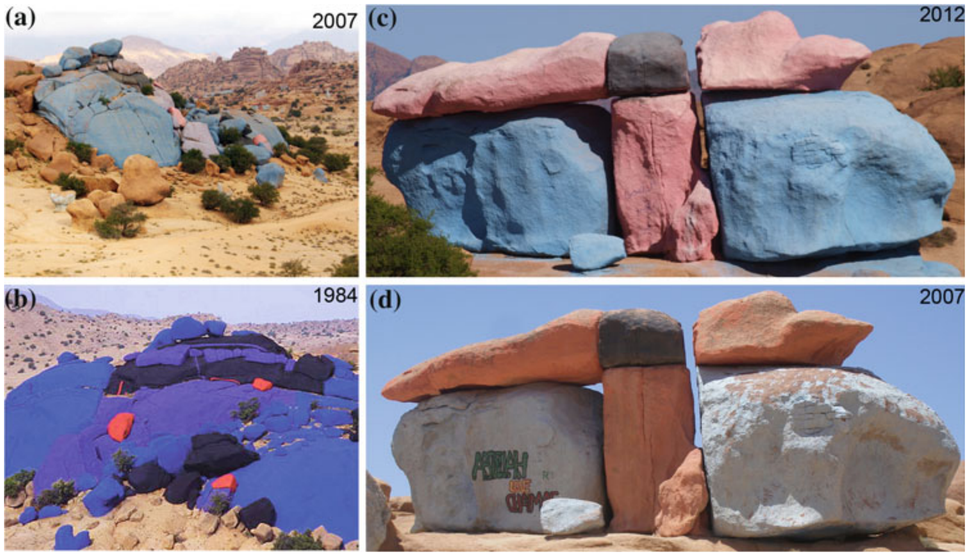

Fig. 3 Examples of one of the landscape paintings performed by the Belgian artist Jean Verame in granitic landforms near Tafraoute, known as the "Roches Peintes". Since created in 1984, the colours become increasingly loose and faded due to weathering by the wind and the strong solar radiation. In 2010, the enterprise "Peintures Atlas" has re-painted some of the site to its former Verame's colours. **a** Some of the painted forms photographed in 2007. **b** The same forms as in (**a**) photographed in 1984 (Verame 1984, reproduced with author's permission, http://www.jeanverame.com/anglais/maroc.php). **c** Another popular form photographed in 2012, 2 years after being re-painted. **d** The same form as in (**c**) photographed in 2007. Notice the presence of superposed graffiti

colours become increasingly loose and faded due to weathering by the wind and the strong solar radiation (Fig. 3a, d). In 2010, the enterprise "Peintures Atlas" went through a renovation project that restored part of the site to the former Verame's colours (Fig. 3c). Divergent opinions exist between those who consider this type of human modification of natural formations as an artwork that improves the landscape and those who object and refute these kind of practices that are damaging the landscape.

The cultural and archaeological heritage of the small villages in the area aesthetically harmonizes with this geological landscape heritage. This is the case of the ancient villages such as Adai, Imyane and Tazekka (Fig. 4a). Many traditional Berber houses were built on the slopes of the granitic promontories and, in this cases, the materials and shapes used in these buildings perfectly match with the natural pinkish-orangish smooth boulders of granite. Finally, it is important to mention here that prehistoric art is also locally represented in this area in the form of rock engravings or petroglyphs. Among them, one of the most visited and appraised carving is the Gazelle near Tazekka (Fig. 4b).

3.2 Valley of the Ameln, North of Tafraoute (VA)

This is a scenic valley bounded to the north by an impressive mountain cliff made of sub-vertical beds of Neoproterozoic (PII) quartzitic rocks (Fig. 5). A sharp contact separates the PII quartzites from the Paleoproterozoic metasedimentary rocks (PI) at the bottom of the valley, a contact which corresponds to a Pan-African shear zone (the Ameln Valley shear zone; Hassenforder 1987; Soulaimani and Piqué 2004).

Several small villages of great beauty and historical-cultural value are harmonically aligned along the base of the cliff such as Tighzt, Tandite and Oumesnate (Fig. 5b). Unfortunately, most of the ancient buildings in the valley are partly or totally abandoned and threatened by ruin.

3.3 Aït-Mansour Gorges, Southeast of Tafraoute (AMG)

This is another site of prime geological and geomorphological heritage. Here, narrow gorges were carved by the river through the PIII Cambrian limestones at the bottom of which there is a magnificent palm forest (Fig. 6). Also prominent from the geoscientific point of view is the unconformity between the folded metamorphic rocks and migmatites of the Eburnian basement and the horizontal Cambrian limestones (Fig. 6a) that can be observed along the zig-zagging road that drives down to the oasis. The most striking scene of this geozone is given by the strong contrast between the brownish rocky cliffs and the green landscape of dense palm trees that dominate the bottom of the valley (Fig. 6b).

Fig. 4 **a** The ancient Berber houses in the village of Tazekka represents a superb example of integrating traditional building with the rocky (here the Tafraoute granite) landscape. On the contrary, mismatching elements are rather frequent in the contemporary architecture (note the white frame on the *lower-right* side of the photograph). **b** Prehistoric rock carving of a gazelle near Tazekka

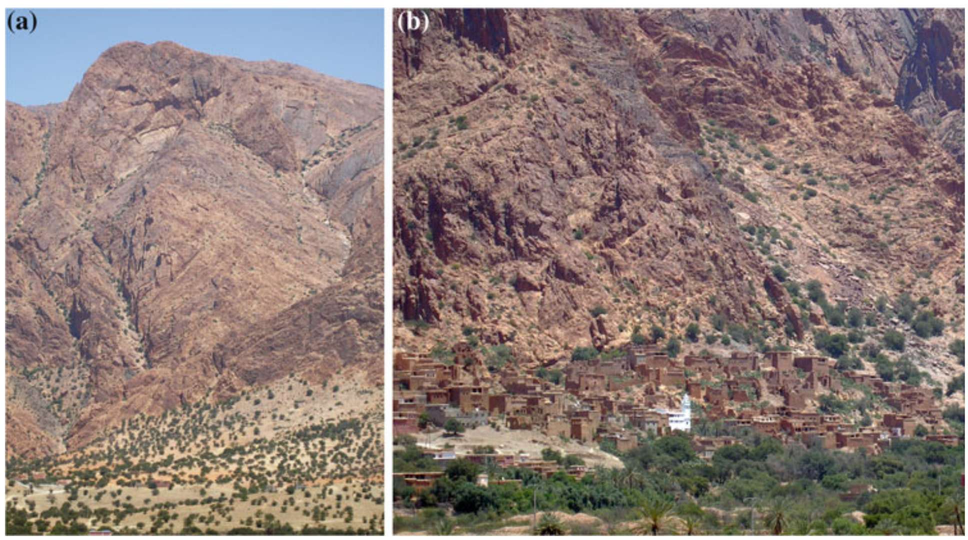

Fig. 5 The PII quartzites conform the impressive cliffs that flanks the Ameln valley to the north (north of Tafraoute). **a** The famous Lion's head, another natural sculpture on top of the quartzite cliffs. **b** View of Oumesnate, one of the many small picturesque towns in the Ameln valley, with the typical adobe constructions only disturbed by a few modern concrete houses and parabolic antennas

3.4 Izerbi Plain (IP)

A singular characteristic of this geozone concerns the contrasting landforms of geological predominance. The Izerbi plain, an extensive semi-desertic flatland conformed by extremely eroded rocks of the Eburnian basement, is bordered to the north by the irregularly shaped mountain cliffs that consist of steeply dipping Neoproterozoic PII quartzites (Fig. 7a). However, the most remarkable aspects of this geozone concerns Earth processes heritage. The contact between both Eburnean and PII units is represented by an east-west trending Pan-African shear zone (the Tasrirt-Tahala shear zone). Together with the previously mentioned Ameln Valley shear zone, northwards in the Kerdous massif, both shear zones represent the major structural features in the Kerdous inlier (Hassenforder 1987; Soulaimani and Piqué 2004). The tectonic structures outcropping in the metamorphic Eburnean basement rocks (folds, crenulations and kink-bands, e.g. Fig. 7b) are of special interest and relevant for the understanding of the Pan-African orogeny. Another remarkable feature in these basement rocks is the widespread presence of swarms of mafic (mainly doleritic) dykes (Fig. 7a; Carreras et al. 2006; Castaño 2010). These mafic dyke swarms are also common in other adjacent inliers (e.g. Ikenne 1997; Hafid 1999), but are especially well exposed in Kerdous inlier, where many intriguing internal and marginal deformation structures in contact with the hosting metamorphic rocks are displayed. These dykes are almost exclusively intruded into the Eburnean metamorphic and granitic rocks, although geochemically affine sills were found in the PII materials (Hassenforder 1987). A debate still remains regarding whether there is one or more magmatic

Fig. 6 The Aït-Mansour Gorges, on the southeast border of the Kerdous inlier. **a** Unconformity between the deformed metamorphic rocks and migmatites of the Eburnian basement (PI) and the horizontal cambrian limestones (PIII). **b** Panoramic view of the Aït-Mansour gorges carved by the sidi mansour river (view is down valley, towards the east). Note the contrasting landscape between the rock walls made of PIII limestones and the palm oasis at the bottom of the valley

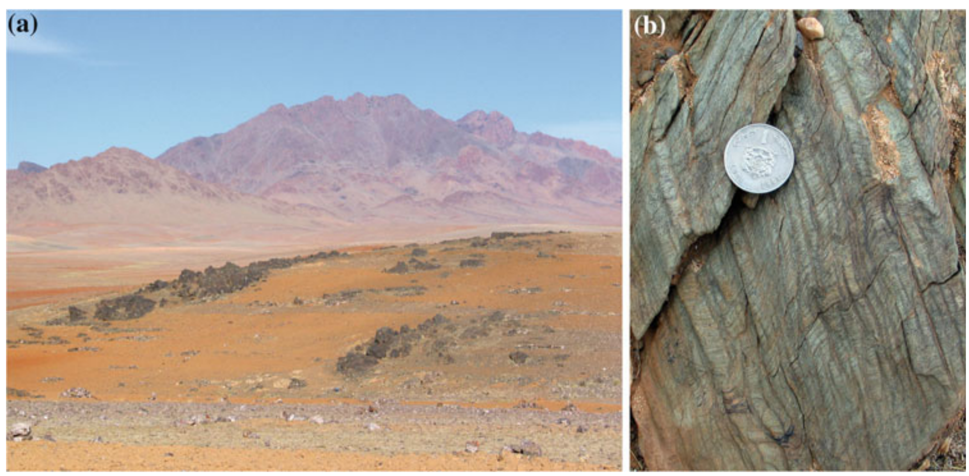

Fig. 7 **a** View to the north of the Izerbi plain. The *dark* rocks that stand out in the landscape are dolerite dykes (likely Panafrican in age) intruded into the brownish Eburnian phyllites that dominate the plain. The cliffs are made of PII quartzites. **b** Fine crenulation cleavage developed in phyllites from the Izerbi plain

events responsible of these mafic dykes, and about their ages and geotectonic significance (Carreras et al. 2006), evidencing that further investigation is required on this subject.

In the four geozones described above, geoheritage is associated to archaeological and architectural heritages, particularly in the Tafraoute granite landforms and Ameln Valley zones. Moreover, geological heritage also coexists with biodiversity in the Kerdous inlier, where several unique animal and vegetal species and ecosystems are present, some of which are under threat. This is the case of the endemic argan tree, the wild boar and the gazelle and other ungulates. Thus, the Kerdous inlier consists of a typical example of convergence of the three main groups of heritage values: geological, historical/archeological, and ecological/biotic.

4 Current State of the Kerdous Geoheritage: Positive Developments Versus Negative Impacts and Threats

A complete assessment of natural and/or cultural heritages requires an evaluation of the nature and quality of the sites (i.e. throughout inventories) but also an estimation of their conservation and vulnerability. This is therefore something to be performed for the case of the Kerdous geoheritage. In what follows we present an outline of the main aspects behind these issues. The present condition of the Kerdous geoheritage is an outcome of the confluence of several socio-economic and cultural circumstances, some of which are generally shared by other Moroccan and North-African countries; others are more specific of this region.

The mainly rural character of the zone and the up-to-date low degree of urban and industrial development allow vast areas of this massif keeping relatively pristine compared to other sites where geological heritage is located in highly urbanized areas. Thus, a large proportion of surface area of the sites of geological interest described in the previous section is in a good state of conservation. Agricultural development is rather restricted to fertile valleys or plains and to cultivations in semi-arid and arid forests such in the case of the Argan, Olive and Almond trees, and they do not imply any significant perturbation or negative impact on the landscapes and/or on the geological formations. Livestock activities (mostly sheep and goats) extend further across the mountains, also being usually well integrated into the landscape.

Negative impacts related to urban development are rather restricted to villages that are growing without environmental-friendly urbanization plans. This is mostly happening around the ancient Berber houses in the villages along the Ameln valley, where modern, but mismatching concrete constructions are proliferating.

As regards to mineral resources, the mining industry is currently increasing in this region, with several gold-bearing (and other metals) deposits being object of exploration in the Kerdous and adjacent inliers, as reported by the Moroccan National Office of Hydrocarbons and Mining (ONHYM) on its web page (http://www.onhym.com/Mining/). Most occurrences are located in the Eburnian basement around the Izerbi plain, the scenic landscapes there being potentially threatened. However, the implementation by ONHYM of an environmental strategy for these mining activities offers certain warranty for geoconservation.

The recent increase of touristic development in this region has also proved to be crucial and particularly challenging in terms of landscape and geological heritage conservation. Tafraoute has become one of the most famous and well reputed touristic destination of the Anti-Atlas region, not only because it is a charming village with a variety of cultural values, but also because it is strategically located in the middle of the picturesque lands whose natural heritage attracts many visitors every year from all around the world. The type of tourism developed on this region plays in favour of geoconservation, because cultural, sportive (hiking, cycling, rock climbing) and general nature leisure activities predominate. The touristic actions that are being developed around Tafraoute can be broadly regarded as positive, because they are mostly based on a sustainable grow and promote a respectful use of landscapes and cultural values. Especially defendable are those actions which are aimed to restore ancient buildings to be used as touristic infrastructures (e.g. rural hotels), and the local and private activities promoting the cultural and natural values (including geological heritage) of the region (e.g. touristic pamphlets provided by some hotels).

On the other hand, the lack of effective geoconservation plans under specific protection policies and regulations make this geological heritage extremely vulnerable to bad use and degradation. The granite landforms, surrounding Tafraoute village, are particularly vulnerable as they are most accessed, being exposed to various threats which are likely to involve their degradation or even their total destruction. These threats come from some bad practices by local populations or by visitors unaware about the geological values and the landscape itself. In this way, certain landforms are masked by mismatching installations (e.g. Fig. 4a) and others are sometimes used for placing advertising panels or making graffiti (e.g. Fig. 3d).

A particular situation is that of the Painted Rocks in the geozone referred here as Granite landforms of Tafraoute, where natural landscape has been artificially modified to some extend through rock painting activities. As stated before, whether this action represents a positive or negative impact to geoheritage is presently a matter of discussion. As recommended by Carreras et al. (2012), in those situations where the effects of human action amplify the interests and enhance access to geological values, the resulting balance should be considered positive and compatible with geoconservation. In the Painted Rocks case, access to and curiosity for geoheritage are clearly amplified, since visitors are attracted by the site, but the enhancement or decrease of the intrinsic geological values is a debatable issue. We consider that the paintings can be maintained as far as the affected area is not further expanded, that is, that the "painted domain" remains restricted to its present location, and if appropriate measures are taken to ensure compatibility between landscape safeguarding and geotourism.

5 Integrating Geoeduction, Geoconservation and Geotourism: A "3Geos" Development Plan for the Kerdous Area

As described in the previous section, geoheritage of the Kerdous inlier is vulnerable to certain negative human impact. The development of merely protectionist policies and regulations can help to prevent the hazards and threats to geological heritage. However, truly effective geoconservation includes the need for educational outreach programs on the significance and need for conservation of the geological heritage. Furthermore, touristic activities and infrastructures, if properly managed, can be not only compatible but also mutually complementary with geoconservation. These are the main principles of geotourism, either if regarded as the tourism that enhances the qualities of a place, including its environment, culture, aesthetics, heritage, and the well-being of its residents (Boley et al. 2011), or more strictly concerning to tourism that is based on sites of geological interest (Hose 2000; Dowling and Newsome 2006; Newsome et al. 2012). It seems then obvious that different public or private organizations or institutions and individuals that are in charge of management of the geotouristic activities in this region are aware of its geological heritage and of geoconservation strategies. Geotourism and geo-education are therefore also directly linked, and together with geoconservation they form a "triangle" of interlinked and interdependent strategies. In the case of the Kerdous inlier, we believe that geoeduction, geoconservation and geotourism should be integrated and mutually considered in any development plan.

In light of these principles and of the specificities of the Kerdous inlier, we consider that this area meets the conditions suitable for being a Global Geopark, as this initiative is specifically targeted to stimulate sustainable economic and cultural development of a region based on the presence of significant geological sites.

A series of stepped actions have to be carried out in order to reach the Geopark tag or any other status that can be satisfactory for the social and cultural development of the Kerdous area and compatible with conservation of its geological heritage. Such actions require intercommunication and coordination between individual geoscientist, scientific or academic institutions (i.e. universities and research centres), industrial developers and local, regional and national authorities and institutions responsible for land management.

The scientific community may take part in these activities through:

- the development of inventories and creation of databases of sites of geological and geomorphological interest;
- evaluating the state of the conservation of the different geosites, the present and potential threats, and suggesting possible solutions to mitigate negative impacts;
- the promotion of geoconservationist and geo-educational values.

Within the framework of these action plans, the regional and local authorities (e.g. municipalities) should consider:

- the geoheritage of this region when implementing rural and urban development plans;
- contributing to geo-education through giving support to information and educational programs (e.g. at the schools) in the field of geoconservation, to increase citizens sensibility towards the geological values;
- setting up measures specific to encourage local and regional, private and public industries (e.g. mines) which deal with land management to implement geoconservation strategies;

The governmental organizations should be able to contribute through, for instance:

- strengthening the co-operation with scientific international organizations and institutions working on the field of the geoheritage conservation.
- ensitizing and educating people and organizations on the geoheritage values and their capabilities for social, cultural and touristic development of the country;

6 Conclusions

Through this work, we have tried to demonstrate the outstanding geological values of the Kerdous inlier in the Western Anti-Atlas of Morocco. The region contains at least four large geozones of international scientific interest which, in addition, include many unique geomorphological features and a variety of scenic geological landscapes. These principal geozones are the granite landforms of Tafraoute (south of Tafraoute village), the Ameln valley (north of Tafraoute), the Aït-Mansour gorges (southeast of Tafraoute) and the Izerbi plain (south of the Kerdous inlier).

This geological heritage of the Kerdous inlier is vulnerable to certain types of human activities. Consequently, it is recommended that regional and local strategies should reconcile the need for economic development and the geoconservational duties. Moreover, it is crucial that any land management activities considers the interdependency between geotourism, geo-education and geoconservation, and the need for coordinating actions among individuals, local associations and regional or national initiatives.

Because of its extraordinary geological heritage, the Kerdous area deserves protection as a natural-cultural site, and it is worthy of acquiring a 'Global Geopark' status. A Geopark in this area will enhance its social, cultural and economic development.

Tafraoute is strategically located and has the potentials to become the "capital" of the aspiring Kerdous Geopark. The Painted Rocks site near Tafraoute, if regulated and managed under geoconservation criteria, could even become a paradigm for geocultural tourism.

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Recommended Geoheritage Trails in Southern Morocco: A 3 Ga Record Between the Sahara Desert and the Atlantic Ocean

Recommandation de deux géoroutes au sud du Maroc: 3 Ga entre le désert du Sahara et l'océan Atlantique

توصية بإحداث جيوطريقين بجنوب المغرب:
ثلاثة ملايير من السنين بين الصحراء والمحيط الأطلسي

O. Saddiqi, E. Rjimati, A. Michard, A. Soulaimani, and H. Ouanaimi

Abstract

The remote regions of Southern Morocco are rich in outstanding geological landscapes and outcrops not well known to the general public. In this paper, we propose two east-trending geotrails (transverse to the regional trend of the structures) with a total of 19 geosites of particular interest for geotourists as well as for geologists. The southernmost, Dakhla-Awsard geotrail gives the opportunity to observe the oldest rocks (Archaean) of Morocco, belonging to the West African Craton (WAC), and their relatively thin Palaeozoic cover. This trail also presents a section across the Variscan nappes thrust over the craton, which is a unique geological setting in Morocco, but extending widely southward to Mauritania. Finally, the trail includes four geosites in the Cretaceous-Cenozoic deposits of the Coastal Basin, close to the Dakhla sea resort. The northern geotrail starts from El Ouatia (Tan-Tan Plage), another sea resort situated 700 km in the north of Dakhla. This trail illustrates the main geological features of the Tarfaya Atlantic margin basin and provides a cross-section of the Anti-Atlas Variscan folds up to the border of the WAC. Here the External Variscan belt differs from that of the

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Dakhla transect by the great thickness of the Palaeozoic series and the contrasting styles of tectonic structures (faults and folds versus thrust nappes). The equipment and the promotion of these geotrails will increase the attractiveness of the wild nature of the Saharan regions of Morocco.

Résumé

Les régions du Grand Sud du Maroc sont riches en paysages géologiques et affleurements remarquables, encore généralement peu connus du public. Dans cet article, nous proposons deux itinéraires géologiques ouest-est, transverses aux structures régionales, avec un total de 19 géosites ayant un intérêt particulier aussi bien pour les géotouristes que pour les géologues. L'itinéraire le plus au sud, entre Dakhla et Awsard, donne l'opportunité d'observer les roches les plus vieilles du Maroc, l'Archéen du Craton de l'Ouest Africain, et leur mince couverture paléozoïque. L'itinéraire montre aussi une coupe dans les nappes varisques (hercyniennes) de l'Adrar Souttouf, charriées sur le craton, un dispositif unique au Maroc mais qui se prolonge longuement en Mauritanie. L'itinéraire propose aussi quatre sites dans les terrains sédimentaires du bassin côtier du Crétacé-Tertiaire, proches de la station balnéaire de Dakhla. L'autre itinéraire part d'El Ouatia (Tan-Tan Plage), une autre station balnéaire à 700 km au nord de Dakhla. Il montre les caractères principaux du bassin côtier atlantique de Tarfaya (marge océanique interne), puis offre une coupe de l'extrémité sud de l'Anti-Atlas jusqu'au bord du craton. Cette coupe au travers de la partie externe de la chaîne hercynienne diffère de la coupe de Dakhla par le grand développement de la série primaire et par son type de déformation (plis et failles versus nappes). L'équipement et la promotion de ces géoroutes augmenteraient l'attractivité de la Nature encore bien préservée de ces régions sahariennes.

ملخص

تتميز المناطق المتواجدة بأقصى جنوب المغرب بغنى مناظرها الجيولوجية ونتوءاتها المتميزة والتي ما تزال عموما غير معروفة لدى عامة الناس. في هذا المقال نقترح مسارين جيولوجيين شرق – غرب، يقطعان البنيات الجيولوجية الإقليمية ويشملان تسعة عشر جيوموقعا دو أهمية خاصة لكل من الجيوسياحيين والجيولوجيين. في أقصى الجنوب يُمَكنُ المسار مابين " الداخلة" و "أوسرد" من مشاهدة أقدم الصخور بالمغرب التي تعود للحقب الأركي، والتي تنتمي إلى الصفيحة الثابتة لغرب أفريقيا، وغطائها الصخري الرقيق المنتمي إلى الحقب القديم (الباليوزي). المسار يُظْهِرُ أيضا مقطعا عبر سدائم العصر الفارسكي (الهرسيني) لأدرار سوتوف المدفوعة على الصفيحة الثابتة، التي تعتبر وضعا جيولوجيا فريدا من نوعه بالمغرب، لكنه يمتد بعيدا نحو موريتانيا. المسار يقترح أيضا أربعة مواقع بالأراضي الرسوبية للحوض الساحلي التي تعود إلى العصر الطباشيري، والمتواجدة على مقربة من منتجع بحر الداخلة. المسار الآخر ينطلق من " الواطية" (شاطئ طانطان)، منتجع بحري آخر يقع على بُعْدِ 700 كلم شمال مدينة الداخلة. وهو يوضح الخصائص الجيولوجية الأساسية للحوض الأطلسي لطرفاية (الهامش المحيطي الداخلي)، والذي يقدم مقطعا لأقصى جنوب الأطلس الصغير إلى حدود الصفيحة الثابتة. هذا المقطع الذي يمر تنمية منطقة الخارجية للسلسلة الهرسينية يختلف عن مقطع الداخلة من حيث السّمك الكبير لسلسة الحقب القديم (الباليوزوي) ونوع التشوهات (طيات وفوالق عو.ض سدائم). إن تجهيز تنمية هذه الجيوطرق ستزيد من جاذبية الطبيعة البرية المحفوظة بشكل جيد بهذه المناطق الصحراوية.

Keywords

Geoheritage • West African Craton • Morocco • Archean • Variscan orogeny • Atlantic passive margin

Mots-clés

Géopatrimoine • Craton ouest africain • Maroc • Archéen • Orogenèse varisque • Marge passive atlantique

الكلمات الرئيسية

جيوتراث • الصفيحة الثابتة لغرب أفريقيا • المغرب • الأركي • تَكَوْنُ الجبال الفاريسكي • الهامش غير الفعال للمحيط الأطلسي

1 Introduction

Morocco is particularly ideal to discovering geology in the field due to the great variety of outcropping geological systems, its deeply-incised relief (Fig. 1) and its relatively arid climate. Some Moroccan geosites have been defined as Global Boundary Stratotype Section and Point (GSSP), such as the Tortonian-Messinian boundary next to the capital city Rabat (Tahiri et al. 2011) and the Eifelian-Givetian boundary south of Rissani (Walliser et al. 1995; Feist and Orth 2000). However, the inventory of the Moroccan geoheritage is still in its early stages, despite localized endeavours (Piqué and Bouabdelli 2000; Ouanaimi et al. 2005; Piqué and Soulaimani 2006; Tahiri et al. 2010; El Hadi et al. 2011; Nahraoui et al. 2011; Errami et al. 2012). In the present paper, we focus on the south-westernmost regions of Morocco, extending from Tan-Tan, 300 km south of Agadir, up to Dakhla on the Tropic of Cancer along the Atlantic Coast (Fig. 2). Most of these regions were occupied by Spain for a long time (Rio de Oro) and have been progressively opened to modern geological studies and mapping only a few decades ago (e.g., Hollard et al. 1985; Rjimati and Zemmouri 2002). From a geological point of view, they are of outstanding interest as they expose the Archaean formations of the West African Craton (WAC), the nappes and folded Palaeozoic belts emplaced on the WAC border during the Variscan collision, and the internal part of the Mesozoic-Cenozoic Atlantic passive margin (Rjimati et al. 2011a).

Fig. 1 Main geological domains of Morocco plotted on an elevation map (GTOPO database), with location of the studied geoheritage area (Fig. 2). Six domains are distinguished: *I* Rif belt; *II* Atlas-Meseta domain; *III* Anti-Atlas domain; *IV* Northern Mauritanide belt; *V* West African Craton; *VI* Atlantic margin and Coastal Basins. State borders are indicative

Fig. 2 Structural domains of Southern Morocco (Google Earth image), with location of the proposed geoheritage trails "A" and "B"

Our work concentrates on the most remarkable sites and transects that should be regarded as protected geosites or geotrails representative of this fascinating region where the Sahara Desert meets the Atlantic Ocean. We emphasize the didactic, scientific and geotouristic values of the selected trails with the aim to promote the conservation of the most exposed geosites and the enhancement of their visibility and accessibility. Our contribution aims to persuade the local authorities responsible for land management about the importance of the geoheritage of these southern Provinces for local sustainable development. This is in line with the El Jadida Declaration (Errami et al. 2012) aiming to promote African geoheritage policies, as well as with the goal of the Ministry of Energy and Mines of Morocco to place the national geological heritage under the protection of law.

2 Geological Setting

Morocco comprises six major geological domains (Michard et al. 2008) that are, from north to south (Fig. 1):

(i) The Rif Belt, which is a subduction-collision Cenozoic belt belonging to the large Alpine system of the Mediterranean domain.

(ii) The Atlas-Meseta domain, which consists of strongly deformed Palaeozoic basement, namely the Meseta Variscan Belt, overlain by a Mesozoic-Cenozoic cover, either thick and folded in the Atlas mountains, or thin and tabular in the plateau areas of the Western and Eastern Mesetas. The Meseta Variscan Belt connects with the southern branch of the Variscan Belt of Europe (Michard et al. 2010) and displays a dominant west verging polarity.

(iii) The Anti-Atlas domain, south of the High Atlas in the sub-Saharan region, typified by a thick, poorly to moderately folded Palaeozoic succession overlying a Precambrian basement that crops out in several antiformal inliers or "boutonnières" (Fig. 2) and showing strong imprints of the Neoproterozoic Pan-African Orogeny (Gasquet et al. 2008). The Palaeozoic fold belt here displays a SE verging polarity; it has been overlain by a thin Mesozoic-Cenozoic cover before being gently uplifted and eroded contemporaneously with the High Atlas mountains uplift (Missenard et al. 2006; Guimerà et al. 2011). Further in the south-east in Algerian territory, the eastern Anti-Atlas structures continue in the Ougarta Chain.

(iv) The Moroccan Mauritanides of the Adrar Souttouf (Oulad Dlim) massif and Dhlou fold belt extending to the west Saharan region and forming a strip of deformed Precambrian and Paleozoic terranes thrust eastward onto the undeformed cratonic areas. The Mauritanide Belt belongs to the large Appalachian-Alleghenian-Variscan Orogen as the Meseta Belt, from which it is separated by the Palaeozoic South Meseta Fault, broadly superimposed by the Mesozoic-Cenozoic South Atlas Fault.

(v) The West African Craton is extensive in the Saharan regions. This major domain has remained basically undeformed since ca 2 Ga. It includes the Precambrian outcrops of the Reguibat Shield or Arch and the Neoproterozoic to Cenozoic sequences of the Tindouf and Taoudenni Basins, north and south of the Reguibat Shield, respectively. The northeastern part of the Reguibat Shield is affected by the Eburnian Orogeny ($\sim$2 Ga) whereas its southwestern part consists of $\sim$3 Ga-old Archaean terranes.

(vi) The Atlantic passive margin and related Coastal Basins developed from the Triassic onwards west of the above cited domains. Its northern segments (e.g., Essaouira Basin) have been more or less deformed during the Atlas and Rif folding events. In contrast, its southern part (Tarfaya-Laayoune-Boujdour Basin) remained virtually undeformed and includes one of the most ancient passive margins preserved the world over.

3 Geosites and Geoheritage Trails Description

The region illustrated in this paper extends over ca 700 km NNE-SSW from Tan-Tan, an old city at the entrance of the Saharan regions, to Dakhla and Awsard close to the Mauritanian border (Fig. 2). The geological domains represented are the Anti-Atlas fold belt, the Mauritanide thrust belt, the West African Craton (Reguibat shield and Tindouf-Zag basin) and the Tarfaya-Boujdour Coastal Basin. As the study area is oriented SW-NE, we selected two trails oriented broadly NW-SE that cross all the geological domains, one in the southernmost region, from Dakhla to Awsard (trail A), and the other in the north, from El Ouatia to Mseid at the southern part of the Anti-Atlas (trail B). Both are located along paved roads, in areas of moderate relief, with altitudes ranging from a few tens metres to about 300 m above sea level. Likewise, both trails include comfortable tourist facilities at their starting points, which correspond to the attractive sea resorts of Dakhla and El Ouatia (also named Tan-Tan plage).

The choice of these two geotrails across the Southern provinces is justified because of their rich and varied geodiversity. The Dakhla-Awsard trail offers the unique opportunity to walk on 3 Ga-old gneisses in the Moroccan territory. Near Awsard, a didactic cross-section shows the transgression of Upper Ordovician (445 Ma) periglacial deposits directly on top of the Archaean gneisses (ca 3 Ga), which is one of the largest stratigraphic unconformities in Africa. Similarly, the trail offers the unique opportunity in Morocco to cross the tectonic system of the Mauritanide crystalline nappes, which formed due to the collision of North America against Africa during the Variscan orogeny (350–330 Ma). In contrast, the Tan-Tan geotrail crosses a quite distinct tectonic system of the Variscan Belt, typical of the Anti-Atlas and characterized by kilometer-scale cylindrical folds formed at the expense of a thick Palaeozoic sedimentary pile.

Finally, both geotrails include geosites showing the Atlantic margin sediments that accumulated on top of the Variscan basement during the Pangaea rifting (250–200 Ma) and subsequent opening of the Atlantic Ocean. However, the southern geotrail mainly illustrates the youngest levels of this sedimentary wedge, namely the Cenozoic deposits, whereas the northern geotrail also gives the opportunity to observe the Upper Cretaceous bituminous shales, i.e., a potential source of shale oil.

Along both geotrails, the geosites have been selected according to their accessibility and didactic values. Most of them are located close to the paved roads with low to moderate traffic and good parking possibilities. Special investments to create geotouristic tracks are only necessary for some of the geosites close to Awsard which is still a poorly developed area. To promote the two geotrails and to highlight the international importance of their geosites, simple geological and geomorphological explanations at a popular level are needed, either in interpretative panels or flyers (brochures) to be made available to visitors in the tourist offices and hotels throughout the whole area.

3.1 Dakhla–Awsard Geotrail

The geotrail "A" from Dakhla to Awsard is a rather lengthy trail (270 km) across Saharan desert landscapes. Most of the related geosites cluster either close to Dakhla or to Awsard, with only two geosites in the medium part of the trail (Fig. 3).

3.1.1 Dakhla Geosites

Geosite A1 is located at the edge of the scenic cliffs formed by the marine "Moghrebian" (Plio-Quaternary) calcarenites along the oceanic side of the peninsula that form a barrier to the lagoon (Fig. 4a). *Geosite A2* is located at the northern limit of the lagoon, next to an artesian well that delivers hot sulphur-laden water from a deep groundwater residing in Cretaceous rocks. This geosite also offers a geological landscape that shows the thick white Miocene marls beneath the slab of Moghrebian calcarenites (Fig. 4b). The lagoon corresponds to an area of thin and easily eroded Moghrebian calcarenites between two NNE-trending, thick Moghrebian deposits (shallow marine to sub-aerial dunes). These two geosites would need adequate interpretative panels that inform geotourists of the origin of the splendid Dakhla lagoon and of the related environmental problems.

Geosites A3 and A4 are located south of the Dakhla lagoon and illustrate the stratigraphy of the Tarfaya-Boujdour basin. *Geosite A3* is located at Portorico beach, about 60 km south of the crossroad at the entrance of the Dakhla peninsula. Its major interest is the outcrops of Eocene formations beneath Miocene deposits (Fig. 5a, b). A fossiliferous bed (containing whale bones and shark teeth; Fig. 5e) close to the base of the Eocene cliff is presently exploited by commercial fossil dealers and amateur fossil collectors, without permission, and clearly deserves protection. The sedimentary layers display remarkable dewatering structures (Fig. 5c) and neptunian dykes (Fig. 5d). These Eocene deposits are coeval with the Boukraa phosphorite beds commercially exploited further in the north at the centre of the Tarfaya-Boujdour basin.

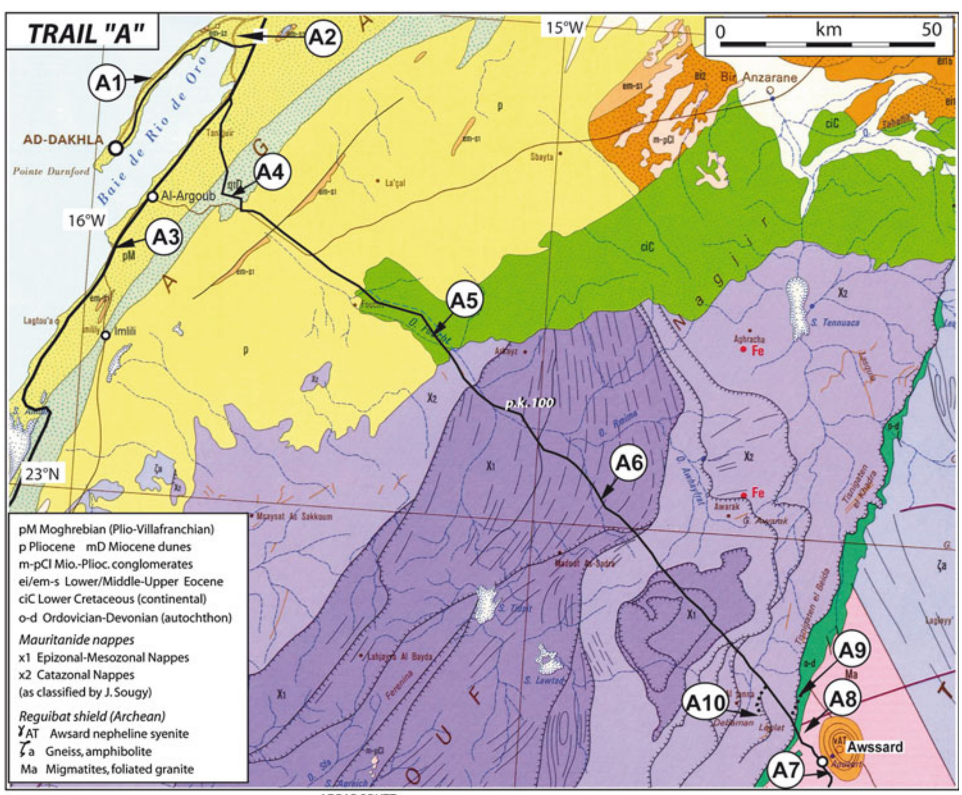

Fig. 3 Route and geosites location of the geoheritage trail "A", plotted on the Geological map of Morocco (Hollard et al. 1985)

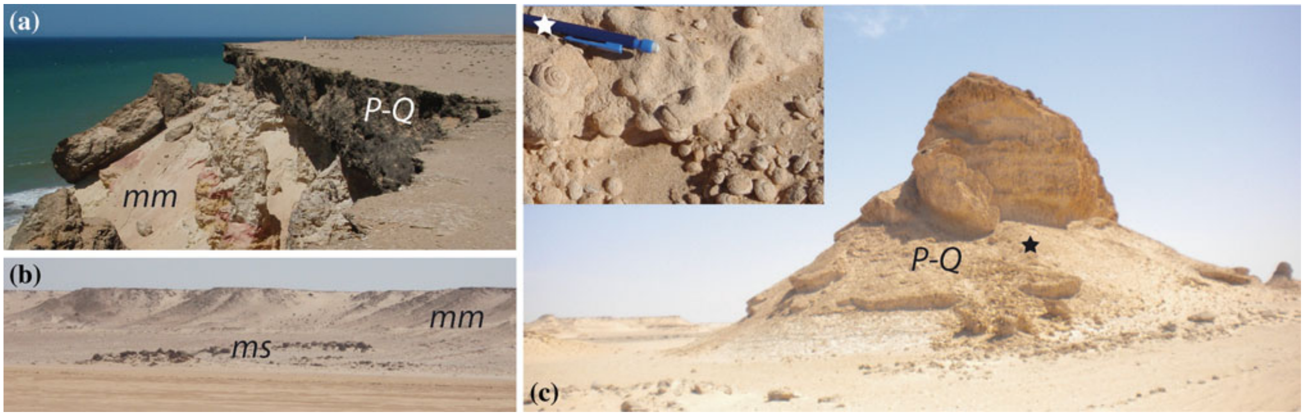

Fig. 4 **a** Typical coastal cliff of the Dakhla peninsula, **b** View of the north border of the Dakhla lagoon north of the artesian well, **c** "Sphinx Rock" with: *mm* Miocene marls; *ms black* Miocene sandstones; *P-Q* Pliocene-Quaternary calcarenites (**a**) and sandstones (**c**); *star* Helix bearing layer

Fig. 5 **a** View of the Portorico beach, looking northward, **b** Lower Eocene Izik Formation with chert nodules, **c** Dewatering fold and, **d** Neptunian dyke in the Izik deposits, **e** Shark tooth collected in the same beds, **f** Detail of the Miocene-Pliocene succession

G*eosite A4* (some 40 km south-east of A2) is located at the base of an isolated rock (the “Sphinx”) close to the road to Awsard (Fig. 4c). This site exposes the continental facies of the Pliocene-Quaternary deposits, rich in fossil *Helix* shells and casts. The Miocene marls of the *geosite A3* (Fig. 5f) are lacking here beneath the Pliocene-Quaternary sands, indicating that the Miocene shoreline was located between *geosites A3* and *A4*.

3.1.2 Midway Geosites A5 and A6

It is necessary to stop about 50 km SW of the “Sphinx” in order to locate the inner boundary of the Dakhla sedimentary basin (southern part of the Tarfaya-Boujdour basin). There, the *geosite A5* shows Lower Cretaceous red beds with a shallow northeast dip. This is the upper, outcropping part of the sandy continental formation that contains the Dakhla groundwater. On a small hill next to the road, one may observe Neolithic engravings on the red sandstone blocks (Fig. 6a). In map view (Fig. 3), it must be noticed that Upper Cretaceous deposits were not identified between the Lower Cretaceous and Cenozoic formations of this southern area, contrasting with the stratigraphy of the Tarfaya-Boujdour Basin farther in the north (see below). The unconformity at the base of the Lower Cretaceous continental sandstones (green color on Fig. 4) that directly overlie the Variscan nappes of the Adrar Souttouf Massif (deep or light violet colors) should be noted here: this is the signature of a long period of erosion after the Variscan Orogeny (Early Carboniferous, ca 330 Ma) and before the Lower Cretaceous (ca 130 Ma).

The geosite A6 is located 55 km farther in the southeast where the road to Awsard crosses the largest metagabbro complex of the Adrar Souttouf massif. This site marks the axis of the Mauritanide nappes in southern Morocco. The outcrops display typical metagabbro facies (Fig. 6b, c). The structural complexity of the metagabbro unit is much more visible in the southeastern Adrar Souttouf (Entajat) massif, due to higher elevation and more deeply incised relief (Rjimati et al. 2011a).

3.1.3 Awsard Geosites

Four geosites situated in the vicinity of the Awsard city centre (Fig. 7) will allow visitors to discover exceptional outcrops with no equivalent elsewhere in northern Morocco. Two of them (*geosites A7*, *A8*) are located in the Reguibat shield; another one (*geosite A9*) is on top of the Palaeozoic autochthonous cover beneath the front of the Mauritanide nappes, and the last site (*geosite A10*) is located within the nappe stack.

The Awsard site sensu stricto (*geosite A7*) is located immediately to the east of the village along the Tichla road. Typical banded and foliated Archaean orthogneiss crops out on both sides of the road. Similar metagranites have been dated some 200 km farther in the south (Tasiast area) at 2.97–2.93 Ga (Mesoarchean; Key et al. 2008). A few hundred metres north of the road, a cluster of rounded hills (Fig. 8a) belong to a circular intrusion of ultrapotassic syenite. This kalsilite and nepheline-aegyrine-bearing syenite is undeformed and shows a vertical magmatic lineation (Fig. 8b), consistent with its relatively young age (2.46 Ga; Bea et al. 2013). Both the foliated granites and at least part of the syenite are crosscut by a basic dyke swarm (Fig. 7).

Geosite A8 is located within the Archaean basement ca 10 km north of Awsard city, close to the Dakhla road at the southern tip of the Dliyat En'Sour ridge. It displays wonderful outcrops of heterogeneous migmatites, with large blocks of basic rocks (Fig. 8c) surrounded and crosscut by granite veins. According to their orientation, these veins are either stretched or folded, which records the high-temperature deformation of the rocks in the partially melted Archaean crust.

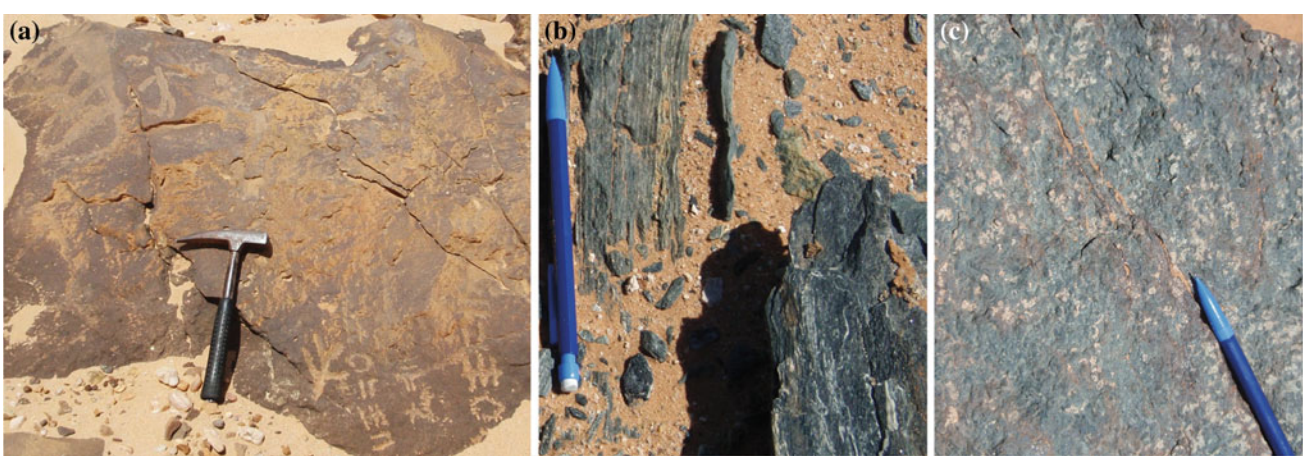

Fig. 6 **a** Neolithic engravings on Lower Cretaceous sandstones, geosite A4; **b** Metabasite, and **c** metagabbro of the Adrar Souttouf massif along the Dakhla-Awsard road

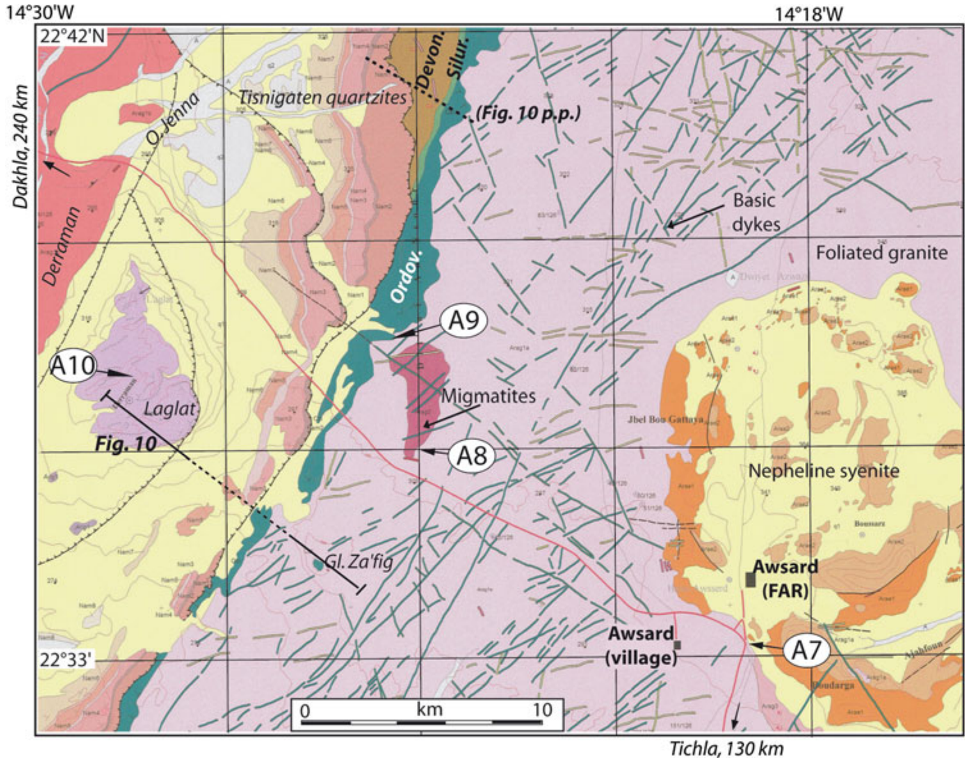

Fig. 7 Detail map of the Awsard area (excerpt of the Geological map of Morocco, scale 1:50,000), with location of geosites *A6–A9* and trace of cross-section Fig. 10. The inner part of the syenite intrusion is made up of kalsilite syenite (Bea et al. 2013)

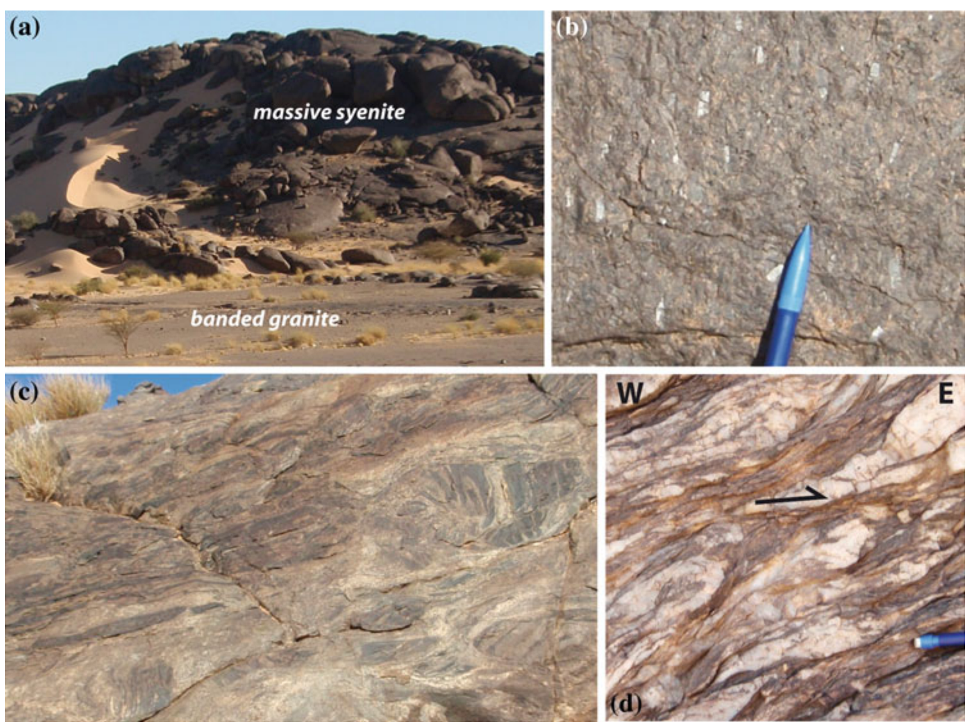

Fig. 8 **a** View of the rounded hills of nepheline syenite next to Awsard, **b** Magmatic lineation marked by feldspar preferred orientation on a *vertical* fracture of the syenite, **c** Dliyat N'sour migmatite with large basic blocks crosscut by granite veins, **d** Laglat mica-schists showing superimposed structures (notice the isoclinal fold on the *left*) with shear bands indicating top-to-the-east kinematics

Geosite A9 can be reached by a short drive (ca 2 km) to the NW on the road to Dakhla, then to the NNE over ca 2 km more on a gravel road, and finally, a short walk to the hill. The Dliyat En'Sour hill offers a beautiful panorama of the Reguibat Shield around Awsard (Fig. 9). The syenite intrusion and the basic dyke swarm are clearly seen amidst whitish, eroded granitic country rocks. Moreover, this site allows the visitors to observe the didactic unconformity between the 3 Ga-old basement and its Late Ordovician cover (Ashgill = Hirnantian, 445 Ma). The latter consists of pebbly

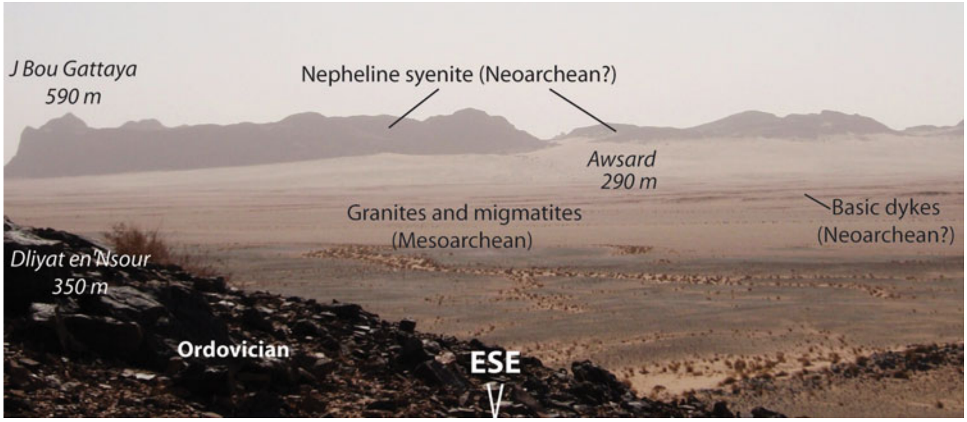

Fig. 9 Awsard panorama as seen from the Dliyat En'Sour Ordovician ridge

quartzites most likely deposited after the dramatic erosion linked to the northward progression of the Hirnantian inlandsis, which capped the Saharan regions at that time (Deynoux et al. 1985). Last, but not least, looking to the west provides a large overview of the frontal units of the Mauritanide thrust nappes, i.e., the Tisnigaten metaquartzites (Neoproterozoic?), the Laglat mica-schists (Archaean metasediments) and overlying Derraman orthogneisses (Archaean metagranites). It can be noted that Silurian pelites and Devonian limestones are mapped (Fig. 7) between the Ordovician quartzites and the nappes north and south of the Dakhla road transect. The cross-section below (Fig. 10) summarizes the structure of the front of the Variscan nappes, which is an unusual system of thin basement slivers thrust directly, or almost directly, on top of the Archaean crust.

Finally, *geosite A10* is located within the Laglat hill (Fig. 7) at short distance from the main road, close to a quiet "zaouia" (holy memorial) in the centre of a silent rocky cirque. The cliffs expose mica-schists most likely of Archaean age (Rjimati and Zemmouri 2002) that show superimposed penetrative structures (Fig. 8d). The youngest kinematic indicators point to a dominant top-to-the-east shearing linked to the post-Devonian (Variscan) emplacement of the Mauritanide nappes. The Variscan metamorphism that affects these nappes has been dated at 333 ± 25/325 ± 43 Ma (Early Carboniferous) in metagabbros from northern Mauritania close to the Moroccan border (Le Goff et al. 2001).

3.2 El Ouatia–Tan-Tan–Mseied Geotrail

This second geotrail is located about 700 km north of the Dakhla-Awsard transect (Fig. 2) and provides the opportunity to view new and contrasting themes: (i) in the western part of the geotrail, close to the El Ouatia sea-side resort, the outcrops show the Cretaceous-Miocene formations of the Atlantic Coastal basin (Tarfaya-Boujdour basin); and (ii) in the eastern part of the geotrail, i.e., from Tan-Tan to Mseied, the outcrops belong to the continental basement and expose the Late Precambrian-Early Carboniferous formations of the southernmost part of the Anti-Atlas belt.

3.2.1 Passive Margin and Atlantic Coastal Basin Around El Ouatia

Starting from El Ouatia to the southwest, a few tens of kilometres along the main road (N1), the first geosite (*geosite B1*) of the trail can be reached (Fig. 11). This geosite is located in the Oued Chebeika estuary, which widely exposes Upper Cretaceous formations typical of the Tarfaya Basin, otherwise concealed under the Moghrebian calcarenites and sands (Fig. 12). These Cenomanian-Turonian beds consist of

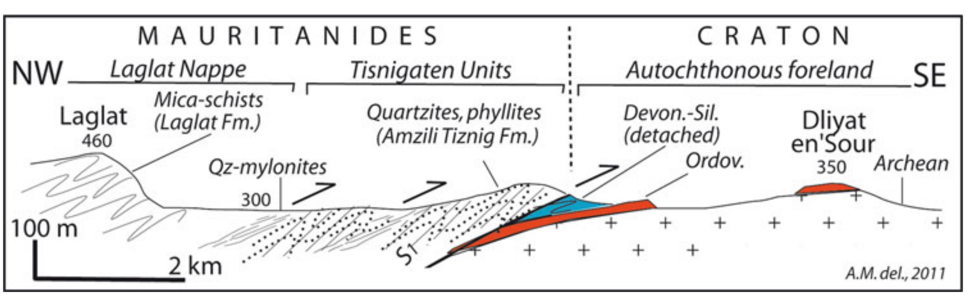

Fig. 10 Cross-section of the front of the Mauritanide nappes in the Awsard area, after Michard et al. (2010). See Fig. 6 for location

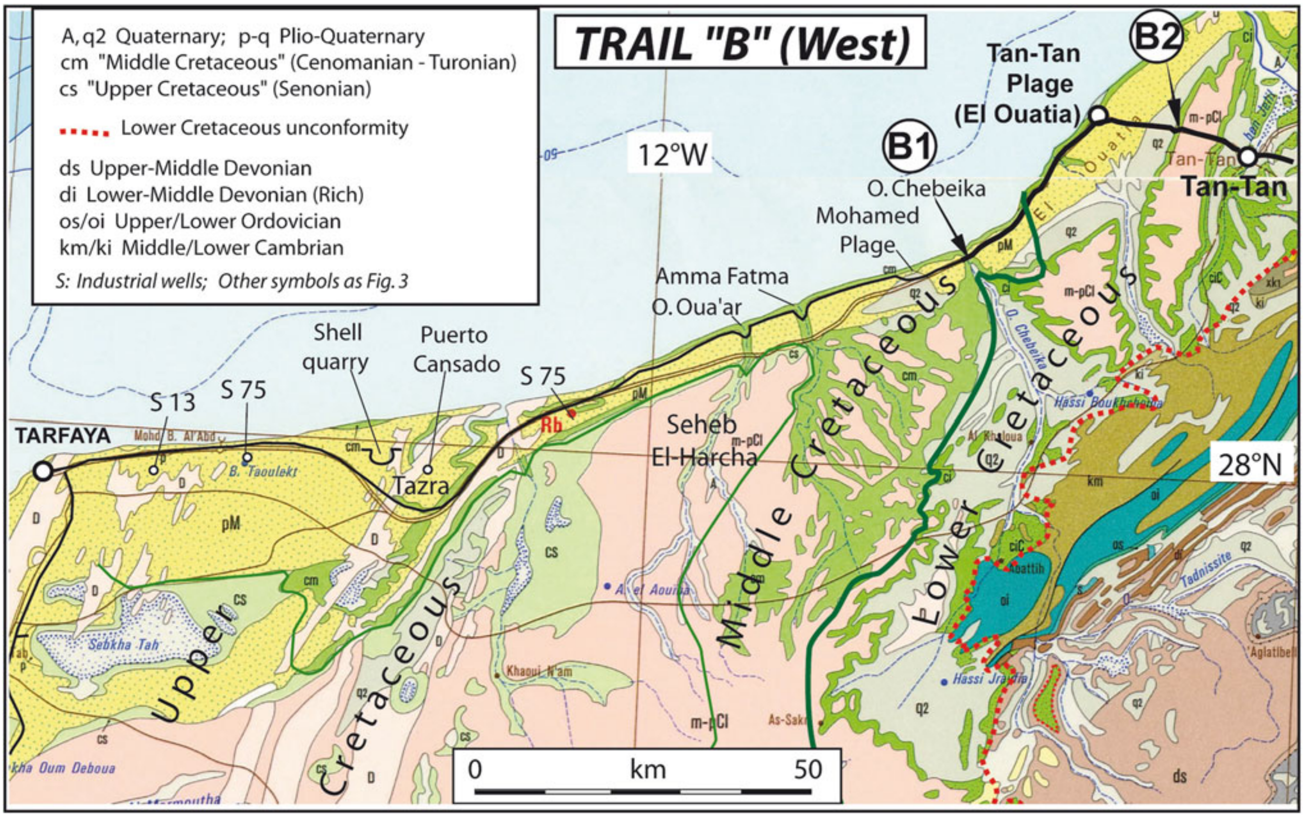

Fig. 11 Route and geosites location of the western part of geotrail "B", plotted on the Geological map of Morocco (Hollard et al. 1985)

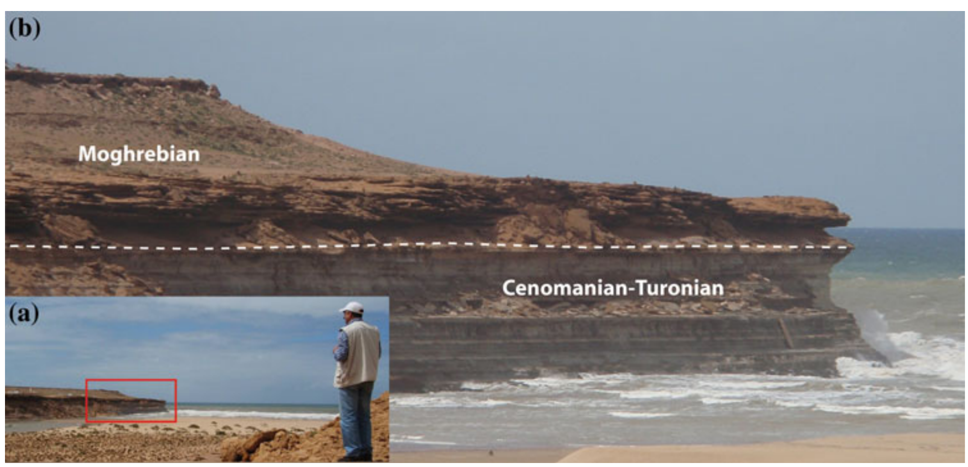

Fig. 12 **a** Oued Chebeika estuary, **b** zoom on the cliffs of the west border of the estuary

planktonic marls or chalks rich in organic matter (bituminous marls), alternating with limestones dominated by coccoliths, benthic foraminifers and pellets (El Albani et al. 1999; Lüning et al. 2004; Mort et al. 2008). They have been deposited in the external platform domain that became progressively deeper (Gebhardt et al. 2004) with dominant anoxic conditions of sedimentation (Keller et al. 2008). Their regular depositional rhythms have been ascribed to orbital forcing (Kuhnt et al. 1997), whereas their remarkable organic-matter richness (Kolonic et al. 2005) records upwelling phenomena along the Atlantic coast. These bituminous marls are potential petroleum source rocks (Sachse et al. 2010) and could be also exploited as "oil shales" (cf. the pilot quarry that was excavated west of Tazra; Rjimati et al. 2011b). The whole region has been intensely explored in the last decades for oil and gas. A 4 km deep industrial well was drilled at Tazra as early as the 1960s (Puerto Cansado well; Choubert et al. 1966), and many other wells have been drilled, both onshore and offshore (Hafid et al. 2008). Drillings have demonstrated the occurrence of Triassic and Jurassic

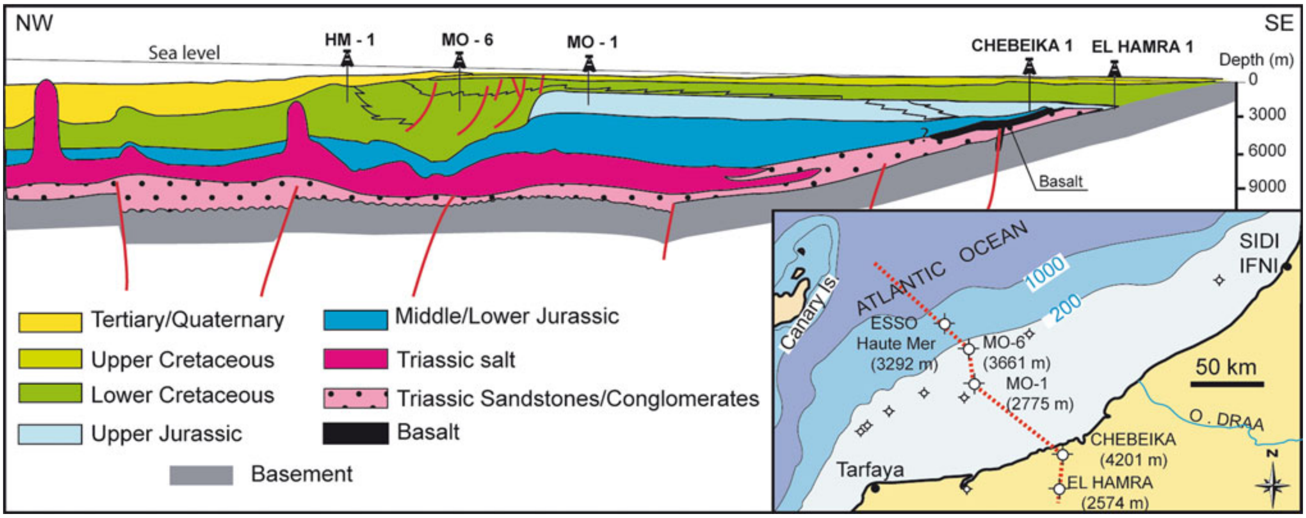

Fig. 13 Interpreted seismic profile with location of the onshore and offshore wells drilled in the northern part of the Tarfaya Basin (Hafid et al. 2008)

deposits at depth, which represent the oldest deposits of the Atlantic passive margin formed through the Pangaea rifting (250–195 Ma) and the subsequent opening of the Central Atlantic Ocean starting at 195–175 Ma. These early sediments are unconformably overlain by the Lower Cretaceous clastic deposits, relatively thick in the external platform (Tan-Tan delta, shown at *geosite B2*). These major geological events and concepts will be explained on the geosite panel based on a seismic profile (Fig. 13).

The *geosite B2* is situated half-way between El Ouatia (Tan-Tan beach) and Tan-Tan city. It exposes coarse, pink continental sands that illustrate a palaeo-delta environment developed during the Early Cretaceous (Fig. 14). The continental sands are red bed formations that encroached onto the Sahara, the Anti-Atlas, the Atlas and the Meseta domains at that time, and began to accumulate as early as the Middle Jurassic in the Central High Atlas (Frizon de Lamotte et al. 2008, with references therein). This sedimentation occurred after a long interval of erosion of the Sahara and Anti-Atlas domains, in such a way that the red beds unconformably overlie the deepest parts of the folded Palaeozoic units and, in places, Precambrian rocks (e.g., Ifni inlier, Fig. 2). The overlying Upper Cretaceous-Tertiary deposits represent a new sedimentary cycle, well developed in the Atlantic Coastal basins (Figs. 12 and 13) but much thinner inland. Let us recall (see above, *geosite A4*) that the Eocene formations from the internal platform contain the phosphate layers exploited at Boukraa, southeast of Laayoune, which are the local equivalent of the renowned phosphate deposits of the Meseta domain (Khouribga plateau).

3.2.2 The Variscan Basement from Tan-Tan to Mseied

This part of the geotrail, about 60 km-long, passes through a folded and mountainous area which is the south-western part of the Anti-Atlas Palaeozoic fold belt (Fig. 15). Although narrow with respect to the Anti-Atlas transects farther in the northeast (e.g., Kerdous-Assa transect, Fig. 2), the present transect is much wider than the narrow strip of Palaeozoic formations observed at Awsard (Fig. 10). The Laayoune-Smara transect, half-way between the Awsard and Tan-Tan transects, offers an interesting cross-section of the fold-thrust structures of the Dhlou Arc (Rjimati et al. 2011a).

Geosite B3, located by the secondary road east of Tan-Tan allows the visitors to observe the border of the

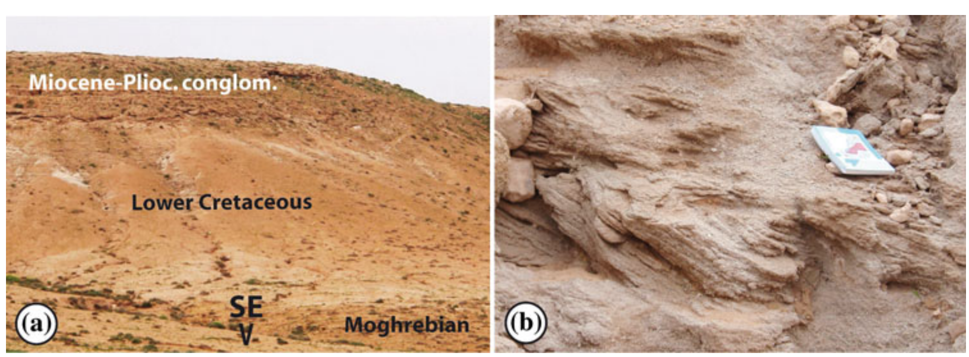

Fig. 14 **a** Lower Cretaceous fluvial sandstones (“Tan-Tan sands”) beneath the Hamada Plateau west of Tan-Tan, **b** Detail of cross-bedding in the fluvial sandstones

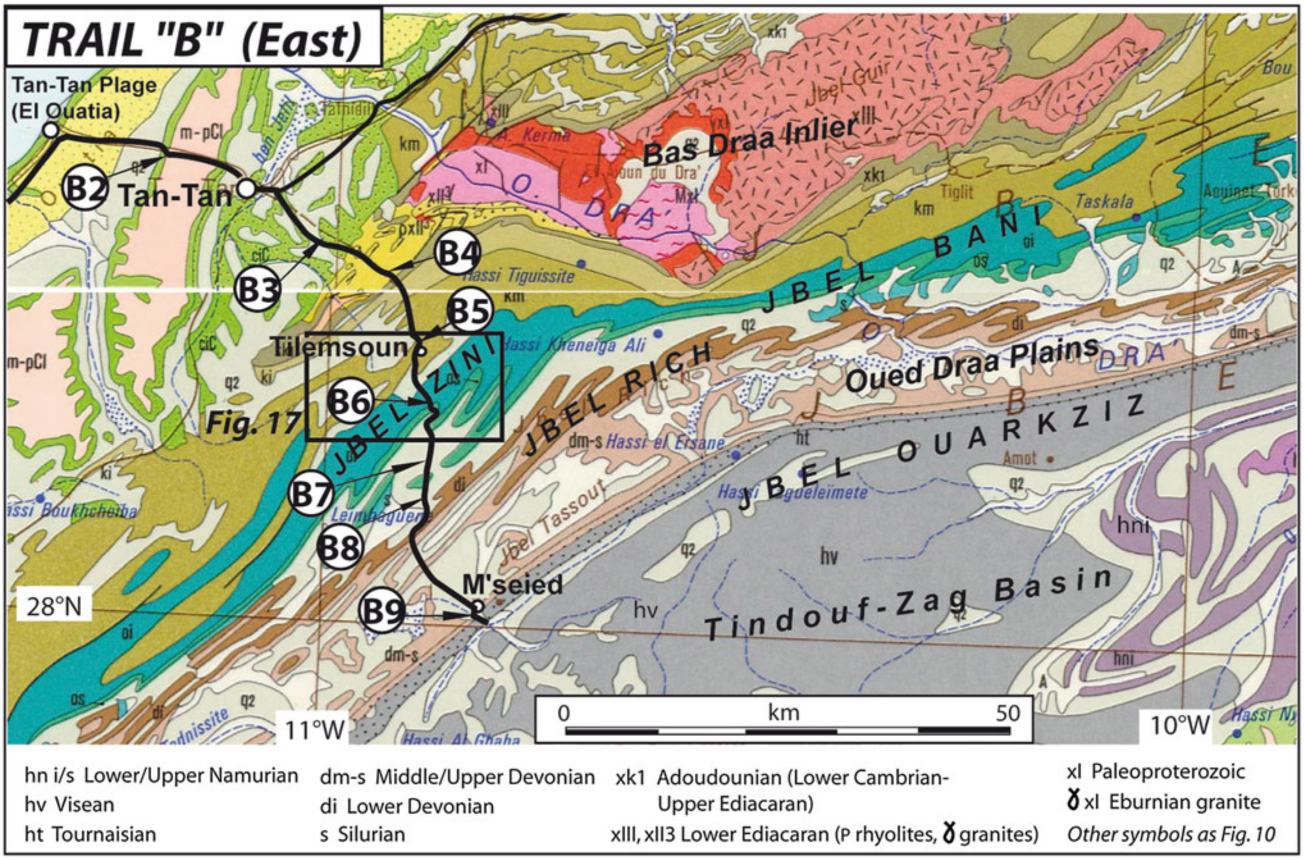

Fig. 15 Route and geosites location of the eastern part of geotrail "B", plotted on the Geological map of Morocco (Hollard et al. 1985)

Tarfaya Basin, the Precambrian crests of the Bas Draa Massif and the Palaeozoic ridges in the background (Fig. 16a).

Geosite B4 is situated within a short distance (1 km) of geosite B3 in a shallow valley incised in the southwestern Bas Draa Massif. The outcrops expose Upper Neoproterozoic (Ediacaran, shown as "PIII" on the geological maps) volcano-clastic conglomerates (Fig. 16b), which, throughout the Anti-Atlas, characterize the earliest post-Pan-African orogenic formations deposited between 570 and 550 Ma (Gasquet et al. 2008). In these outcrops, the Ediacaran conglomerates are obviously affected by low-grade metamorphism and ductile deformation, which has resulted in two superimposed foliations whose relative obliquity points to a top-to-the-SE shear, consistent with the bulk orientation of the folds around the massif. The Variscan deformation affected the Precambrian basement itself, which illustrates the "thick-skinned" tectonic style of the Anti-Atlas (Burkhard et al. 2006). The low ridge bounding the valley to the southeast corresponds to the Lower Cambrian clastics and carbonates, which mark the very base of the marine Palaeozoic series on top of the Bas Draa Precambrian basement. At some distance (ca 25 km) in the east, these Lower Cambrian formations host the Azougar n'Tilili polymetallic and gold mine prospect (El Hasnaoui et al. 2011).

Geosite B5 is located ca 10 km farther in the south of geosite B4 where the entrance to the Tilemsoun village is marked by vertical, faulted quartzite beds (Fig. 16c). These massive quartzite beds belong to the upper part of the Middle Cambrian "Schistes à Paradoxides" ("km" in Fig. 15, "km1a" in Fig. 17); they are labelled "Barre quartzitique de Goulimine" ("km1b"). Their geomorphologic role is very important and compares with that of the Tabanit Sandstones of the uppermost Middle Cambrian ("km2").

Once past the Cambrian quartzite landmark, the road to Mseied crosses younger and younger clastic (Tabanit Sandstones) and shaly (Fezouata shales) deposits up to a pass across the Jbel Zini Quartzites of Lower Ordovician age. *Geosite B6* offers outcrops along the road cuts, and a panoramic view toward the south (Fig. 18a) in the direction of the end of the trail (Jbel Ouarkziz). A few ten metres after the pass, the outcrops expose coarse, conglomeratic quartzites, which belong to the Upper Ordovician. These pebbly quartzites are equivalent to those described above at Awsard (*geosite A9*), both being related to the Hirnantian glacial event that affected the whole Saharan domain. In both cases,

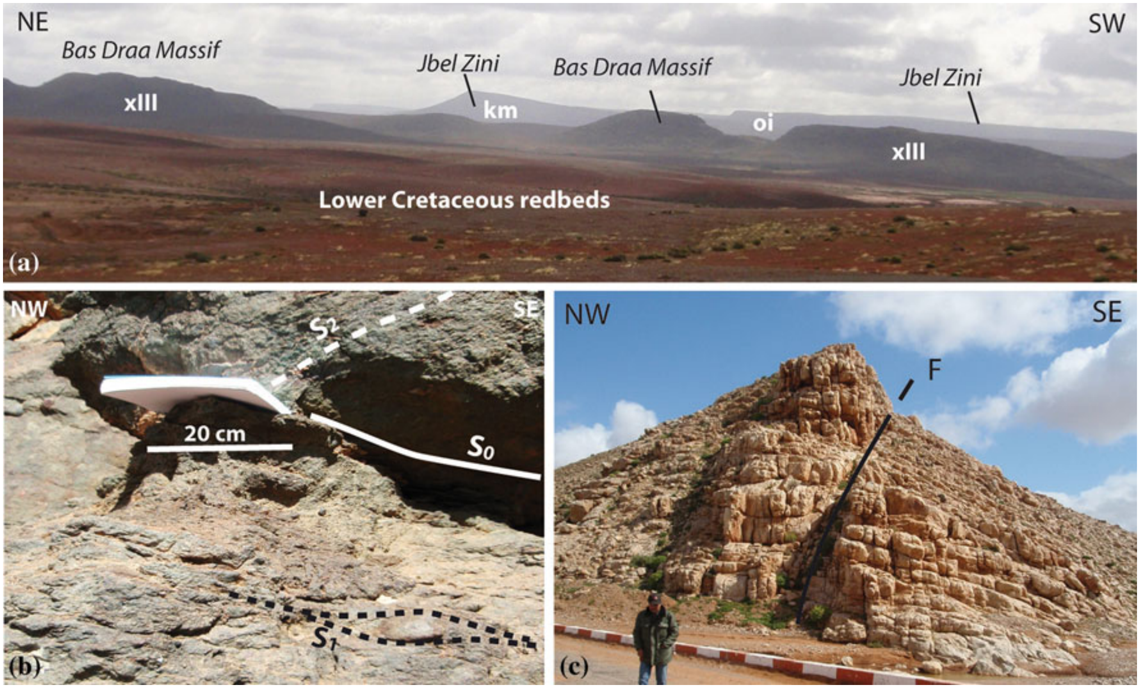

Fig. 16 **a** Transgression of the Lower Cretaceous redbeds on the Bas Draa Precambrian Massif (Geosite *C1*), **b** Upper Precambrian (Ediacaran) metaconglomerates at the south-western tip of the Bas Draa inlier, showing a Variscan foliation S_2 superimposed onto the Pan-African fabric S_0–S_1, **c** Vertical Cambrian quartzites ("Barre de Goulimine") with shallow dipping joints crosscut by a directional fault (*F*), west of Tilemsoun village

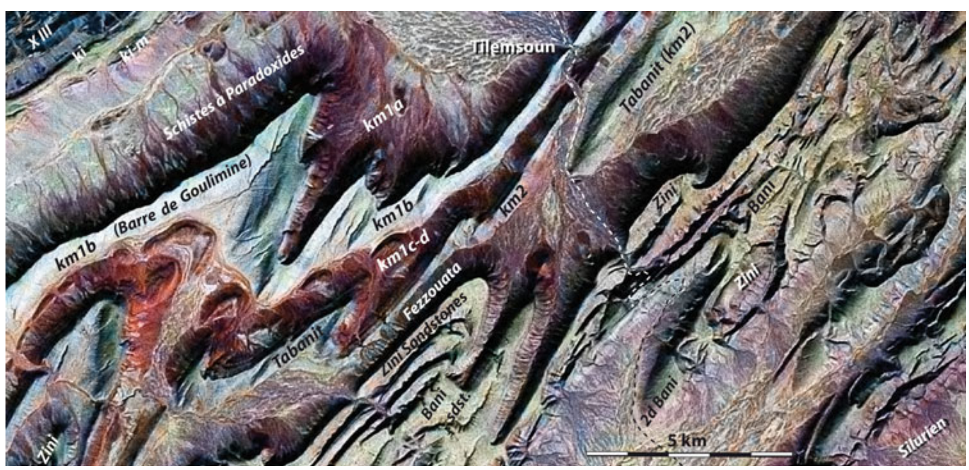

Fig. 17 NE-trending, SW-plunging fold train in the J. Zini Cambrian-Ordovician massif south of the Bas Draa massif (Landsat scene). The folds are marked by the competent quartzite beds interbedded with incompetent metapelites. *Dashed* road to Mseied. See Fig. 15 for location

a hiatus occurs beneath the periglacial deposits. Here in the Jbel Zini, several hundred metres of Middle Ordovician shales and sandstones are lacking beneath the Upper Ordovician disconformable deposits.

Leaving the pass area, the road goes down into lowlands underlain by the Silurian and Lower Devonian silts and clays. The sebkha Liemhagen that extends in these lowlands is a favorite stop-over for many species of migratory birds, especially the pink flamingo. The best stratigraphic cross-section of the Ordovician sequence of the Jbel Zini area is exposed within a breached anticline along the western border of the sebkha (Fig. 18b). Although seen from the distance at geosite B7, this succession clearly shows in a dark rusty color the Lower Ordovician (Llanvirn) oolithic iron bed (Fig. 18c) that occurs extensively in the Anti-Atlas domain, and is locally exploited (Imi n'Tourza, north of Alnif in the Eastern Anti-Atlas; Raddi et al. 2011). The geometry of the large, almost cylindrical anticlines formed by the competent Ordovician quartzites intercalated between the incompetent Cambrian and Silurian shales is shown strikingly in the desert landscape. This is a fine example of Appalachian-type relief derived from the Variscan fold belt, first eroded and

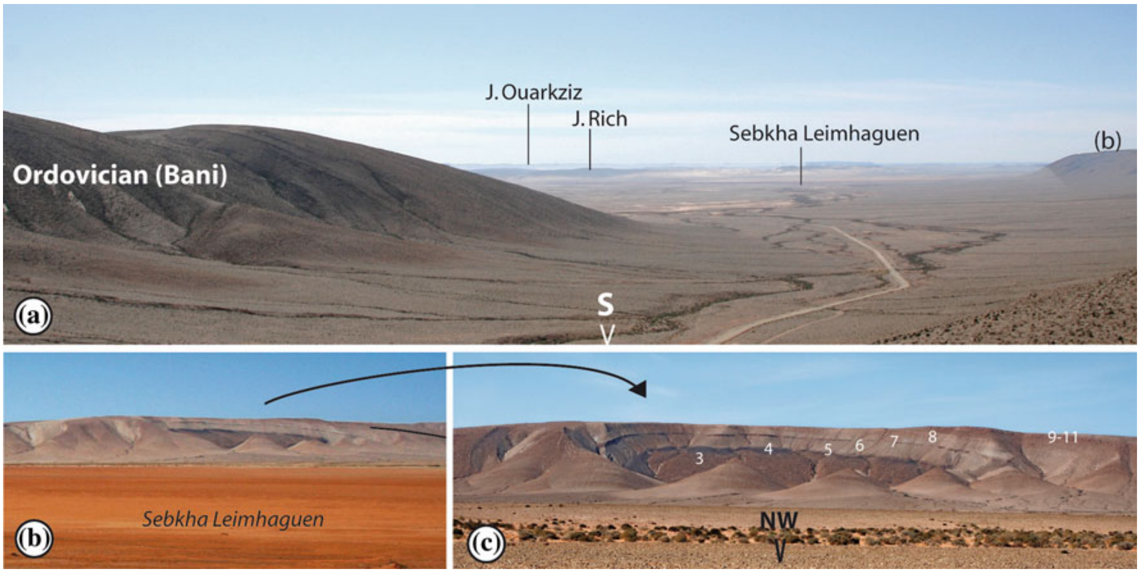

Fig. 18 **a** View from the Zini Pass looking southward to the broadly cylindrical folds of Ordovician quartzites plunging under the Silurian black shales of Sebkha Leimhagen, **b** View of the breached fold east of the sebkha (for location, see Fig. 19a), **c** Detail of the eroded hinge of fold (**b**). Numbers correspond to stratigraphic levels as follows (Destombes 2006): *1* Zini Fm (Middle Arenig), *grey* quartzite; *2–8* Tachilla Fm (Llanvirn) with *2* coarse *Lingula* sandstones; *3* oolithic iron and clay layers; *4* sandy clay; *5 green* sandstone; *6* sandy clays with worm tracks; *7* bedded sandstones; *8* micaceous sandstones with worm tracks, followed upward by micaceous clay; *9–11* Premier Bani Group (Llandeilo), with *9* metre-*thick* sandstone beds intercalated with *thin*-bedded sandstone; *10* fine-grained *thin* bedded sandstones with one *Asaphidaea* cephalon (*Ogygiocaris* ? sp.); *11* massive *greyish green* quartzite with *Vexillium*

converted into a low peneplain, then recently uplifted and subjected to differential erosion.

The eastern border of the Liemhagen lowland corridor consists of a remarkable system of open folds, labelled the Jbel Rich (Fig. 19a). Their axes are parallel to those of the Jbel Zini folds, but the folded beds now belong to the Lower-Middle Devonian System. Geosite B8 illustrates folded structure and stratigraphy, which is typified by the repetition of limestone-clay-sandstone lithologies (“Rich”) that corresponds to superimposed transgression-regression cycles at the northern border of the West African Craton (Lubeseder et al. 2009). An educational panel should be emplaced at geosite B8 at the southwest extremity of a typical perched syncline formed by Rich 1 and Rich 2 at the northwest border of the Jbel Rich fold train (Fig. 19b). The Rich succession has economic potential as it includes *Orthoceras*- and Goniatite-rich limestones similar to those exploited for the marble industry in the Tafilalt region (Eastern Anti-Atlas; Saddiqi et al. 2011).

Once across the Rich folds, the road to Mseied goes straight across a wide plain with poor, shaly outcrops. This corridor is underlain by the Middle-Upper Devonian silts and shales,

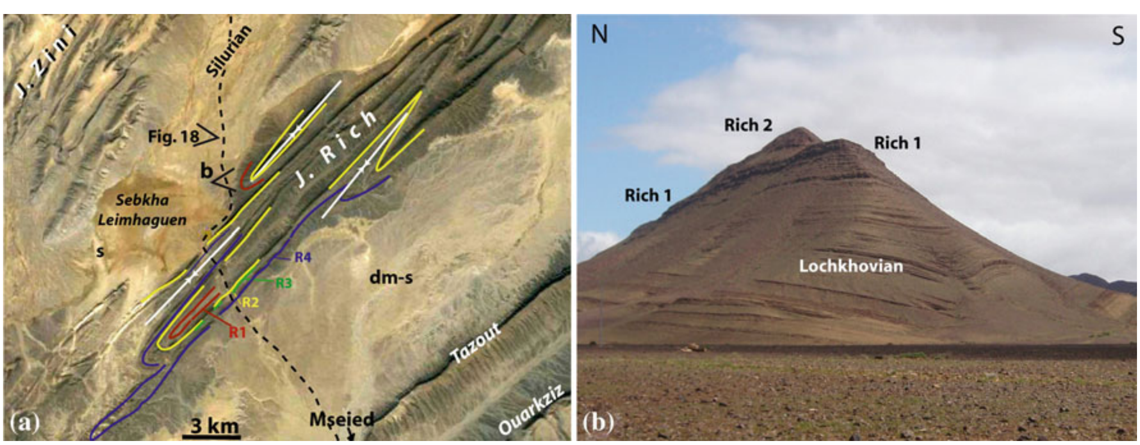

Fig. 19 **a** Interpretation of the Google Earth image of the Jbel Rich folds west of Mseied. The successive Rich formations are numbered *R1–R4*. *Double white arrows* synclinal axes. **b** South-western tip of the isolated perched syncline west of the J. Rich folds train

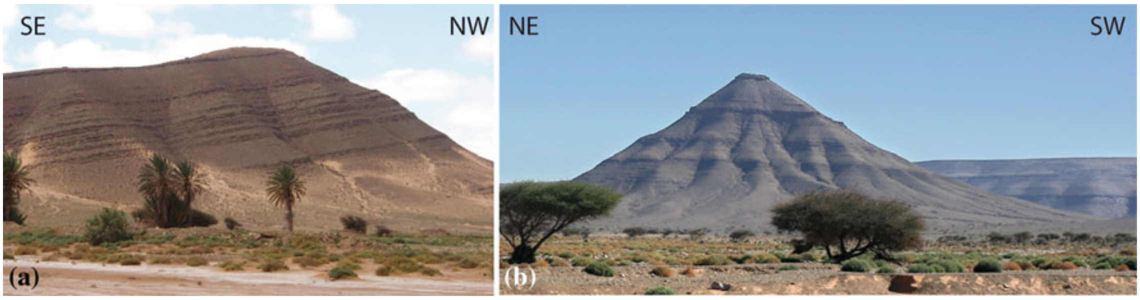

Fig. 20 **a** Jbel Tazout cuesta (Tournaisian) as seen from Mseied, **b** Jbel Ouarziz cuesta (Visean) south of Mseied

whose apparent thickness is increased by NE-trending folds (Rjimati et al. 2011a). These folds are the south-easternmost record of the Variscan deformation. Just in front of Mseied village (*geosite B9*), the Tournaisian (lowermost Carboniferous) sandstones and limestones form a monocline (Jbel Tazout cuesta) dipping weakly southeastward (Fig. 20a). This marks the entrance into the cratonic and undeformed part of the Tindouf-Zag Basin sensu lato, the deformed part of which corresponds to the Anti-Atlas domain. A few hundred metres farther in the southeast, the Visean (upper Lower Carboniferous) horizontal limestones of the Jbel Ouarkziz (Fig. 20b) characterize the cratonic domain. Farther in the east but not seen from here, the Tindouf-Zag Basin also contains Late Carboniferous deposits (Fig. 15), composed of continental clastic sediments that correspond to the erosion of the recently uplifted Variscan belt (Cavaroc et al. 1976).

4 Discussion and Conclusions

Two potential geotrails have been described above, which altogether involve 19 geosites offering scenic landscapes and/or excellent outcrops (Table 1). The Dakhla–Awsard trail "A" traverses the southernmost part of the Moroccan Southern Provinces, whereas the El Ouatia–Tan-Tan–Mseied trail "B" traverses their northern border.

Considering the international significance of the trails, we may emphasize that they involve three major geotectonic structures, namely the West African Craton (WAC), the Variscan Belt and the Atlantic continental margin. The WAC is one of the largest cratons of Africa and extends southward up to the Ivory Coast. The Variscan Belt and the superimposed Atlantic margin extend in several West African and European countries, and have their counterpart in the eastern countries of America.

From a pedagogical point of view, several major geological concepts can be introduced into the educational panel at the proposed varied geosites along the trails, as follows:

- The concept of *continental craton*: this is encountered first at Awsard, where the WAC is represented by the Reguibat *Shield*, made up of Archaean rocks (ca 3 Ga) and overlain by a thin Palaeozoic cover (Fig. 21, profile A). Again, the WAC is encountered farther in the north at Mseied (Fig. 21, profile B, East) with a younger continental basement (Eburnian, ca 2 Ga) and a much thicker Palaeozoic cover (Tindouf-Zag cratonic basin).
- The less popular concept of *metacraton*: this is illustrated in the Bas Draa massif (Fig. 21, profile B East), at the northern rim of the WAC (Eburnian basement) modified by the Pan-African orogenic cycle (extension, collision, post-orogenic magmatism and volcano-clastic accumulation). The same metacratonic border of the WAC was deformed again during the Variscan orogeny, first during the Cambrian extension and then during the Carboniferous collision.
- The concepts of *orogeny* and *orogenic cycle*: these are well illustrated along two transects of the Variscan Belt (Fig. 21, profiles A and B East). The Cambrian rifting and Ordovician-Devonian subsidence of the continental crust clearly appears in the Bas Draa transect. Evidence of collision tectonics is conspicuous in both the southern and northern transects (Mauritanide nappes west of Awsard, thick-skinned shortening of the Bas Draa area with inversion of the palaeomargin normal faults and folding of the thick overlying sediments).
- *Plate tectonics*: this is inevitably called upon to explain the Variscan collision (closure of the Rheic paleo-ocean between Laurussia and Gondwana) and correlative Pangaea building, whereas the outcrops and well data presented next to El Ouatia illustrate the Pangaea breakup process, which formed the Triassic rift basin and the Jurassic passive margin.
- In the stratigraphic domain, the concept of major *unconformity*: this is illustrated twice, firstly by the Upper Ordovician transgression onto the Archaean basement, due to the Hirnantian glaciation, and secondly by the Lower Cretaceous red bed deposits on the deeply eroded continental domain and adjacent passive margin (Fig. 21).
- *Varied petrographic facies*: these are encountered from one geosite to the other, ranging from fossiliferous calcarenites or limestones to low-grade metagreywackes, to high temperature migmatites.

Table 1 Location and main themes of the selected geosites of trails "A" and "B" across the Southern Provinces of Morocco

Geosite	GPS coordinates (N × W a° b′ c″)	Distance to paved road	Structural domain	Main themes illustrated
A1	23 45 20 × 15 55 30	30 m	Atlantic margin basin	Sedimentation. Continental uplift
				Coastal erosion
A2	23 53 97 × 15 42 67	400 m	Atlantic margin basin	Hydrological resources. Artesian well
				Stratigraphy
A3	23 28 42 × 15 57 10	300 m	Atlantic margin basin	Sedimentology. Marine fossils. Phosphate genesis
A4	23 35 27 × 15 41 53	50 m	Atlantic margin basin	Continental fossils and sedimentation. Paleogeography
A5	23 19 36 × 15 13 58	300 m	Atlantic margin basin	Continental sedimentation. Unconformity. Neolithic engraving
A6	23 11 87 × 15 04 78	100 m	Adrar Souttouf nappes	Metamorphism (metagabbros). Structural geology
A7	22 33 01 × 14 19 02	20–150 m	Reguibat Shield (WAC)	Metamorphism (orthogneiss). Magmatism (dyke and pluton intrusions). Archean geology
A8	22 35 52 × 14 24 09	100 m	Reguibat Shield (WAC)	Metamorphism (migmatites). Deep petrogenesis. Structural geology
A9	22 37 38 × 14 24 29	3.5 km	WAC Palaeozoic cover	Upper Ordovician glaciation. Unconformity. Archean geology
A10	22 36 44 × 14 28 57	5.5 km	Adrar Souttouf nappes	Structural geology. Nappe kinematics. Metamorphism (metapelites)
B1	28 17 44 × 11 31 30	50–500 m	Atlantic margin basin	Sedimentology (bituminous marls). Economic geology (oil and gas). Estuarine morphology
B2	28 28 45 × 11 12 15	20 m	Atlantic margin basin	Continental sedimentation. Geomorphology (marine terraces). Paleogeography
B3	28 23 24 × 11 01 01	20 m	Anti-Atlas fold belt	Lecture of a landscape. Unconformity. Paleogeography and morphology
B4	28 20 46 × 10 56 03	100 m	Anti-Atlas fold belt	Structural geology (basement-cover relationships; tectonic cleavage)
B5	28 16 40 × 10 54 07	50 m	Anti-Atlas fold belt	Stratigraphy (Cambrian quartzites). Structural geology (joint systems)
B6	28 13 22 × 13 53 12	100 m	Anti-Atlas fold belt	Stratigraphy (Ordovician periglacial deposit). Appalachian morphology
B7	28 03 33 × 10 53 19	10 m	Anti-Atlas fold belt	Structural geology (cylindrical anticline). Economic resources (oolithic iron). Sebkha
B8	28 06 47 × 10 52 54	10 m	Anti-Atlas fold belt	Stratigraphy and structure (perched syncline). Sedimentology (subsidence, basin infilling)
B9	28 00 58 × 10 49 01	200 m	Tindouf-Zag basin	Regional structure (cratonic basin versus fold belt)

- Finally, several *mining prospects* can be cited along the trails: these include the Fe-U-REE-bearing carbonatites of the Adrar Souttouf massif, the Cu-Au veins of the Bas Draa region, the oil and gas plays of the Tarfaya basin and the Boukrâa phosphorites. The hydrogeology of the deep water resources is also presented in the Dakhla area.

To conclude, the Southern Provinces geotrails offer outstanding pedagogic potentialities to the public. Let us also emphasize that there are some poorly-known regions and problems of geology that would be of interest to geologists; these include: (i) dating of the varied dykes that crosscut the Archaean gneisses; (ii) dating of the protoliths of the Mauritanide nappes; (iii) dating the carbonatites that intrude the latter nappes; (iv) the interpretation of the deep contrast between the Awsard and Bas Draa transects of the Variscan belt; this has been provisionally correlated with the northward thickening of the Palaeozoic series by Michard et al. (2010); (v) the understanding and calibration of the Lower Cretaceous unconformity that implies a large, regional epirogeny, which has been tentatively ascribed to Late Jurassic asthenosphere uplift (Frizon de Lamotte et al. 2009), and finally, (vi) the dating and calibration of the Mesozoic to Recent exhumation and uplift of the continental basement east of the Atlantic margin based on low-temperature thermochronology, which would permit useful comparison with the Anti-Atlas exhumation (Ruiz et al. 2011; Oukassou et al. 2013), as well as the discussion of the hypothetical role of the recent asthenosphere uplift evidenced further in the north (Missenard et al. 2006).

However, the development of the proposed geotrails faces several political and pedagogical challenges. Firstly, it is necessary to make the regional Authorities sensitive to the

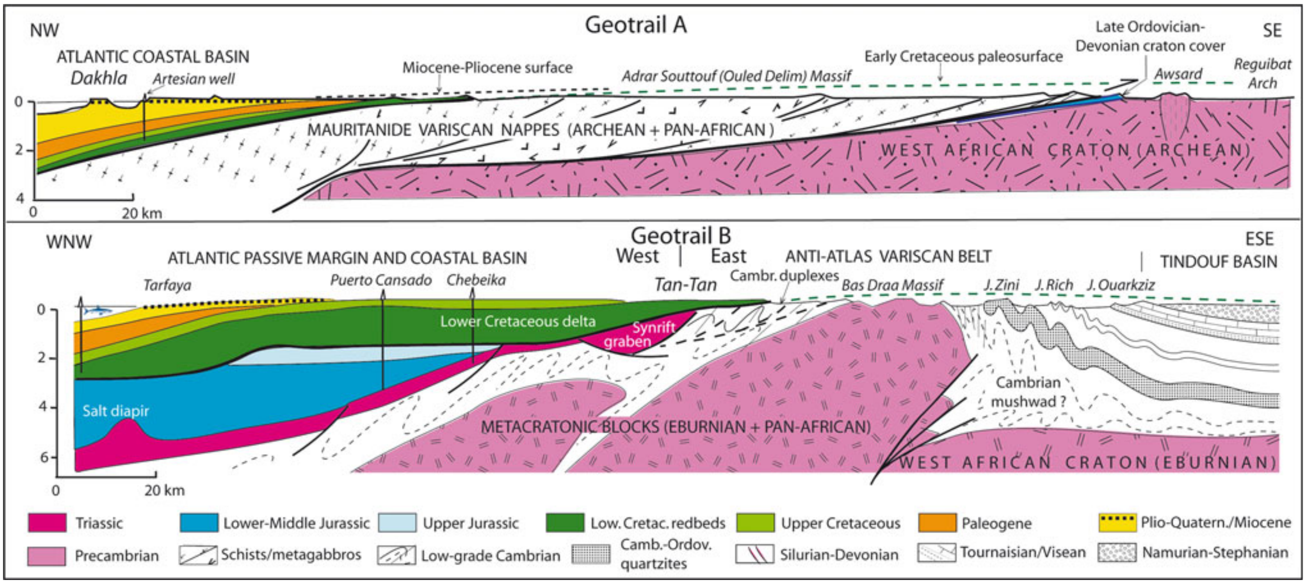

Fig. 21 Schematic cross-sections along the geoheritage trails "A" (*above*) and "B" (*below*) presented in this work. See text for comments

interest of the project, and to facilitate positive decisions by finding official support and potential sponsors for the practical lay-out of the geosites (signage, parking adjustment, explanatory panels, etc.). Support may be obtained from the Ministry of Energy and Mines, Water and Environment, and potentially, from the National Office of Hydrocarbons and Mines (ONHYM), the Ministry of Education, and the Ministry of Tourism. Sponsorship should be sought from the major mining and petroleum companies. Furthermore, geoscientists committed in the project would need to carefully adjust their explanations in order to make accessible the interest of the geosites to a larger public. Indeed, this pedagogical challenge should be addressed as early as possible in the first contacts with the regional Authorities.

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The Geoheritage of the Doukkala-Abda Region (Morocco): An Opportunity for Local Socio-Economic Sustainable Development

Le géopatrimoine de la région Doukkala-Abda (Maroc): une opportunité pour un développement socio-économique local durable

جيوتراث منطقة دكالة-عبدة (المغرب) فرصة لتنمية اجتماعية واقتصادية محلية مستدامة

A. Enniouar, E. Errami, A. Lagnaoui, and O. Bouaala

Abstract

The Doukkala-Abda region has a rich natural heritage, making it an important attraction for national and international tourists. However, its geoheritage remains little known to the general public, despite the numerous multidisciplinary scientific studies that have been carried out. A preliminary inventory has identified 36 geosites, reflecting the geomorphological, geological and environmental history of the region. The scientific, technical and ecological aspects of 14 of these geosites are described in this paper. They are: the Precambrian rhyolites, the Sidi Saïd Mâachou basin with its numerous geosites, consolidated and unconsolidated dunes, Jbel Irhoud, the escarpments of Jorf Lasfar, Sidi Bouzid and Lalla Fatna, Sidi Moussa-Oualidia lagoon complexes, Zima Lake and El Goraan, El Khenzira and the Oualidia caves. The rich bio- and geodiversity of these sites has an important geotouristic potential. An objective evaluation of these sites is needed. This will allow the development of geotourism and ecotourism as new component of cultural tourism. A network of geotrails linking coastal geosites to sites in the hinterland would help promote socio-economic activities and create jobs which will increase the income of the local population whose economy is mainly based on agriculture and cattle breeding.

Résumé

La région des Doukkala-Abda possède un patrimoine naturel riche, qui en fait une attraction importante des touristes nationaux et internationaux, bien que son géopatrimoine reste inconnu pour le grand public. Cela malgré les nombreux travaux scientifiques pluridisciplinaires menés sur le territoire. Un inventaire préliminaire a permis d'identifier trente-six géosites reflétant l'histoire géomorphologique, géologique et environnementale de la région. Dans le présent article, nous avons décrit les aspects scientifiques, techniques et écologiques de quatorze géosites seulement. Ces sites sont: les rhyolites du Précambrien, le bassin de Sidi Saïd Maachou avec ses nombreux géosites, les dunes consolidées et non consolidées, Jbel Irhoud, les falaises de Jorf Lasfar, de Sidi Bouzid et de Lalla Fatna, le complexe lagunaire de Sidi

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Moussa-Oualidia, le Lac Zima, les grottes d'El Goraan, d'El khenzira et de Oualidia. La grande bio-géodiversité de ces géosites leur confère un important potentiel géotouristique. Pour promouvoir ce géopatrimoine et en faire un pilier pour un développement socio-économique local durable, une valorisation rationnelle s'avère nécessaire. Celle ci pourrait se faire par l'intermédiaire du développement de l'écotourisme et du géotourisme comme nouvelle composante du tourisme culturel dans la région. Ainsi, la création et le développement de géocircuits reliant la zone côtière à l'arrière-pays pourrait promouvoir les activités socio-économiques et la création de l'emploi qui participeront à augmenter les revenus des populations locales dont l'économie est basée principalement sur l'agriculture et l'élevage.

ملخص

توفر منطقة دكالة-عبدة على تراث طبيعي غني ، يجعل منها عَامِلَ جذب مهم للسياح المحليين والدوليين، على الرغم من أن جيوتراثها مازال مجهولا عند عامة الناس. وهذا برغم الأبحاث العلمية المتنوعة والمتعددة التخصصات التي أجريت على المنطقة.الجر د الأولي مَكَّنَ من تحديد ستا وثلاثين جيومواقعا يعكس التاريخ الجيومورفلوجي والجيولوجي والبيئي للمنطقة. في هذا المقال قمنا بوصف الجوانب العلمية والتقنية والبيئية لأربعة عشر جيو موقعا فقط. وهذه المواقع هي الحمم البركانية للزمن ما قبل الكمبري، حوض سيدي سعيد معاشو بمواقعه العديدة، الكثبان المتماسكة وغير المتماسكة، جبل إيغود،الجرف الأصفر، جرف سيدي بوزيد و جرف لالة فاطنة، مجمّع بحيرة سيدي موسى-الوليدية، بحيرة زيما، كهوف الكوران والخنزيرة والوليدية. إن التنوع البيولوجي والجيولوجي والجيومورفلوجي الكبير لهذه الموقع يعطيها إمكانات جيوسياحية هامة. لتطوير تراثها الجيولوجي وجعله ركيزة للتنمية الاجتماعية والاقتصادية المحلية المستدامة، فإن التقييم الموضوعي يعد أمرا ضروريا. هذا الأخير يمكن القيام به عبر تنمية السياحة البيئية والجيو سياحة كَمُكَونٍ جديد من للسياحة الثقافية بالمنطقة. إن خلق وتطوير شبكة طرق جيوسياحية تربط المناطق الساحلية بالمناطق النائية، من شأنها تعزيز الأنشطة السوسيو-اقتصادية وخلق فرص شغل بالمنطقة. مما سوف يزيد من دخل الساكنة المحلية التي يعتمد اقتصادها أساسا على الزراعة وتربية المواشي.

Keywords

Doukkala-Abda region • Morocco • Geoheritage • Inventory • Geotourism • Local socio-economic sustainable development

Mots-clés

Région de Doukkala-Abda • Maroc • Géopatrimoine • Inventaire • Géotourisme • Développement socio-économique durable

الكلمات الرئيسية

منطقة دكالة-عبدة • المغرب • الجيوتراث • الجرد • الجيوسياحة • التنمية الاجتماعية والاقتصادية المحلية المستدامة

1 Introduction

Doukkala-Abda region, study area, is located in the north-western part of central Morocco, bordering the Atlantic coast at the crossroads between three of Morocco's main tourist destinations—Casablanca, Marrakech, and Agadir. It covers an area of approximately 14,285 km^2 and incorporates four provinces, El Jadida, Sidi Bennour, Safi and Youssoufia (Fig. 1). The population of the region is 4,284,039 inhabitants. Geographically, the region consists of two main zones: the coastal zone and the hinterland. The latter, which corresponds to the Doukkala-Abda plain, is characterized by three geomorphological features: (1) base of slope colluvial deposits, described by Gigout (1951) as loose and unconsolidated sediments deposited at the base of hill-slopes by either rainwash, sheetwash, slow continuous downslope creep, or a combination of these processes; (2) present day and fossil valleys, principally two main river systems, Oued Oum Er-Rbia and Oued Tensift, and several smaller and secondary rivers; and (3) the Plio-Quaternary dunes complex, with regular dune morphology separated by inter-dune depressions, the dune ridges extending over large distances with a SSW trend (Aboumaria 1993).

The coastal area consists of four geomorphological elements: (1) the beaches, which are quite commonly rocky, especially in the south-western part of the region, and sandy in the north-eastern part; (2) the Plio-Quaternary consolidated dunes complex, which is aligned sub-parallel to the present

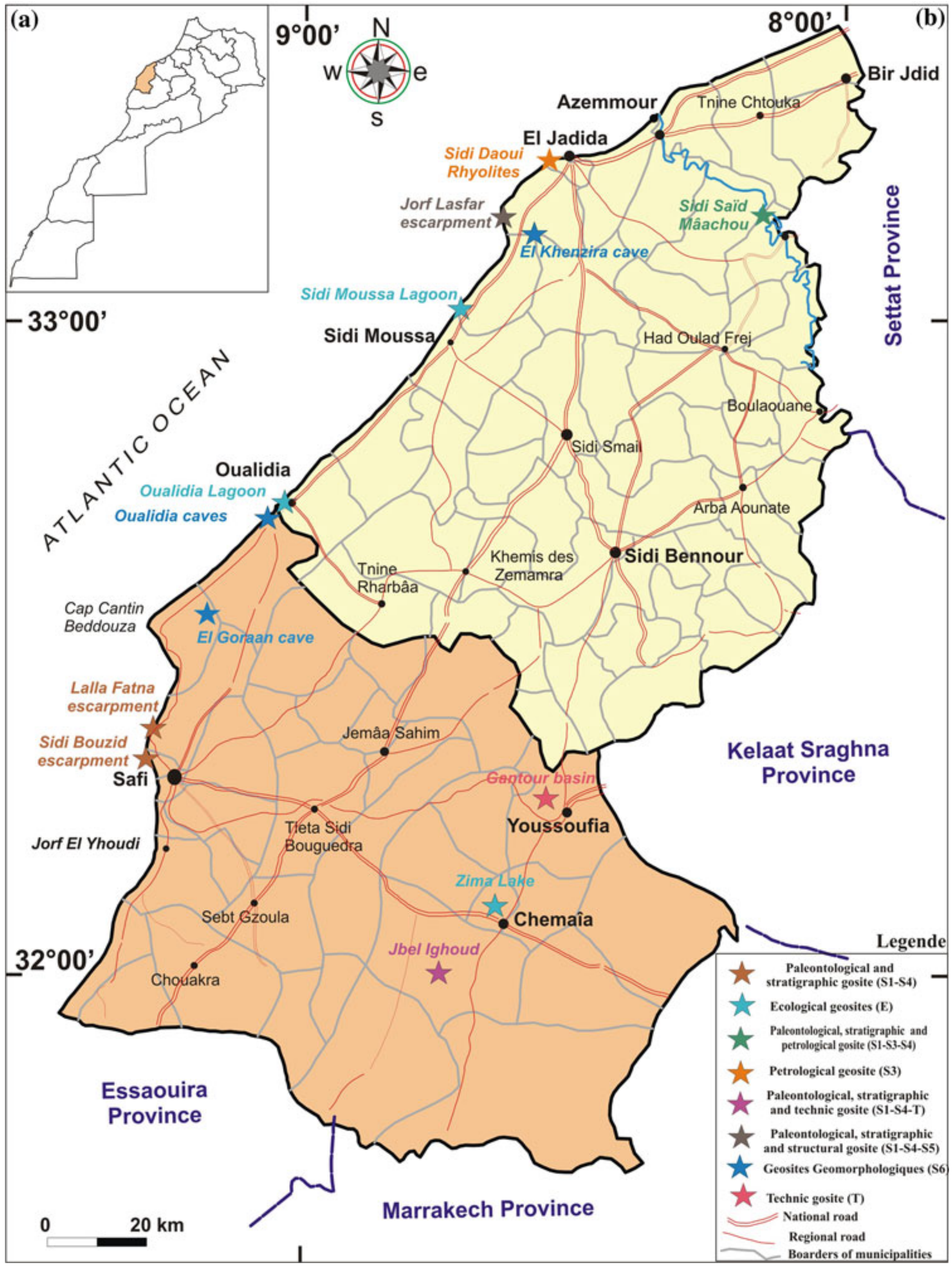

Fig. 1 Administrative subdivision of Doukkala-Abda region showing the locations of the geosites described in the paper

coastline; but is absent in the southern part of the area near Abda; (3) A belt of unconsolidated coastal dunes along the coastal strip; and (4) the fossil escarpments, especially dominating in the south-west part, that were formed during numerous hydrodynamic cycles (Ouadia 1998).

The region also displays a wealth of karst landforms, the products of its geology, geography and climate and the prevailing, hydrological conditions. Karst topography, limestone pavements, caves, sinkholes, and uvalas (a collection of multiple smaller individual sinkholes that coalesce into a compound sinkhole) are all represented. From the geological point of view, the Doukkala-Abda region belongs to the Coastal Block, defined by Michard et al. (1989) as a stable Variscan zone in the coastal part of the western Moroccan Meseta. The Coastal Block comprises subtabular Mesozoic and Cenozoic formations overlying folded Palaeozoic rocks, the Mesozoic succession representing the northern part of the El Jadida-Agadir basin (Bouaouda 2004). The region as a whole, however, is characterized by a wide variety of volcanic, sedimentary and metamorphic rocks that range in age from Precambrian to Miocene, and the older formations are covered by Plio-Quaternary transgressive deposits (Fig. 2) (Ferré and Ruhard 1975; Gigout 1965; Khatmi 1999).

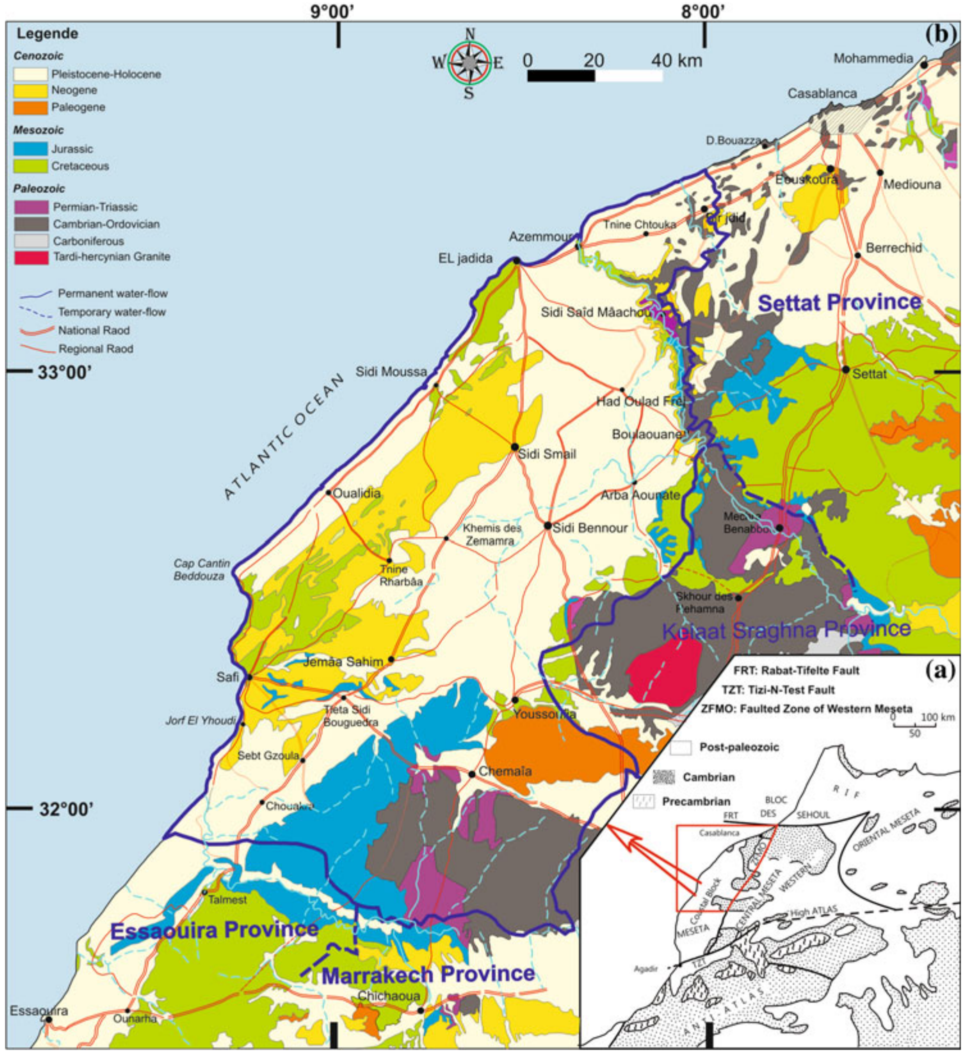

Fig. 2 Simplified geological map of Doukkala-Abda (adapted from Michard et al. 2008)

This paper aims to present results of the preliminary detailed inventory of the geoheritage of Doukkala-Abda region. Thirty-six geosites have been classified, taking into consideration their scientific importance and value, their degree of vulnerability and the nature of conservation required, through to proposals for various geotourist trails, in order to offer visitors other activities in addition to enjoying the natural and cultural heritage that exists in the vicinity of the sites.

2 Materials and Methods

The Doukkala-Abda region preserves a rich geoheritage. This paper outlines the results of efforts to prepare an inventory of the main geosites, based on their scientific and/or educational and/or socio-economic attributes and values. The study, undertaken in 2010, is based on literatures and field surveys. The inventory adopts a simplified classification commonly used for the regional geoheritage (Viette 2007; Table 1). The final aim of that work is to develop strategies for the protection, the sustainable management of the inventoried geosites and the development of proposals for geotourist trails in the region.

The inventoried sites are classified principally as either type S or T, respectively sites of scientific interest or technical interest, such as mines, quarries, brick-making, etc. However, we have added a third type, E, for the scientific sites which include all biological and ecological features. The 14 geosites described in the paper are listed in Table 2.

3 Description of the Doukkala-Abda Geosites

3.1 Geosites of Scientific Interest

3.1.1 Late Neoproterozoic Rhyolites

The Precambrian rocks are less well exposed in the Moroccan Meseta than in southern Morocco, in the Anti-Atlas. Their only outcrop in the Doukkala-Abda region is situated on the

Table 1 Geosites typology (modified after Viette (2007))

Geosites		Including
S1	Palaeontological	All fossil objects of palaeontological and/or palaeoecological interest
S2	Mineralogical	All minerals and mineralization forms
S3	Petrological	All rock types
S4	Stratigraphical	All types of strata, sections and series
S5	Structural	All types of structures
S6	Geomorphological	All models, reliefs and their modes of alteration (including pedological)
E	Ecological	All biological and ecological geosites (lagoons, lakes, etc.)
T	Technical	All technical sites (history of the exploitation of geological resources)

Table 2 Described geosites of Doukkala-Abda region

Geosites	Geographic coordinates	Typology
Late Precambrian rhyolites of Sidi Daoui	33°14′00″N–8°30′00″W	Petrological geosite (S3)
Sidi Saïd Mâachou Basin	33°00′–33°15′N, 8°00′–8°15′W	Palaeontological, stratigraphical and petrological geosites (S1-S3-S4)
Jbel Irhoud	Not provided, vulnerable geosites	Palaeontological, stratigraphical and technical geosites (S1-S4-T)
Lalla Fatna escarpment	32°23′54, 15″N, 9°15′44, 54″W	Palaeontological and stratigraphical geosites (S1-S4)
Sidi Bouzid escarpment	32°18′01″N–9°15′04″W	
Jorf Lasfar escarpment	33°09′24, 66″N–08°37′24, 74″W	Palaeontological, stratigraphical and structural geosites (S1-S4-S5)
Consolidated and unconsolidated dunes	Sahel of Doukkala region	Geomorphological geosites (S6)
El Goraan cave	32°33′27″N, 9°15′15″W	
El Khénzira cave	33°09′24,64″N–08°37′23″W	
Oualidia caves	32°40′42″–32°47′07″, 8°52′ 30″–9°02′50″	
Oualidia Lagoon	32°40′42″–32°47′07″, 8°52′ 30″–9°02′50″	Ecological geosites (E)
Sidi Moussa Lagoon	32°52′0″, 8°51′05″	
Zima Lake	32°04’48″N–08°39’36″W	
Phosphate deposit of Ganntour	32°7′48″N–8°30′0″E Elevation 534 m	Technical geosite (T)

headland at Sidi Daoui, on the Atlantic coast of El Jadida. At this locality, Neoproterozoic rhyolites are exposed in the core of an anticline where they are overlain unconformably by Early Cambrian dolomites (Fig. 3). The correlation of these volcanic outcrops with the late Neoproterozoic formations of the Anti-Atlas (e.g. Ouarzazate Group, Thomas et al. 2002), dated at 543 Ma, is generally accepted (Choubert 1963; Ez-zouhairi et al. 2007).

This outcrop provides a fascinating insight into the geological history of the region during the late Neoproterozoic and merits protection. However, the geosite is vulnerable to coastal erosion and weathering. Recently, a large part of the outcrop was covered during the construction of the coastal road between El Jadida town and Sidi Bouzid village. Nevertheless, despite its vulnerability, the remarkable position of this site enhances its tourist potential.

3.1.2 Sidi Saïd Mâachou Basin

The Sidi Saïd Mâachou (SSM) basin is oriented NNW-SSE, covering an area approximately 6 km in length and 4 km in width. Located between two administrative regions, the Doukkala-Abda and Chaouia-Ourdigha (Fig. 1), it consists of numerous stratigraphic, petrological and palaeontological geosites rich in minerals and fossils. The basin is cut by the Oum Er-Rbia River, which presents several geomorphological outcrops of educational value.

Geologically, the basin is comprised of sedimentary, igneous and metamorphic rocks, reflecting continental and

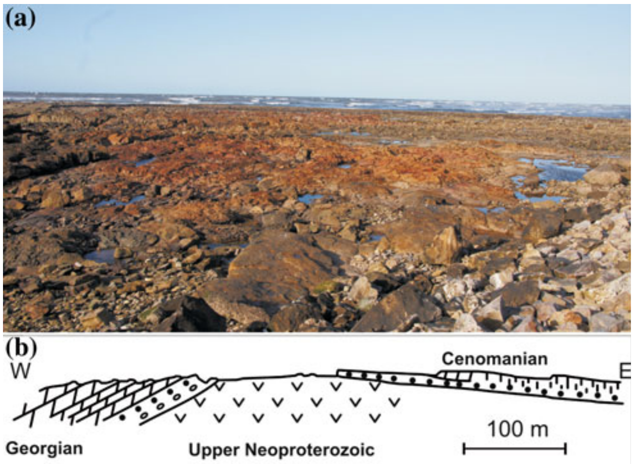

Fig. 3 **a** The oldest volcanic rocks in Doukkala-Abda (Late Neoproterozoic rhyolites. **b** Simplified lithostratigraphic section of El Jadida headland with late Precambrian rhyolites in the core of the anticline

marine environments. The rocks have been tectonically deformed and show structural features (various foliations, folds, and faults), which are useful both for educational and tourist purposes. The succession is made up of three main formations: middle Cambrian rocks, predominantly shales (Fig. 4a), unconformably overlain by continental Triassic rocks (Fig. 4b) and marine Plio-Quaternary sedimentary units (see Fig. 4c, d, e and Gigout 1956; El Attari 2001; Hminna 2005, Hminna et al. 2013). The volcanic complex of the SSM consists of dolerite dykes and sills feeding basaltic flows on the surface (Fig. 5a, b). The emplacement of the dolerites was synchronous with the sedimentation of the Acadian (Middle Cambrian) Paradoxides shales. It represents a period of extensional intraplate alkaline magmatism within Gondwana during the Cambrian (Ezzouhairi et al. 2004). The Triassic formations correspond to a deposit within a playa-like, fluvio-lacustrine system under semi-arid conditions (Hminna et al. 2013). The Triassic red-beds have yielded the most interesting fossils, which include plant prints, rhizoliths, fish scales, and invertebrate and vertebrate traces (Hminna et al. 2013). Tetrapod footprints recorded in this area are assigned to *Brachychirotherium parvum*, and are considered the first record of Triassic tetrapod footprints in Morocco outside of the High Atlas, and, indeed, the first record of the species in Africa (Hminna et al. 2013). The Late Triassic is marked by several intercalated tholeiitic basalt flows (Fig. 5c), linked to central Atlantic rifting. These flows crop out generally along the Oued Oum Er-Rbia. They vary in thickness and color, the latter ranging from grey to greenish, and they show varying stages of alteration (Hminna 2005).

With its scenic value, the SSM basin is a geosite of high heritage interest that needs to be evaluated with the goal of increasing the income of the local communities (Enniouar et al. 2011, 2013). It is important to note that almost no socio-economic activities generating revenues for local populations exists in the SSM village, whose name was given to the first dam to be built in Moroccan territory in 1929 (*in the official website of Ministry of Energy, Mines, Water and Environment, Department of Water,* http://www.water.gov.ma/index.cfm) (Fig. 4c). Several 1-day georoutes could be developed within the basin.

3.1.3 Jbel Irhoud

Jbel Irhoud (Jbel means mountain in Arabic) represents a faulted anticline of Early Cambrian karstic limestones and shales. The succession in the general vicinity is 400–500 m thick and, in addition to the deformed Palaeozoic rocks, also preserves Triassic red beds and Quaternary calcareous sandstones, in unconformable relationships to the older units. This geosite is one of the most important fossil localities in the Doukkala-Abda region (Fig. 6). It is known for its numerous hominid remains (see below), and also for its barite mines. The Early Cambrian shales preserve A*rcheocyathus,* reef-building marine organisms of early Cambrian age that lived in warm tropical and subtropical waters (Huvelin 1977).

The Jebel Irhoud limestones contain many caves and other examples of karst landforms. One of the caves, which might have been used by Neanderthals, has yielded several discoveries, the most important being that of the juvenile *Homo sapiens*, dated at 160,000 years. It is the oldest member of modern *Homo* known with developed features in Morocco (Hublin et al. 1987; Hublin and Tillier 1988; Amani and Geraads 1993, 1998; Smith et al. 2007). The cave has also provided more than 425 pieces of worked stone and tools of a Levallois-Mousterian technique. The smoothness of some tool-tips suggests the high level of intelligence of the Neanderthals (Hublin and Tillier 1988).

In summary, the stratigraphical, palaeontological and archaeological richness of Jbel Irhoud makes it one of the most important geosites in the region. Its scientific, historical and cultural values make it a site of heritage importance; however, its location in a remote mining area increases its vulnerability. Its preservation should be a matter of priority for the local authorities.

3.1.4 Lalla Fatna Escarpment

The Lalla Fatna geosite offers two contrasting coastal attractions: one scientific, the other touristic. The escarpment, comprising a rock sequence of Mesozoic age, is situated at the top of a sandy beach, and is a rich source of fossils (ammonites, brachiopods, bryozoa, cnidaria, echinoids). The beach itself offers considerable tourist potential.

The escarpment ranges between 115 and 150 m in height. It consists mainly of three geological units forming part of an anticlinal structure. (Fig. 7a, b, Ettachfini et al. 1998). The units mark a transition from the Jurassic to the Cretaceous

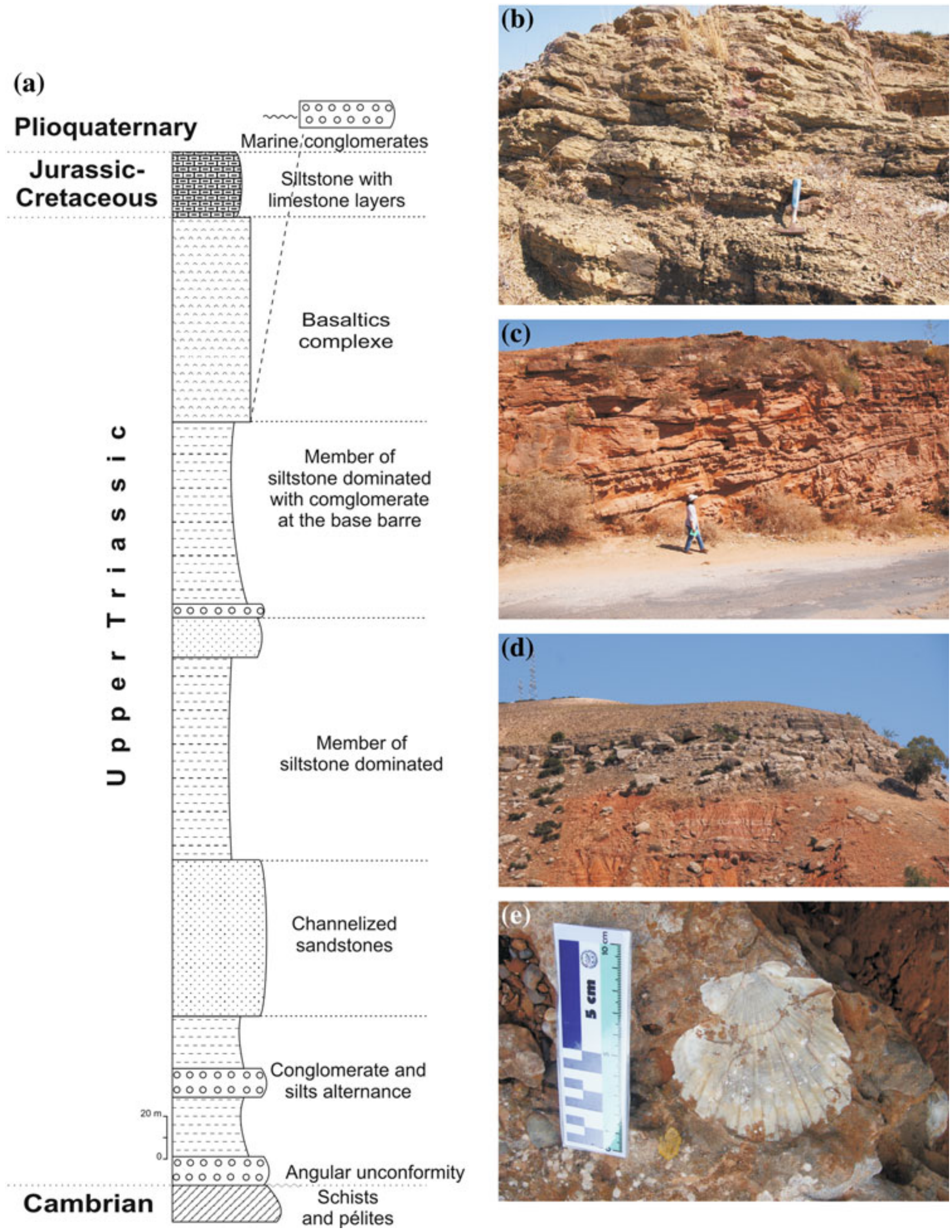

Fig. 4 **a** Lithostratigraphic subdivision of the Palaeozoic and Mesozoic formations in the Sidi said Mâachou basin. **b** Middle Cambrian shales and sandstones. **c** Triassic sandstone-dominated *red-beds*. **d** Plio-Quaternary conglomerates rich in marine fossils (*Photo* **e**)

(Fig. 7a); from the base of the escarpment to the top these are:

(1) A basal unit of white-coloured gypsiferous evaporites displaying salt tectonic structures, overlain by alternating dolomite, marl and gypsum layers showing a variety of sedimentary features (laminations, tepee structure, breccia and bioturbation). These rocks are overlain by massive and azoic yellowish dolomites. The basal unit was deposited during the Late Jurassic in a confined hot, arid environment.

(2) The Lower Limestones is a unit formed principally of limestones preserving a rich marine fauna (ammonites, brachiopods, gastropods and echinoids). They are capped by a red oxidized ferruginous surface ('hard ground'), which is also rich in marine fossils (brachiopods, bryozoa, cnidaria, and echinoids). An extensive marine depositional environment, possibly associated with rapid sea-level rise, and accompanying low sedimentation rates, is invoked (Fig. 7a, b, Ettachfini et al. 1998), however the hard ground could be an indicative of oxidation in a subaerial tropical environment.

(3) The uppermost rocks exposed in the escarpment are mainly brown clay stones with a few intercalated limestone layers deposited in an open marine environment such as platform type (Ettachfini et al. 1998).

In summary, the sedimentary and palaeontological information preserved in the rocks, that form the escarpment,

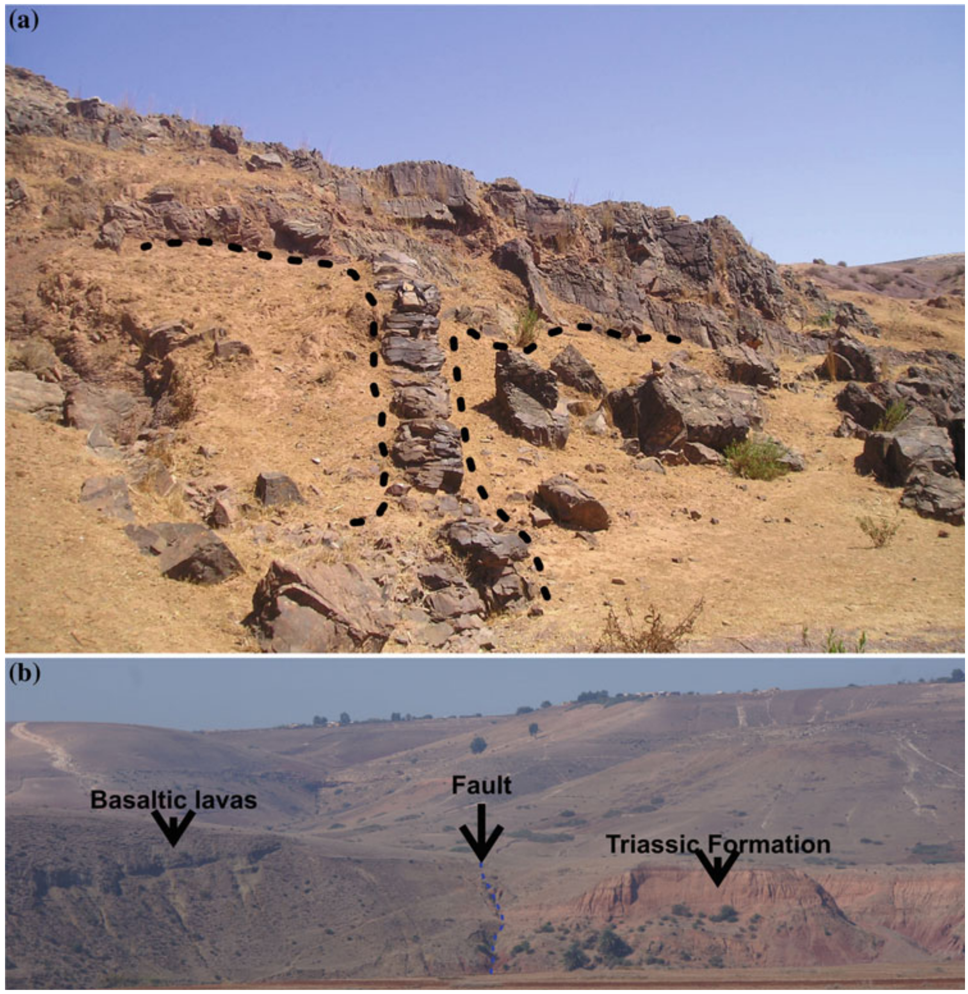

Fig. 5 **a** Middle Cambrian dolerite dykes and sills associated to Paradoxides schists. **b** Triassic basaltic lava flows; linked to the rifting of the central Atlantic, in faulted contact with the Triassic siltstones

make a valuable contribution to palaeo-biogeographical and palaeoclimatic interpretations as well as to stratigraphical correlations both regionally and globally. In addition, the Lalla Fatna beach is a popular tourist destination. Recently, the road to the beach was paved and the stairs upgraded.

3.1.5 Sidi Bouzid Escarpment

The Sidi Bouzid escarpment extends for several kilometres along the coast South-West from Safi town. It offers a panoramic view over the town and provides a beautiful beach frequently visited by vacationers. The 160–200 m thick succession of Early Cretaceous sedimentary rocks making up the escarpment is subdivided into three formations which are, from the base to the top:

(1) The Late Berriasian—Early Valanginian Lower Limestone Formation, contains a concentrated marine fauna (Rey et al. 1989; Ettachfini et al. 1998).
(2) The early Late Valanginian Brown Claystone Formation which overlies both the previous formations, and is rich in ammonites (Rey et al. 1989; Ettachfini et al. 1998).
(3) The Late Hauterivian Dridrat Limestone Formation is rich in marine fossils, including cup corals, brachiopods, bryozoa, echnoids, serpulids, spatangoids, ammonites and calpionellids (Gigout 1951).

The various palaeontological assemblages found at this site are of great scientific interest in terms of their palaeoecological and palaeo-bio-geographical significance. In addition, the site has proven tourist value. According to the magazine “Surf”, Safi has one of the ten best surfing waves in the world, related to large depressions in the seabed, especially in autumn, and due to the physical presence of Sidi Bouzid escarpment. Prominent among the artistic and cultural activities organized each year in Safi town is the “Amwaj Assafi” festival (“Amwage” meaning ‘waves’ in Arabic). The festival aims to promote Safi as a town of art and culture, and as a tourist destination.

3.1.6 Jorf Lasfar Escarpment

The Jorf Lasfar escarpment gives rise to beautiful landscape along the coastal road and provides a good view of Jorf Lasfar harbour. The escarpment has a markedly yellow

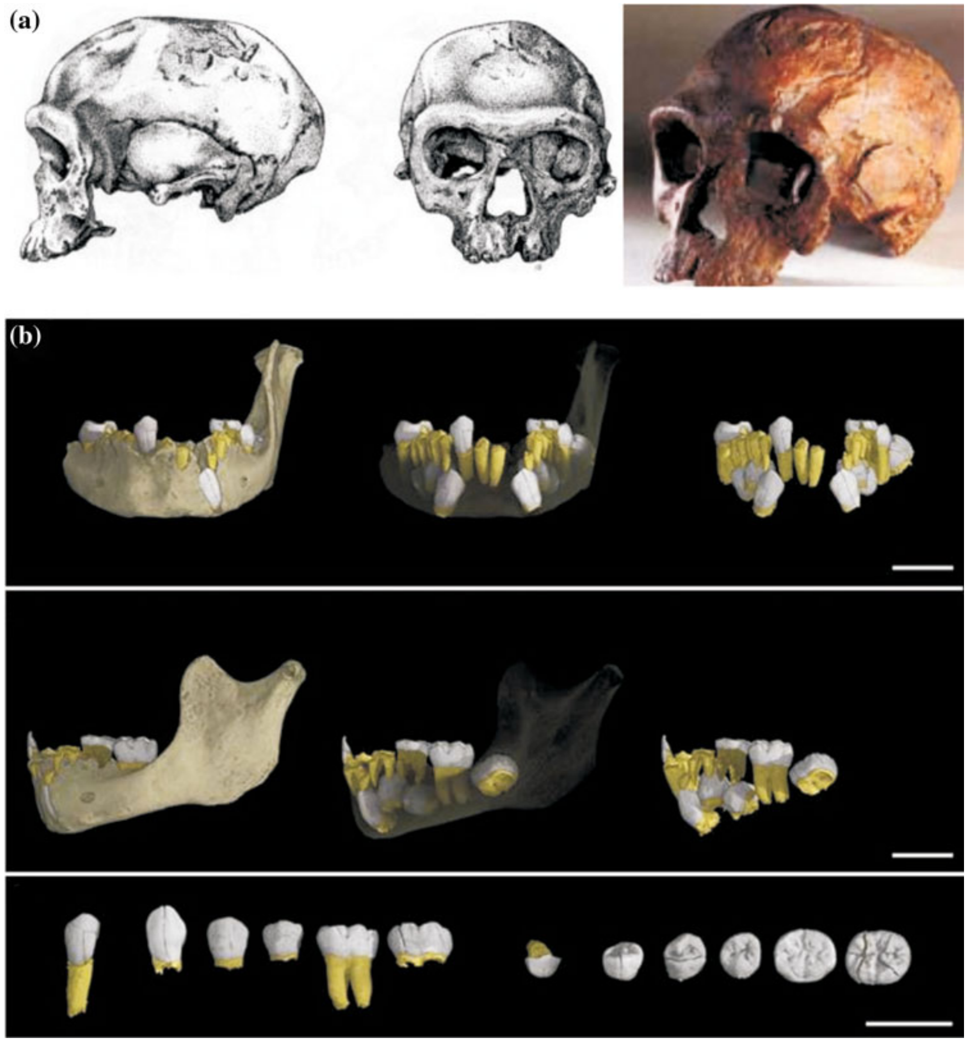

Fig. 6 Human remains excavated from Jbel Irhoud, Western Jbilet. **a** Skull of the Juvenile *Homo sapiens* of Jbel Irhoud. **b** Remains of jaws and teeth of *Homo Sapiens* of Jbel Irhoud. *Bar scales* 2 cm. *Photos* taken from Smith et al. (2007)

colour as indicated by the name of the site, "Jorf Lasfar" meaning "yellow cliff" in Arabic. The geology consists of Cretaceous formations with neotectonic activity (Ouadia 1998). Furthermore, the morphological changes of the shoreline inform the teaching of modern concepts of vertical weathering changes in cliffs and the lateral changes of the present shoreline (Duane 2013).

3.1.7 Consolidated and Unconsolidated Dunes

The coastal area of Doukkala-Abda region consists of varied landscapes comprising mainly consolidated and unconsolidated dunes (Aboumaria 1993; Ouadia 1998). The decrease in sea level and the action of trade winds are responsible for the development of the old dune cordons of late Pleistocene (Soltanian) age (Weisrock 1982; Ouadia et al. 1993). These dunes trend Northeast-Southwest and the slope is steeper on the inland, Oulja (Coastal wetland influenced by swamp) side, than on the Ocean side (Ouadia 1998), reflecting a wind direction from West to East (Gigout 1951). Both the consolidated and unconsolidated dunes are very important for the stability of the inland and coastal ecosystems, protecting coastal areas from erosion and the hinterland from winds and desertification. The intensive quarrying of sand from these dunes (at 147 quarries sites, according to the Ministry of Equipment and Transport 2013) is causing serious damage to the environment. The recognition of just one of the extraction sites as a designated geosite would help to demonstrate the value of the dune fields as a whole, and the importance of preserving them, and tt would play an important role in alerting the local population and the decision-makers.

3.1.8 Karst Landscapes

The Doukkala-Abda region is characterized by its karstic features and landscapes, especially in the coastal zone where caves, which were used and adapted by prehistoric man during the Quaternary, are one of the most important geomorphological features. Two types of cave are distinguished: dissolution caves and man-made caves. Climatic parameters (wet), the geological and the structural characteristics

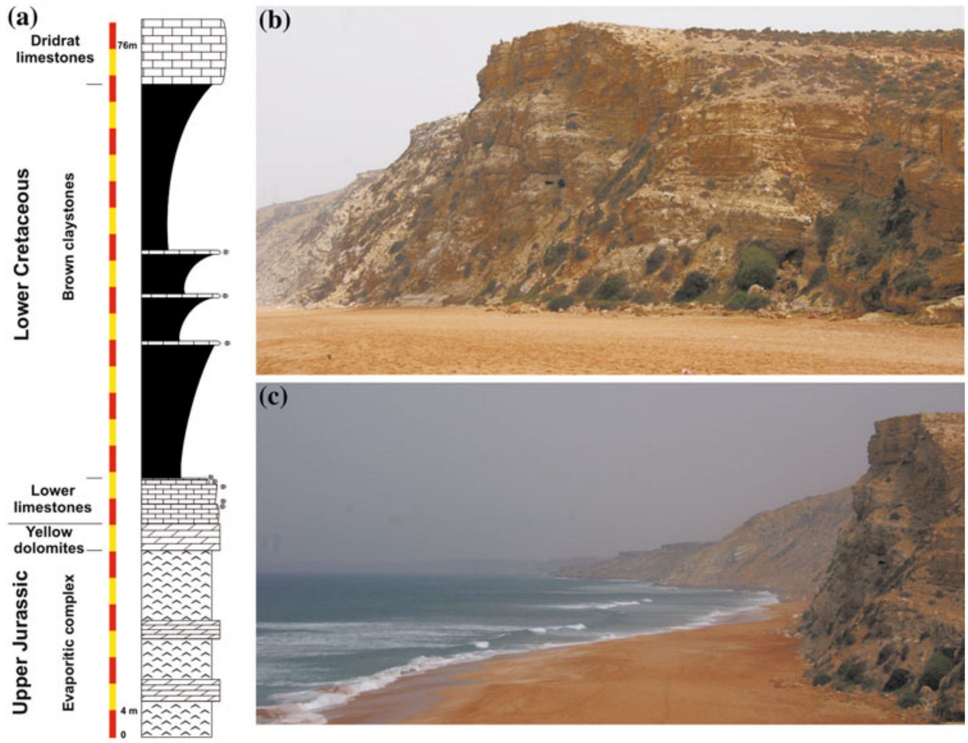

Fig. 7 **a** Lithostratigraphic subdivision of Mesozoic deposits of Lalla Fatna escarpment (After Ettachfini et al. 1998). **b** Panoramic view of Lalla Fatna escarpment. **c** Lalla Fatna beach

(fractured limestones), hydrogeological and geographical barriers to the flow of surface water into the ocean all contribute to the karstification of the substrate.

Several caves have been described in the region (Ouadia et al. 2008). The best known are El Goraan and El Khenzira caves, which are judged to be significant archaeological sites in need of special investigation by archaeologists and palaeoanthropologists. The variation in the functional role of caves in this area in the past provides a good example of the interrelationship between man and his environment. Caves at three sites are described below:

El Goraan: El Goraan is a deep cave with an entrance about 2 m in diameter (Fig. 8a, b). It consists of several chambers and branching tunnels, some of which have been investigated, while others are still unexplored (Boualla and Mehdi 2011). The cave's interior reveals splendid stalactites, stalagmites, draperies, eccentrics and pillars, all of which reflect long-term dissolution of the limestones (Fig. 8c, d). Some rock carvings featuring boomerangs and arrowheads have been discovered, as well diverse pottery fragments, as yet unstudied, indicating that the cave was used as a human refuge.

El Khenzira: It is one of the most studied deep and natural caves (Ouadia and Aberkan 1992; Ouadia et al. 1993). It has yielded man-made tools attributed to the Aterian, again witnessing the use of the cave as shelter for prehistoric humans (Ruhlmann 1936).

Oualidia: At least three caves are natural and result from marine erosion. They are only accessible at low tide (Fig. 9). Recently, they have been subject to many changes made by visitors, such as the construction of additional window-like openings to the sea. In addition to the sea caves, several shelters under overhanging rocks are visible along the escarpments around Oualidia village. These have been used, as shelters and watchtowers, by sailors and soldiers who have haunted the coast, certainly since the Phoenician period (Ouadia et al. 2008).

The great diversity of the karstic features in this area is of high scientific value. The study of their forms and the nature of the caves and, importantly, their contents helps to reconstruct the palaeoclimatic, palaeoenvironmental and geomorphological evolution of the region during the Quaternary (Ouadia et al. 2008). Furthermore, the discoveries of rock carvings and man-made tools reveal that the caves have been used by human beings since prehistoric times, demonstrating their archeological importance (Ruhlmann 1936; Ouadia et al. 2008).

A multidisciplinary study of the caves would provide yet more information about their mode of formation and their use, and, again, would help to raise awareness of their value and the need for their protection. In addition, such studies would assist in the development of their tourist potential and thereby contribute to local development and the local economy. For many years the Doukkala-Abda region has

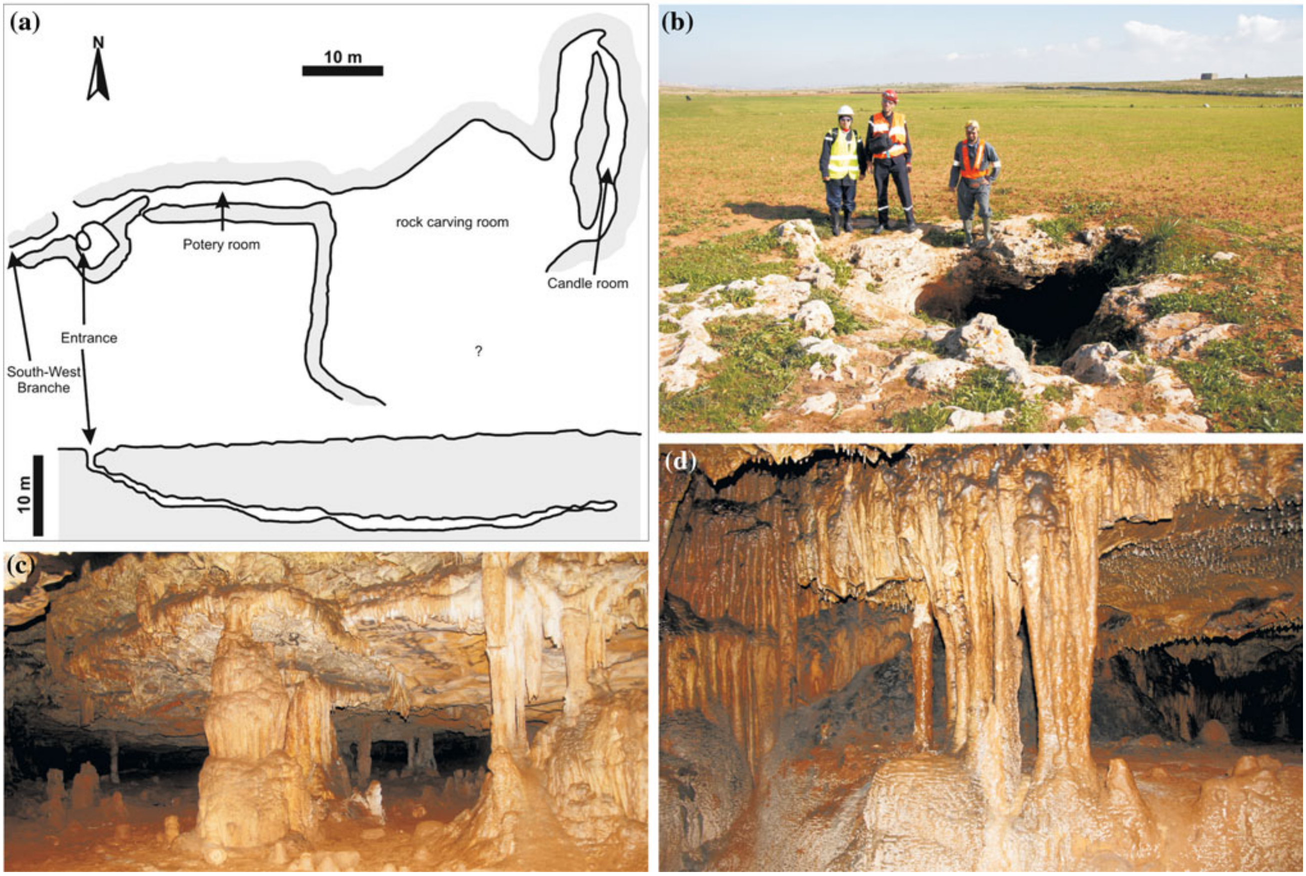

Fig. 8 **a** Simplified sketch and longitudinal section of the eastern branch of the El Goraan cave in Beddouza headland. **b** The entrance to the cave. **c**, **d** Diverse stalactitic and stalagmite structures, resulting from ground-water flow

Fig. 9 Oualidia cave of marine origin, modified by human activities

also been well known for the instability and subsidence of its substrate, leaving the coastal escarpments vulnerable to collapse. A detailed study of the area is considered necessary, in order to minimize the consequences of any such collapse which would impact on the local inhabitants and infrastructure.

3.2 Ecological Geosites

3.2.1 Wetlands: Sidi Moussa—Oualidia Lagoon Complex

The region, situated along the Atlantic coast, is well known for its wetlands, which are resources with a rich biodiversity. Covering an area of approximately 10,000 ha, the Oualidia and Sidi Moussa lagoons were classified as a *Ramsar* site in 2005, and as a Site of Biological and Ecological Interest (SIBE) (Fig. 10). These ecosystems are relatively rich in endemic species and represent important breeding and wintering sites as well as a stopover area for hundreds of thousands of migratory birds. Several rare or endangered species at risk of extinction, such as the *Black-winged Stilt*, are resident here: The lagoons are the only site of international importance for the *Black-winged Stilt* in Morocco (El Hamoumi et al. 2000; El Hamoumi and Dakki 2010; Benajah et al. 2010), and the wetlands play a key role in maintaining the ecological balance of most ecosystems, in addition to the important socio-economic benefits they bring to the surrounding areas, especially through tourism.

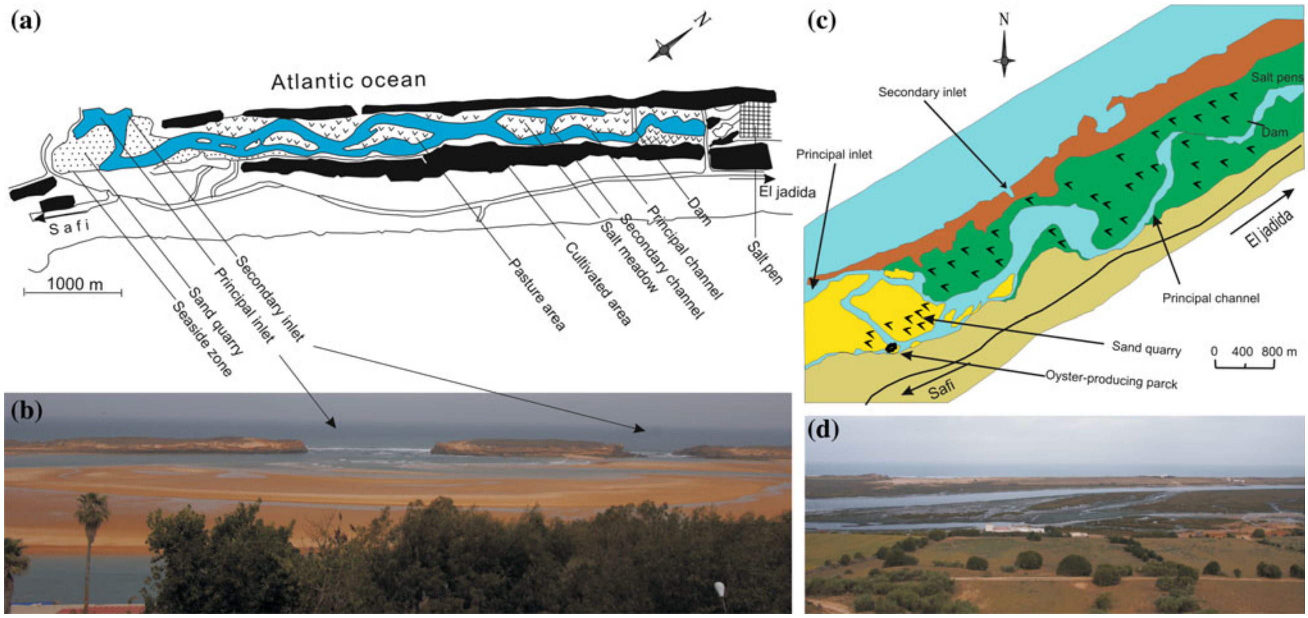

Fig. 10 **a** Morphological map of Oualidia lagoon; **b** Oualidia lagoon's principal channel, with primary and secondary tidal inlet. **c** Morphological map of Sidi Moussa lagoon. **d** Sidi Moussa lagoon's principal and secondary channels

The geology of the Oualidia lagoon (Fig. 10a, b) consists of clayey sands, sandstones and calcareous and marl formations of Late Jurassic age, overlain by Plio-Quaternary consolidated dunes (Canérot et al. 1982; Taj-Eddine et al. 1985; Witam 1988; Ouadia 1998; Fakir 2001). The numerous geological, ecological and biological investigations made of this lagoon reflect its regional and global importance. Furthermore, it is one of the few sites in Morocco where traditional oyster cultivation has been developed since the 1950s. The lagoon is characterized by special species such as *Chondrus crispus*, *Palmaria palmata*, *Sacchoriza polyschides*, *Enteromorpha crispa* and *Ulva linza* (Farid et al. 2009). The variety of species is influenced by environmental factors, such as substratum, water temperature, light, wave action, salinity and pH (Fang et al. 1996).

The Sidi Moussa lagoon (Fig. 10c, d) is a marginal system with a significant marine influence. It is classified in the semi-arid range (Atillah 1994), and is characterized by warm temperate climate (Maanan 2003). Geomorphologically, it consists of a depression resulting from the post-Ouljian regression (Quaternary) (Bidet and Carruesco 1982; Carruesco 1989). It is biologically rich, comprising a variety of fish exhibiting seasonal variability (sole, bar, etc.) and several invertebrates such as decapods, isopods, cnidarians, gastropods and bivalves (Bennouna 1999). Fishing is one of the important activities in this area, but it is still traditional and seasonal.

The Sidi Moussa-Oualidia lagoon complex has an exceptionally rich and diverse heritage as it performs several ecological functions such as: control and self-purification of water, protection against floods, organic production, special biotope of bird species for nesting and breeding with high heritage value (migratory birds), and growth of a remarkable flora (Hammada 2007). Moreover, it is a field-area for palaeoclimatic and climatic studies, drawing upon evidence of historical weather events preserved in the fine-grained sediments.

These wetlands are, however, subject to conflicts of interest between the economy and ecology (Guo and Ma 2008). The protection of bird species is dependent on the protection of their wetland habitats. Without adequate conservation measures, these stopover sites may become the weak link in the chain of migration, which, if broken, will probably result in the extinction of the wild bird populations that depend on them (Higuchi 1991). Consequently, the preservation of this heritage will contribute to improvements in the quality of life of the local population. Due to anthropogenic pressures, the wetland areas are at risk (drying, saltwater intrusion in the coastal border, over-exploitation of marine organisms, and destruction of natural barriers (sand dunes etc.). Accordingly, a better understanding of these ecosystems is necessary to improve and rationalize their management in order to preserve them against environmental threats. In fact, conflicts of interests between the use of the wetlands and ecosystem protection need careful evaluation to contribute in the local development.

3.2.2 Zima Lake

The Zima Lake is a salt wetland of 600 ha (Fig. 11). It has a high ecological potential and is classified as a *Ramsar* site,

Fig. 11 Panoramic view of Zima lake with drain water channel, vegetation and salt deposit

as a site of biological and ecological interest (SIBE), and as a reserve where hunting is strictly forbidden.

Geologically, the Zima Lake is located in sandstones in the core of a Palaeozoic syncline. These sandstone beds are overlain by Permo-Triassic deposits which consist of red sandstone and marl with salt intercalations, succeeded by Late Jurassic and Cretaceous sedimentary rocks, predominantly marls and marly-limestones with gypsum intrusions. The sequence is completed by various Quaternary deposits, saline silts, sands, conglomerates, gravels and calcretes. The surrounding soils are carbonated humus, very dark, sometimes red (El Mokhtar et al. 2012).

The area is characterized by low rainfalls (150–200 mm), a very high evaporation (876 mm in 1993–1994) and a Mediterranean arid to temperate winter climate.

The entire wetland is surrounded by a belt of halophytic vegetation covered by a thick layer of filamentous algae and angiosperms *Potamogeton pectinatus* providing great floristic richness (Negre 1960; Abbad 1993). More than thirty species of plants have been documented at this locality including *Aeluropus littoralis*, *Agrostis stolonifera*, *Arthrocnemum indicum*, and *A. halimus*, among others. Moreover, the Lake supports many species adapted to hypersaline seasonal wetlands, including two rare endemic plants, species of Caryophyllales (Angiosperms): *Halopelis amplicauli* and *Spergularia tenuifolia*.

This site also has great ornithological value, for both wintering and breeding. It hosts abundant aquatic birds: 99,000 during wet years and an average of 3,860 birds during the period from 1996 to 2000 (Radi et al. 2004; Thévenot et al. 2003). Furthermore, this vast wetland could become one of the most important areas in Morocco for avifauna which includes *Gull-billed Tern*, *Kentish Plover*, *Black-winged Stilt* and *White Stork*, if it were to benefit from even a minimum of protection. More than forty species of birds have been recorded in the salt sabkha, with a maximum number of 3000 birds recorded during the last 12 years, including approximately 1,000 *Pink Flamingo* and 2,000 *Anseriform* birds with at least two interesting species, *Shelduck* and *Marbled Teal,* as well as *Shoveller*, *Northern Pintail* and *Ruddy Shelduck*. The lake is home to several threatened and vulnerable bird species listed on the Red List of the International Union for Conservation of Nature, such as: *Marbled teal Marmaronetta angustirostris and Ruddy Shelduck Tadorna ferruginea*, *Greater Flamingo Phoenicopterus ruber*, *Shelduck* and *Tadorna tadorna*; and some protected species in France that are listed in category A2 of the Agreement on migratory birds of African-Eurasian Migratory Water-birds (AEWA), such as *Sterne Hansel, Sterna nilotica* (Radi et al. 2004; Thévenot et al. 2003).

The Zima Lake is known for its salt deposits, and is considered one of the most important continental salt sources in Doukkala-Abda region, with an annual production of 30,000 tons. The salt derives from sub-surface saline flows at shallow depth, migrating from the ground-water of the Chemaia plain (El Mokhtar et al. 2012). Extraction of the salt, for use by the food-industries, is undertaken by the Cherifian Society of Salt (*SCS*) that provides jobs for fifty workers from the surrounding villages.

The lake area supports, particularly, pastoral agriculture, and possesses high aesthetic and recreational value, which could be better promoted to encourage recreational activities.

However, the preservation of this rich biodiversity and enhancing recognition of its value is an indispensable preliminary step towards the sustainable development of geotourism, especially ecotourism.

4 Technical Geosites: The Mining Heritage of Doukkala-Abda

The mineral potential of the Doukkala-Abda region is significant and well known. The main deposits are the phosphates of the Ganntour basin, which represent 37 % of the national reserves (Annual Report of the Chérifian Office of Phosphates 2011), the barite deposits worked at Jbel Irhoud, the gypsum vein deposits of the Chemmaia basin, and the Zima Lake salt deposits.

We focus here only on the Ganntour sedimentary phosphate deposit, because it is Morocco's most important mineral resource. The Ganntour basin deposit underlies an area of approximately 125 km in length, 15 km in width and oriented E-W. The reserves are estimated to be 2 billion m^3 (*Official website of the Cherifian Office of Phosphate* (*OCP*)).

The phosphates were deposited during the Late Cretaceous (Maastrichtian) to Early Eocene (Early Lutetian) interval (Noubhani 1993). The sedimentary rocks that host the deposits are also some of the country's richest in fossils, yielding many marine varieties and, occasionally, as in the Ouled Abdoun basin, well-preserved continental vertebrate remains. Apart from Selachian (sharks, rays) teeth, which are the most abundant and diversified fauna (see below), they contain bony fishes, marine reptiles including plesiosaurs, mosasaurs, crocodiles, as well as terrestrial sauropods and mammals (the oldest proboscideans) (Bardet et al. in press). The Ganntour basin has provided 138 species of Selachians, including species identified here for the first time and which are exclusive to this basin. They include *Ginglymostoma erramii*, *Ginglymostoma botmaense*, *Plicatoscyllium gharbii*, and *Foumtizia gadaensis* (Noubhani 1993; Noubhani and Cappetta 1997).

In the framework of the OCP Group's recent ecological and sustainable development strategy, some of the phosphate deposits merit formal declaration as geoparks (Noubhani 2011). The palaeontological wealth of the phosphate formations has, however, led the OCP Group to plan the establishment of a museum of palaeontology in the mining town of Khouribga, to display the fossils collected from the phosphate basins.

In this context the Gantour basin could also form part of the proposed thematic geotrail, linking key phosphate outcrops and industrial areas (extraction sites and treatment). A combined interpretative center and museum would assist to promote sustainable socio-economic activities in the region, *cf.* the museum planned for the Ouled Abdoun basin (Noubhani 2011).

5 Discussion and Conclusions

An aspiring geopark region, the Doukkala-Abda is characterized by a varied and rich natural heritage, which includes geomorphological, geological and cultural features. Its biodiversity and geodiversity and significant geotourist potential offer the prospect of sustainable development cultural geotrails for both education and tourism. This will require full evaluation and, at present, the geoheritage component in particular is currently under-valued and poorly known by the local communities, visitors and policy makers. Indeed, visitors come, for the most part, during the summer holidays to enjoy the region's numerous and beautiful beaches. In order to stimulate their interest towards other kinds of activities, and to encourage them to learn more about the region they are visiting, appropriate methods need to promoted, such as the creation of interpretative centers and information panels, and museums. Moreover, the development of instructional geotrails linking geosites in the coastal zone to those in hinterland will help to develop the region in a sustainable and holistic way, and will offer a new year round tourist product (Errami et al. 2013). This strategy will promote and benefit rural destinations situated in the hinterland of the region.

However, this process of evaluation and strategy development should include all the components of the region's heritage, not only the many sites and features of geological interest and value. For this reason, several mechanisms and measures are highly recommended:

(1) The continued preparation and completion of detailed inventories of sites of high patrimonial significance through the creation of a GIS databases (Geographic/Geologic Information System database);
(2) The promotion of geoheritage and its importance to society by offering organized field trips for not only scientists, but students, scholars, associations, the local people and the wider public, including tourists. Such activities could provide a source of entertainment and intellectual enrichment;
(3) To increase awareness of the importance of natural, geographical, geological, and cultural heritages through the organization of cultural activities such as conferences, workshops, exhibitions, and use of 'the media' via local and national TV, publications radio and Internet based systems;
(4) The creation of indicative and interpretative panels, interpretative centers, museums, and geotrails will help to emphasise the importance of valuing and conserving our regional heritage, and provide the opportunity to promote and develop our local products.
(5) A closer link between the geosites outlined in this paper and the historical and cultural monuments of the

Doukkala-Abda region (e.g., the Portuguese city of Mazagan, a World Heritage Site), and also a link to the region's intangible heritage (e.g., falconry at Lakouassem, registered as an Oral and Intangible Heritage of Humanity), all three forming part of the process of promoting local sustainable tourism (e.g. Errami et al. 2013), would give strong support to the realisation of other geotourism projects.

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Late Cretaceous and Lower Paleogene Moroccan Phosphates: Geotourism Opportunities

Les phosphates du Crétacé terminal et Paléogène inférieur du Maroc: Opportunités du géotourisme

فوسفات العصر الطباشيري و الفجري القديم السفلي للمغرب فرص لجيوسياحة

Abdelmajid Noubhani

Abstract

Late Cretaceous and lower Paleogene Moroccan phosphate deposits are one of the best examples of Moroccan geological heritage. These deposits are rich in well-preserved fossil remains including giant marine reptiles, as well as teeth of extinct sharks and rays which have been collected in vast quantities. The Cherifian Office of Phosphates Group (OCP) has recently outlined a strategy to promote sustainable ecological development. In this context, certain sites within the phosphate deposits could be incorporated into a modern Geosite Trail for tourism. Such a trail might start with a visit to the "*Museum of Palaeontology*" planned in the mining town of Khouribga. This would position visitors within walking distance of sites to be designated within the mining areas, including key representative sections of different geological strata. Besides showcasing the natural beauty of the landscape, these sections present a panoramic view of the lithology and stratigraphy of the phosphate series, displaying both geological features and mining operations. To ensure sustainability, the area would need to be declared a *Geopark* where geological activities are encouraged but regulated. In addition to the protection and the enhancement of the palaeontological riches, such a declaration would benefit the economy of the local population for whom collecting fossils is a principle economic activity supplementing agriculture and cattle breeding.

Résumé

Les gisements u à phosphate Crétacé terminal - Paléogène inférieur sont un des meilleurs exemples du géopatrimoine marocain. Ces dépôts sont riches en restes fossiles extraordinairement bien préservés dont des reptiles marins géants et des dents de requins et de raies qui se collectent par millions. Le groupe Office Chérifien des Phosphates (OCP) a, récemment, défini une stratégie visant à promouvoir le développement écologique durable. Dans ce contexte, certains sites des gisements de phosphate pourraient être intégrés dans un circuit moderne de *Géotourisme*. L'excursion peut commencer par la visite du "*Musée de Paléontologie*" dont la construction est prévue dans la ville minière de Khouribga. Cela placera les visiteurs à quelques minutes de marche des sites qui seront désignés dans les zones minières avec les coupes représentatives des différentes couches géologiques. En plus de la beauté naturelle du

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paysage, ces sections présentent une vue panoramique de la lithologie et de la stratigraphie de la série phosphatée, montrant aussi bien les caractéristiques géologiques que les opérations minières. Pour assurer le développement durable, la zone devrait être déclarée comme un *Géoparc* où les activités géologiques sont encouragées mais réglementées. En plus de la protection et la valorisation des richesses paléontologiques, une telle déclaration serait bénéfique pour l'économie des populations locales pour lesquelles la collecte des fossiles est la principale activité à côté de l'agriculture et l'élevage.

ملخص

تعتبر رواسب فوسفات أواخر عصري الطباشيري و الباليوسين السفلي واحدة من أفضل الأمثلة للجيوتراث المغربي. هذه الترسبات غنية ببقايا مستحثات محفوظة بشكل جيد، بما في ذلك الزواحف البحرية العملاقة وأسنان القرش والشفنين البحري التي تجمع بالملايين.لقد وضعت مجموعة المكتب الشريف للفوسفاط مؤخرا إستراتيجية تستهدف تعزيز التنمية البيئية المستدامة. ويمكن، في هذا الإطار، إدراج بعض المواقع لرواسب الفوسفات ضمن طرق حديثة للجيوسياحة. يمكن أن تُستهل الجولة بزيارة متحف الحفريات المزمع تشييده بالمدينة المنجمية لخريبكة. الشيء الذي يجعل الزوار على مسافة قريبة من المواقع التي سيتم اختيارها داخل المناطق المنجمية بما في ذلك مقاطع تُمَثِّلُ مختلف الطبقات الجيولوجية. فبالإضافة إلى جمالية المناظر الطبيعية، فإن هذه المقاطع تُشَكِّلُ إطلالة بانورامية على الخصائص الصخرية والطبقاتية لسلسلة الفوسفاط، وتبين الخصائص الجيولوجية وعمليات التعدين على حد سواء.لضمان تنمية مستدامة، ينبغي إعلان هذه المنطقة جيومنتوها حيث يتم تشجيع الأنشطة الجيولوجية مع تقنينها. إضافة إلى حماية وتقييم ثروة الموارد الحفرية، فإن بيانا مماثلا سيكون مفيدا للاقتصاد بالنسبة للساكنة المحلية، التي يعتبر جمع الحفريات نشاطها الرئيسي إلى جانب الزراعة والرعي.

Keywords

Morocco • Phosphates • OCP group • Geological and palaeontological heritage • Geotourism • Geopark • Sustainable development

Motsclés

Maroc • Phosphates • Groupe OCP • Géopatrimoine • Géotourisme • Géoparc • Développement durable

الكلمات الرئيسية

المغرب • فوسفات • مجموعة المكتب الشريف للفوسفاط • جيوتراث • جيوسياحة • جيومنتزه • تنمية مستدامة

1 Introduction

Morocco lies at the juncture of Africa and Europe, bordered to the north by the Mediterranean Sea and to the west by the Atlantic Ocean. The country has a diverse geography and climate, from the temperate Rif, in the north zone, to the Sahara Desert in the south. In addition, the geological heritage is so rich that early French explorers described Morocco as a "*Paradis des géologues*" (geologist's paradise). Indeed, the geological record of Morocco spans more than 2,700 Ma from Precambrian (Archaean) to the Quaternary (Fig. 1). Morocco has yielded fossils of many kinds, and human fossil remains such as *Homo erectus* (Salé, Thoma's quarry), modern *Homo* (Jbel Irhoud), and the possible presence of Neanderthals (*Homo neanderthalensis*) as indicated by retouched artifacts in the cave Cabililla of Benzú, Ceuta enclave, testifying common socio-cultural relations on both sides of the Strait of Gibraltar during the middle and upper Pleistocene (Ramos 2013). If confirmed by fossils, these North African Neanderthals would be the first hominids to have populated Europe.

Thus, in addition to the many scientific endeavours already underway, Morocco has the potential to sponsor cultural activities such as *Geotourism*. Geotourism is a promising and environmentally-sustainable business endeavour that will focus on the natural beauty of landscapes and the world-renowned richness of Moroccan minerals and fossils. If properly managed, geotourism promises to promote business development while also elevating global awareness of the value and preciousness of Moroccan environmental resources.

The presented proposal focuses on the late Cretaceous and lower Paleogene phosphate deposits, which are natural resources that play an essential role in the national economy. Promising opportunities emerge from the rich geoheritage of these deposits. These opportunities would involve:

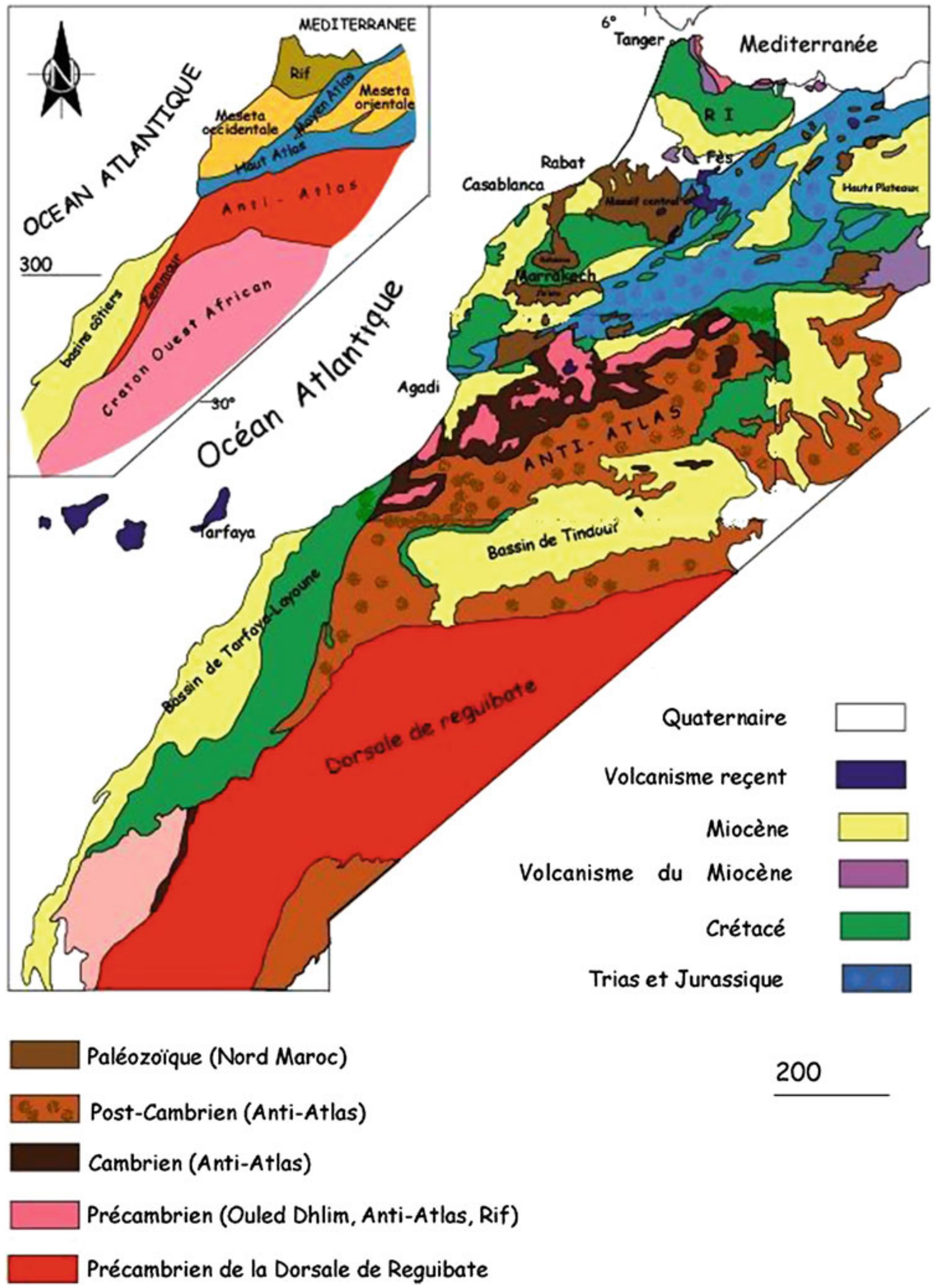

Fig. 1 Main geological domains of Morocco

- \- The *Protection* and *conservation* of the country's palaeontological heritage. - The *Promotion of sustainable development*. - The *Education* of the general public and students, by familiarizing them with the richness and value of the palaeontological heritage.

Morocco is the world leader in the production of phosphate and its derivatives. The phosphate deposits are exposed in four basins, which, from the North to the South, are (Fig. 2): Ouled Abdoun, with the mining town of Khouribga; Ganntour, with the towns of Youssoufia and Benguerir; Meskala, a small basin without great economic importance East of the town of Essaouira; and Oued Eddahab in the Moroccan Sahara, with Laäyoune as the administrative-mining town with the Port.

The Moroccan phosphate series consists of an intercropping friable, to more or less indurate, phosphate horizons with sterile layers of a varying lithology [clays, marl, limestone and flint in patches or scattered (Fig. 3)]. One of the interesting characteristics of Moroccan phosphate deposits is that the layers are generally horizontal except in proximity to the Atlas Mountains (such as in Imin Tanout, near the town of Marrakech), which facilitates easy and detailed sampling (Fig. 4).

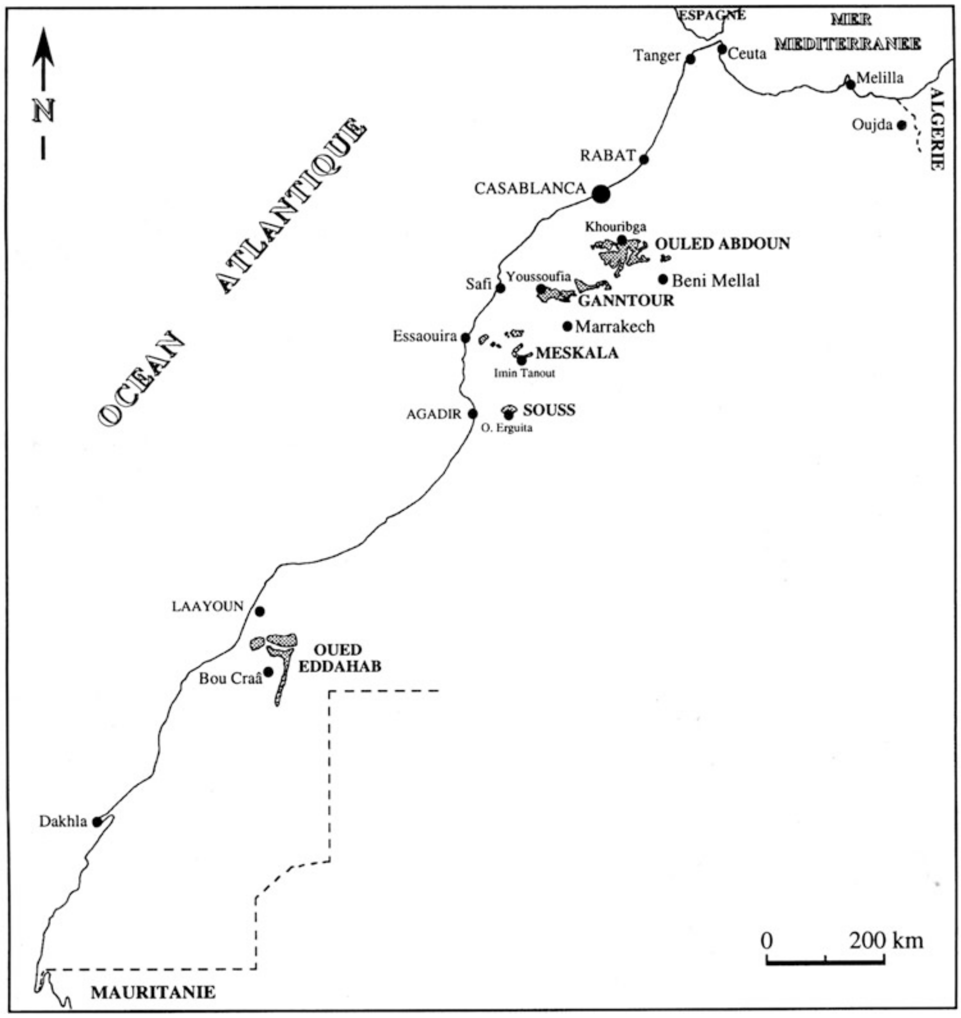

Fig. 2 Phosphate basins of Morocco (Noubhani and Cappetta 1997)

2 Palaeontology of the Phosphates

In Morocco, marine phosphates had been deposited from the late Cretaceous (Maastrichtian) through the lower Paleogene (Eocene), for over 25 Ma. They are world famous for the abundance of fossil remains, mainly selachian fish, the group of sharks and rays whose teeth have been collected in large quantities, and have an historical value. Indeed, the stratigraphy of these deposits was established in the 1930s–1950s through systematic study (Arambourg 1935, 1952). They have, subsequently, been intensively studied for more than 40 years (Herman 1973; Cappetta 1981, 1983, 1992; Noubhani 1993, 2010; Noubhani and Cappetta 1992, 1997, 2002). In 1993 a systematic faunal list was developed which includes 218 species (Noubhani 1993; Noubhani and Cappetta 1997). This list is, however, far from exhaustive, having since been expanded to include approximately 250 species (Bardet et al. forthcoming).

Reptiles are well represented in Moroccan phosphates with approximately 50 species divided between turtles, squamates (snakes; Rage and Wouters 1979), crocodiles (Arambourg 1952; Jouve 2004; Jouve et al. 2005), sauropods (some bones, a femur; Pereda Suberbiola et al. 2004), plesiosaurs (cervical vertebrae) and elasmosaurs (Vincent et al. 2011), mosasaurs including the formidable marine predators at the end of the Cretaceous (Bardet et al. 2004, 2005, 2010), and pterosaurs, extinct flying reptiles (Pereda Suberbiola et al. 2003; Bardet et al. forthcoming).

Five species of birds have also been recognized, which may represent the oldest modern seabirds in Africa (Bourdon 2006, 2011; Bardet et al. forthcoming).

Fossil mammals of the Moroccan phosphates have been popularized by the discovery of the oldest proboscidean known, *Phosphatherium escuilliei*, published in the journal, *Nature* (Gheerbrant et al. 1996; see Fig. 5). This proboscidean species, close to the ancestral stock of living elephants, was first described on the basis of an upper jawbone, which

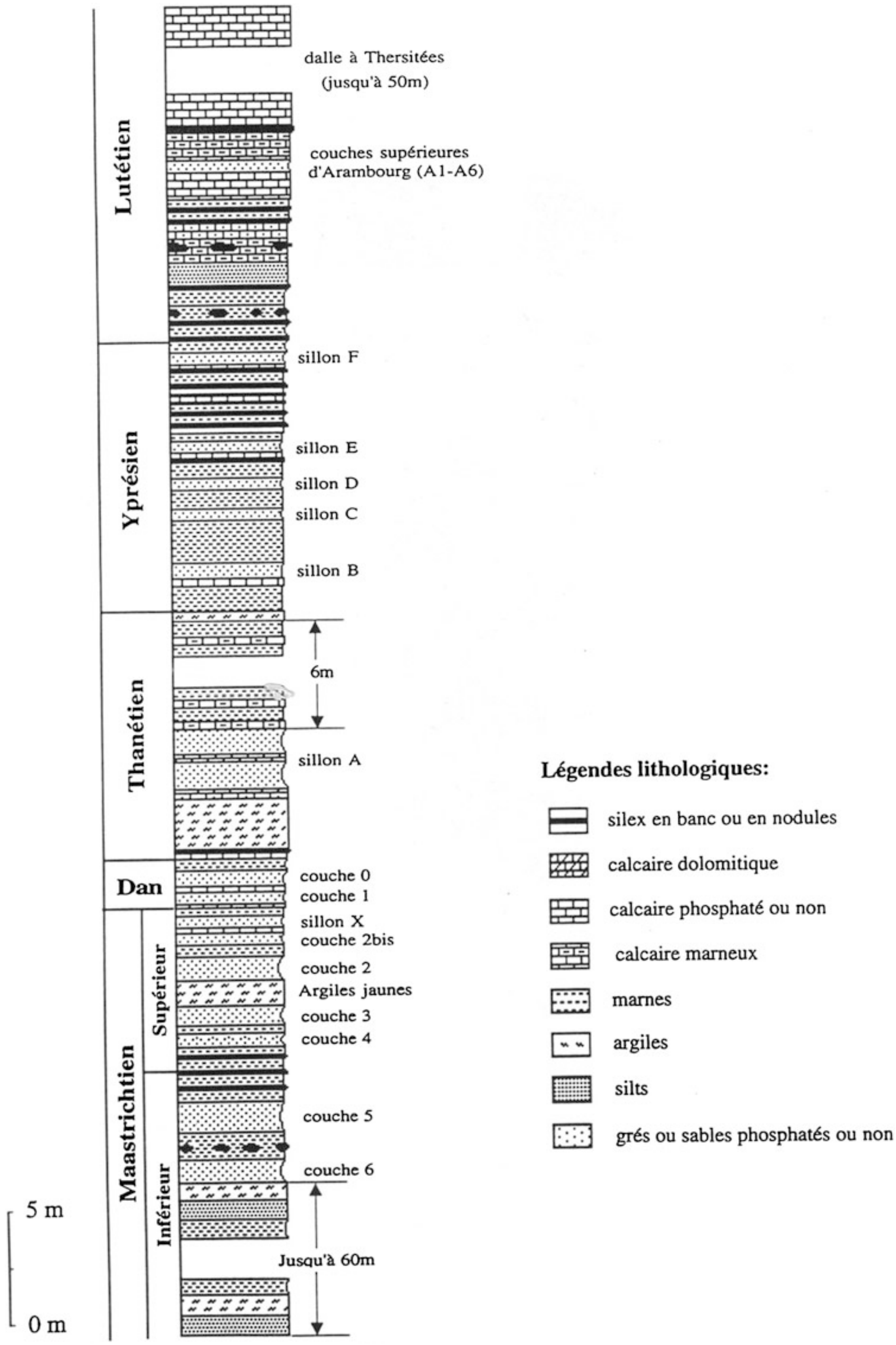

Fig. 3 Synthetic lithostratigraphic section in the Ganntour basin (Noubhani and Cappetta 1997)

brought to the forefront, for the OCP Group, the great scientific and economic importance of the palaeontological contents of the phosphates deposits. Indeed, this maxillary bone was bought in a French fossil market, underscoring the close relationship between the commercial fossil trade, in Morocco, and important scientific discoveries. Along with *Numidotherium koholense* Jaeger 1986 (Fig. 6), another proboscidean species from the middle Eocene of Algeria described 10 years earlier (Mahboubi et al. 1984, 1986; see also Noubhani et al. 2008 for the biometrical study of the quite important population), these fossils still represent the oldest representatives of the order *Proboscidea*.

Other mammalian fossils (about 10 species) have also been recovered representing individuals that belong to the orders of hyaenodontids, hyracoids and condylarths (Gheerbrant et al. 2002, 2006). They may be among the

Fig. 4 Section showing the horizontality of phosphate layers (Ouled Abdoun basin)

Fig. 5 *Phosphatherium escuilliei* Gheerbrant et al. 1996

oldest placental mammals of Africa and the oldest modern ungulates known in the world (Bardet et al. forthcoming).

The copious collections made by the OCP Group, with the cooperative excavation work of the local populations (Ouled Bou Ali and Ouled Bou Aziz...), will be exhibited in the planned "*Museum of Palaeontology*", and amounts to an illustration of these extraordinarily fossil faunas that are unmatched worldwide in their breadth and completeness.

3 Geotourism Opportunities

Morocco adopted the "National Charter of Environment and Sustainable Development", on April 22, 2010. Therefore, the project proposed here dovetails well with this current focus of the Moroccan government, which lays the groundwork for enlarging the country's national collections of palaeontological and geological discoveries for museum exhibitions. Such growth can also encourage sustainable development of Morocco's geological and palaeontological heritage, with the project being particularly promising from an educational point of view.

In this respect, the OCP Group has, recently, placed several social and economic actions on the agenda of its citizen policy, in order to rehabilitate, sustainably, old mining sites. Indeed, in September 10, 2007, the "*Green Mining*" project was launched by the king Mohamed VI. This project is of great importance following the examples of ecological towns (or an "*Ecopolis*"), as built in other countries such as *Dongtan* (China), *Akademia* (Russia) and *Masdar* (Abou Dhabi).

The OCP Group project relies on the establishment of two museums:

1. *A mining museum* which will display the history of the exploitation of phosphate ore, including an underground gallery, as well as a pilot trench, an example demonstrating

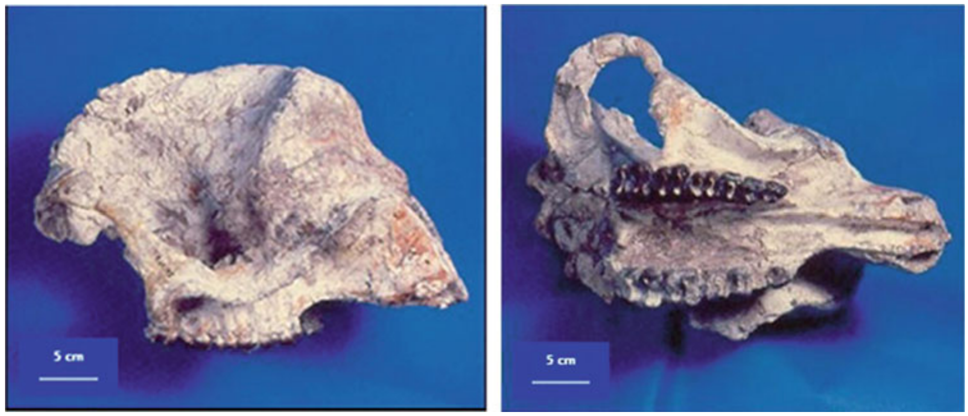

Fig. 6 *Numidotherium koholense* Jaeger 1986 in lateral and occlusal view

the stratigraphy of the deposits at various stages of exploitation.

2. *A palaeontology museum* for the exhibition of the more than 25 Ma of geologic history and faunal evolution recorded in the Moroccan epicontinental sea at the north margin of the Western African Craton (the "*Phosphates*' *Sea*" of Salvan 1986).

Following these worthwhile initiatives, it would be of value to incorporate some phosphate deposit areas into a geotourism trail. For this, it is thought that such areas should be declared a *Geopark* which will increase sustainable development and contribute to the:

1. *Conservation* of the country's palaeontological heritage by reducing the illegal sale of fossils.
2. *Geotourism* by fostering development of structures within the local economy that will generate new jobs and additional sources of income such as the construction of hotels and restaurants, which would benefit residents by promoting local services and employment, and by encouraging the production of local products (e.g. handicrafts).
3. *Education* by familiarizing the public with the palaeontological heritage of its country. This endeavour will also present an opportunity to bring students closer to Earth Sciences, particularly students who have lost motivation subsequent to the introduction of the LMD (License-Master-Doctorate) system, which has restricted links between Life and Earth sciences.

Indeed, it recently became difficult, if not impossible, to have students dedicated to carrying out research in the field of palaeontology. This challenge renders this discipline as extinct as the fossils that are its subject of investigation. Initiatives to construct geoparks would, certainly, stimulate students and encourage them to pursue studies in the field of palaeontology.

In the concept of a geopark, the planned museum of palaeontology would incorporate fossiliferous mining areas by drawing on experiments pioneered in other countries as a model, such as the Royal Tyrrell Museum (Drumheller, Canada) and Dinosaur National Monument (Utah, USA). For example, in the USA there is a large phosphate mine in Aurora, North Carolina (Potash Corporation) where the company allows supervised collecting by groups on specific days (C. Underwood, Professor at Birkbeck University of London, pers. com.).

By the celebrity of their extraordinary fossils, the Oued Zem and Sidi Chenane localities, within the Ouled Abdoun basin, are good candidates for such a purpose.

3.1 Moroccan Phosphates and the End-Mesozoic Biological Crisis

Morocco is unique in the world, in having a series of fossiliferous marine phosphate deposits that span, continuously, without sedimentary hiatus, from the end of the late Cretaceous (Maastrichtian) up to the base of the middle Eocene (Lutetian). This time span incorporates approximately 25 Ma. It should, therefore, record the famous stratigraphic boundary and biological crisis known as the K/Pg boundary, dated at 65 Ma. The impact of this biological crisis can be observed in the selachians' faunas, in which 96 % species of sharks and rays did not survive the K/Pg boundary (Noubhani 1993, 2010; Noubhani and Cappetta 1997). Thus, by crossing this stratigraphic boundary, tourists will see, in situ, the replacement of extinct species by new species, and also reptiles change at this boundary especially the formidable Mosasaur that haunted all the world seas.

4 Conclusion

The reknowned richness of fossils in Moroccan phosphate deposits could be enhanced by development of cultural activities such as geotourism, by the declaration of certain sites within the mining areas as a geopark. Considering the current focus of the Moroccan government, incorporating such a project into the sustainable ecological development strategy, recently outlined by the OCP Group and the Moroccan government, make it highly feasible, and potentially successful.

This promising and environmentally sustainable business endeavour would contribute to sustainable development by generating economic opportunities for local populations (hotels, restaurants, local products, etc.). It would also elevate global awareness of the value of Moroccan environmental resources as well as encouraging students to pursue studies and research in the field of palaeontology. Nevertheless, it should be noted that a geopark can only be economically viable if proper institutional support of the local communities and NGOs are involved. Furthermore, much can be learned from examples of pilot projects in countries that might be taken as a model of sustainable development.

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El Kef, Conservatory of the Memory of Earth and Humans in Tunisia: A Geodiversity to Discover and a Heritage to Protect

El Kef, mémoire de la Terre et des humains en Tunisie: Une géodiversité à découvrir et un patrimoine à protéger

الكاف، موقع لحفظ ذاكرة الإنسان والأرض بتونس
جيو تنوع جدير بالتعريف والحماية

N. Ben Haj Ali, L. Memmi, and M. Ben Haj Ali

Abstract

El Kef region, located in the northwestern part of Tunisia, is of exceptional geoheritage value. It comprises a substantial number of sites that are remarkable in terms of their scientific quality, rarity, aesthetic appeal and educational value. The long period of time recorded in the rocks (245 Ma ago to the present) has rendered it a subject of scientific study for more than a century. The diversity of rocks and fossils reflects the variety of sedimentary environments. Many sites of high educational value were identified. In this paper, we draw particular attention to eight geosites, namely Koudiat El Mrira, Hammam Mellegue, Dyr El Kef, Table of Jugurtha, Oued Mellegue Dam and Jebel Jerissa Mine, the Lower Paleolithic Sidi Zine site and Neolithic Sidi Mansour caves. This preliminary inventory of geosites aims to increase the awareness of local populations and decision-makers about the necessity to inventory, protect and promote the sites of geoheritage significance for a local sustainable development.

Résumé

La région d'El Kef, située dans la partie nord-ouest de la Tunisie, est dotée d'un géopatrimoine d'une valeur exceptionnelle. Il comprend un grand nombre de géosites remarquables en termes de leur qualité scientifique, leur rareté, leurs valeurs esthétique et éducative. La longue période du temps enregistrés dans ces roches (depuis 245 Ma) l'a rendu un objet d'étude scientifique depuis plus d'un siècle. La diversité des roches et des fossiles reflète la variété de leurs environnements sédimentaires. De nombreux sites de grande valeur éducative ont été identifiés dans le cadre de ce travail. Dans cet article, nous attirons une attention particulière à huit géosites, à savoir Koudiat El Mrira, Hammam Mellegue, Dyr El Kef, Table de Jugurtha,

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barrage Oued Mellegue et la mine Jebel Jerissa, le site paléolithique inférieur de Sidi Zine et les grottes néolithiques de Sidi Mansour. Cet inventaire préliminaire des géosites vise à sensibiliser les populations locales et les décideurs sur la nécessité d'inventorier, de protéger et de promouvoir les sites d'importance géopatrimoniale pour un développement local durable.

ملخص

تتميز منطقة الكاف الواقعة في الجزء الشمالي الغربي من تونس بجيوتراث ذا قيمة استثنائية. فهو يضم عددا كبيرا من جيومواقع لافتة للنظر من حيث جودتها العلمية وندرتها وجماليتها وقيمتها التربوية. الفترة الطويلة من الأزمنة الجيولوجية المسجلة بالصخور (منذ 245 مليون سنة) جعلتها موضوع العديد من الدراسات العلمية لأزيد من قرن من الزمن. إن تنوع الصخور والمستحثات يعكس تنوع بنياتها الرسوبية. وقد تم، في إطار هذا العمل، جرد العديد من المواقع ذات القيمة التربوية الكبيرة. ونود في هذا المقال أن نُولِي عناية خاصة لثمانية جيومواقع، وهي كدية "المريرة"، حمام "ملاك"، دير "الكاف"، جدول "جوغرطة"، سد وادي "ملاق" ومنجم جبل "جريسا"، موقع العصر الحجري القديم السفلي لسيدي زين وكهوف العصر الحجري الحديث لسيدي منصور. تهدف هذه القائمة الأولية للجيومواقع إلى تحسيس الساكنة المحلية وصناع القرار بضرورة جرد وحماية وتعزيز مواقع الجيوتراث الهامة من أجل تنمية محلية مستدامة.

Keywords
El kef • Tunisia • Geoheritage

Mots-clés
El kef • Tunisie • Géopatrimoine

الكلمات الرئيسية
الكاف • تونس • جيوتراث

1 Introduction

The study area, situated around El Kef city in the governorate of Kef, is located in the northwestern part of Tunisia, close to the eastern Algerian border (Fig. 1a). Covering more than 4,965 km^2, it belongs to the High-Tell between the Ouargha massif to the north and the Tajerouine plateau to the south. It is divided into two natural regions, to the west and north, a hilly landscape region with the Dyr El Kef (1,084 m) as the highest point and the Jugurtha Table (1,271 m) in the southeast. The region is crossed from the SW to the NE by tributaries of the Medjerda and Mellegue rivers. To the southeast, it has a less prominent landscape comprised of plateaux and low hills between the valleys of the Oued Medjerda and those of its tributaries (Mellegue, Sarrath, Rmel). The altitude of the region varies from 300 to 1,271 m above sea level, with very distinct seasons and very variable precipitation during the year. The governorate of Kef is characterized by a continental climate. Winter has low temperatures, among the lowest in Tunisia, and there is a frequent and regular snowfall on the hills.

Although, relatively more populated in the past, the region today presents a negative growth because of the rural exodus. The population comprises 58,000 inhabitants (13,000 in rural areas and 45,000 in El Kef city). The population density is about 51 inhabitants per km^2.

El Kef region is a zone where forests prevail on the heights (suber oak, and pine of Aleppo) and there is thick undergrowth (cistus, rosemary, green oak and heather). Most of the economy is based on agricultural activity centred on cereal and pasture-lands.

El Kef Governorate presents great diversity in landscapes and varied natural housing environments. It has two natural national reserves; the most important one being the reserve of Jebel Seddine located 20 km in the South of El Kef city.

This contribution aims to highlight the natural and cultural richness of El Kef region and to raise awareness about the necessity for the protection and the valorization of its geoheritage values which are of international importance.

2 Geological Setting

The geological outcrops in the study area are relatively easily accessible. Consequently, during the 19th century, the region attracted numerous geological researchers and acquired international importance for its richness in palaeontology and mineralogy.

The geology of the area includes 245 Ma of the Earth's history (from the Triassic to the present) and it shows a contrast between an area of mountainous and hilly landscapes in the north, belonging to the Cretaceous base of the

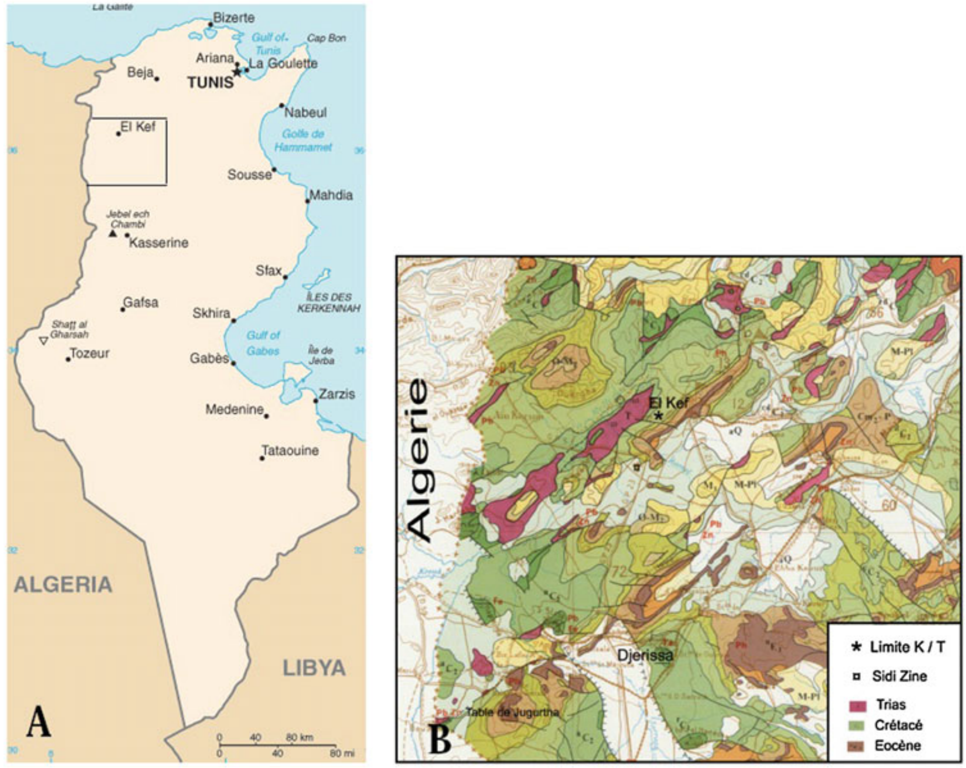

Fig. 1 **a** Geographical location of Tunisia and position of El Kef area. **b** Geological map (detail of Fig. 1a) (From geological map of Tunisia at 1/500,000)

Tunisian Atlas, and an area of flat and tabular landscapes in the south, characterized by the superposition of the very fossiliferous Mesozoic and Cenozoic formations (Fig. 1b).

The oldest deposits exposed in the area are the Mesozoic formations, with the Jurassic and a part of the Lower Cretaceous missing. The stratigraphic series is marked by the preponderance of the upper Cretaceous and Palaeogene, mainly in the western part of El Kef area.

The region includes the largest mining area in central western Tunisia. It is rich in iron, lead and zinc. It contains the largest iron-ore field in the country, i.e., Jebel Jerissa. It is also known for its hot springs, two of which are noted for their therapeutic values. The most famous of these springs is Hammam Mellegue which is a traditional public bath, once used by the Romans as evidenced by the remains of the old thermal baths.

The region has a unique human heritage which includes the famous Palaeolithic site of Sidi Zine and the Neolithic site of Jebel Sidi Mansour where paintings depict early human settlement.

El Kef governorate has long been known for its palaeontology. A museum planned for the future to be called "Memory of Earth" will exhibit a wide variety of rocks, minerals and fossils described or collected from geological sites in the region. It provides an opportunity for continuing research because the region has numerous fossil deposits of vertebrate and other fossils and contains many archaeological sites. It also offers opportunities for collaboration with national and international university teams. This museum will also provide information on water resources, thermal and mineral water as well as mining resources (Fe, Pb, Zn) and other useful materials.

3 Geosites Description

The preliminary inventory allowed us to choose 8 geosites to be described in this paper (Fig. 2). The choice was based on their scientific and cultural importance (Table 1).

3.1 Triassic Formations of Koudiat El Mrira (G1, Fig. 2)

On the right bank of Oued Mellegue, the Triassic-deposits of Koudiat El Mrira comprise clay-gypsum and calcareous sandstone with two spilitic diabase flows that are accompanied by subaqueous projections (pillow lavas or tuffs). This stratigraphic sequence is dominated by evaporites, cropping out in the core of the anticlinal structures as diapers or as blades along SW-NE orientations. The geosite consists of yellow dolomite, lamellar and saccharoidal gypsum, with bipyramidal quartz crystals, pyrite dodecahedrons and dolomitic rhomboids. These yellowish dolomites have yielded

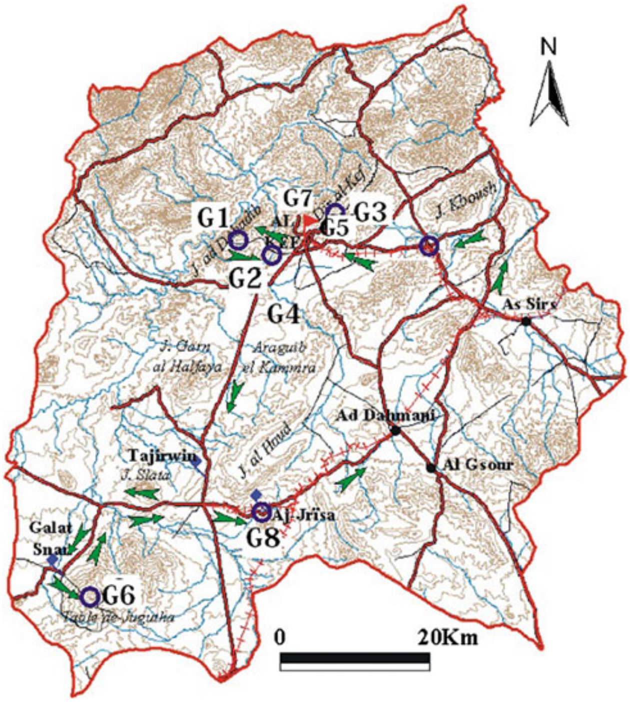

Fig. 2 Inventory geosites in El Kef area (Tunisia)

Table 1 Chosen geosites

Geosites	Interest of the site
Triassic formations of Koudiat El Mrira	The oldest deposits of Mesozoic age in the region
Hammam Mellege track section	Showing reference type section (global stratotype section and point GSSP) for the Cretaceous-Tertiary (K/Pg) boundary in the Tethyan region
Dyr El Kef	An Eocene syncline
Lower Palaeolithic of Sidi Zin	Archaeological and historical interest
Neolithic Sidi Mansour caves	Archaeological and historical interest
Table of Jugurtha	An Eocene syncline with historical interest
Oued Mellegue dam	Hydraulic reservoir, the first dam in Tunisia
Jebel Jerissa mine	The most important area in mineral exploitation in Tunisia

Myophoria goldfussi, *Lopha montiscaprilis*, *Gervillea* sp. indicating a Ladinian and Carnian middle Triassic age (Burollet and Sainfeld 1956). This site exposes the oldest deposit (of Mesozoic age) in the region. It shows beautiful cross-sections of Triassic formations packed in gypsum and its contacts are rich in needles of black tourmaline and small crystals of quartz.

3.2 Section of Hammam Mellegue Track: The Cretaceous/Tertiary Boundary (G2, Fig. 2)

This section was selected as a reference type section (Global Stratotype Section and Point GSSP) for the Cretaceous-Tertiary boundary (K/Pg) in the Tethyan region (Dalbiez 1956; Donze 1979; Keller 1988a, b; Rocchia et al. 1992, 1995; Cowie et al. 1989). At the top of the upper member of the Abiod Formation (Upper Campanian-Lower Maestrichtian), there is dark grey, brown laminated clay and marl with a few thin intercalations of limestone in the lower and middle parts. This section is the El Haría Formation (Maestrichtian to Upper Paleocene). Marl deposits yield microfauna of the *Globotruncana falsostuarti* and *Abathomphalus mayaroensis* zone which indicates the uppermost Maastrichtian. There are also some intercalations of limestones with ammonites (*Desmophyllites* sp.).

The exact boundary between the Cretaceous and Tertiary (Fig. 3) corresponds to a millimetric thin layer of reddish clay, rich in iron oxide and extraterrestrial materials (iridium and nickel magnetites and spinels (Robin et al. 1998). This layer records the effect of the great cosmic event that occurred 65 Ma ago (Keller and Lindinger 1989). Experts consider this section as the most comprehensive type section across the Cretaceous-Tertiary boundary because it records quiet and continued sedimentation in a deep marine environment. The section shows the effect of a meteorite impact

Fig. 3 Cretaceous/Tertiary boundary at the Hammam Mellegue track section

on organisms living at the time. It is inferred to have caused one of the largest mass extinctions on our Planet, causing the disappearance of dinosaurs and many other organisms (several groups of marine invertebrates such as ammonites, belemnites, rudists, inoceramids, and a number of planktonic foraminifera).

Above this sedimentary sequence, the marls yielded the microfauna of *Globigerina eugubina* and *G. fringa* that characterise zones from the basal Danian. This is followed by the *M. pseudobulloides* zone, an indicator of the Danian, within a stratigraphic member generally comprised of dark grey clays and thin white or beige limestones with corals, brachiopods and lamellibranchs in the lower layers. The microfauna are from *M. pseudobulloides* zone and *P. compressa* subzone. This sequence is overlain by clays of the upper member which yields fossils of the *Trinidadensis* and *Inconstans* zones at the top (Dalbiez 1956; Ben Abdelkader 1995).

3.3 Nummulitic Rocks of Dyr El Kef Syncline (G3, Fig. 2)

The time interval of Palaeogene covers about 20 Ma and can be observed in several places. The Lower Eocene is overlain by thick nummulitic rocks which show an evolution of the environments since the Palaeocene (~65 Ma) (Fig. 4). At the base, there are marls with a few limestone beds intercalated with phosphate layers and glauconitic marls, initially indicating more or less deep marine sedimentation but progressing towards Eocene platform environments.

The geosite exhibits accumulations of the foraminifer *Nummulites* (*Nummulites rollandi* Fisher and *N. irregularis* Desh) (Burollet and Sainfeld 1956). The number of fossil species, the variations of their shape and size, the degree of transport and their associations with other fossils and rock types, have been used to reconstruct the sedimentary environments, the depth, the former hydrodynamic energy, the climate and the Tunisian palaeogeography, and to improve the knowledge of petroleum systems. At Jebel Dyr, the upper part of the Eocene shows moderately thick alternating marl, sandstone and limestone rich in oysters (*Ostrea bogharensis*, *O. roncona*), the latter indicating a Lutetian age (Souar Formation).

The Upper Eocene shows a gradual evolution to regression and general emergence. In Oued Rmel region, brown beds of sandstone, sand, and sandy clay represent the Oligocene according to Burollet and Sainfeld (1956), with the Oligocene period marking a broad denudation. This emergence, associated with an important tectonic phase, is well marked by transgressive Miocene layers.

3.4 Sidi Zin Paleolithic Site (G4)

El Kef region is exceptional for its prehistoric archaeology recording human presence as early as the lower Palaeolithic (the bifaces civilization). There was an industry associated

Fig. 4 Nummulites accumulations of Eocene limestone at Dyr El Kef syncline

with different types of man-made pebble bifaces and cleavers, and tools of predominantly African tradition, the work of the *Atlanthropus mauritanicus*. It comes from Sidi Zine, a site 9 km west of El Kef, and Koum El Magen, 20 km north of El Kef (Touiref). Sidi Zine has also yielded the bones of elephants (*Elephas atlanticus*), with gazelles (*Gazella dorca* and *G. cuvieri*), rhinoceros (*Rhinoceros simus*), antelopes, zebras, etc. indicating a hot and humid climate. This Chad-Zambezian fauna inhabited savanna, swamps and forests, and served for hunting. At Sidi Zine, three levels of remains of the lower Palaeolithic are covered by tuff that yielded a Mousterian industry of Middle Palaeolithic age (100,000–35,000 BC): yielding scrapers, blades, and points. Between Tajerouine and El Kef (Oued El Ogla) sampling sites have yielded bones and pieces of pottery from the Mediterranean Neolithic made by *Homo sapiens* (Gobert 1950; Vaufrey 1955; Tlili 2007).

3.5 Neolithic Caves of Sidi Mansour (G5)

Jebel Dyr, at Sidi Mansour (Fig. 5), consists of caves with paintings, Protohistoric megaliths and Neolithic industries. To the southeast of El Kef, remarkable megaliths, such as dolmens, were erected to mark the location of graves (Tlili 2006).

3.6 Table of Jugurtha (G6)

Jugurtha (160–104 BC) reunited the Numidia and formed a resistance against the Romans. He chose, as a place for the resistance, the Table of Jugurtha which rises to 1,271 m (Fig. 6a, b).

The Table is a large tabular body of Eocene nummulitic limestone that was deposited on clays of El Haría Formation (Maestrichtian-Paleocene). These subhorizontal limestones, 40–50 m thick, make up a wall, on its side cut off by 150 steps, halfway along which there is a door, the arc of which is of the Byzantine age.

The spectacular panorama at this site shows the Ouenza Mountains (Algeria) to the west, the plains and the hills of the Ouled Bou Rhanem to the northwest and the Oued Sarrath to the southeast.

Occupied since prehistoric times, as shown by the remains of ash, snails and flints, the plateau served on several occasions as a site of refuge as evidenced by the remains of water tanks and collective granaries of underground bunkers dug in the rock. There are also traces of habitation and a medieval mosque. Currently, the vegetation, though rare, serves as pasture-land for sheep. Twice a year, in spring and autumn, Sidi Abdel Jaouad Zerda commemorates the past feats and the Numidian heritage (Ayachi 2007).

3.7 Oued Mellegue Dam (G7, Fig. 2)

The Jebel Dyr Perched Syncline is a hydraulic reservoir in which water from precipitation (450–600 mm per year) infiltrates the much fractured Ypresian limestones (45 m thick). In the 3rd century, the Romans built a small temple (Nymphae) and a hydraulic structure dedicated to water engineering whose remains still exist. Located 6 km from

Fig. 5 Panoramic view of the caves of Sidi Mansour

Fig. 6 Table of Jugurtha (perched syncline) (**a**) and its spectacular panorama (**b**)

Nebeur north of El Kef, the Oued Mellegue dam was built from 1947 to 1957 to regulate the torrential course of the oued and to capture the exceptional rainfall and flood waters. The lake surface is 1,150 ha and has several uses. It is used for drinking water supply, irrigation of the plains (mainly cereals culture), recharging the groundwater, and producing electricity. However, every year, debris flows into the lake and traps sediments which reduce the capacity of the dam.

The Oued Mellegue Valley is incised into Cretaceous (Aptian to Senonian) rocks and the Oued Mellegue dam is on very high Aptian limestone dipping 60°–80°. The main dam consists on multiplying vaults that include five oblique semi-cylindrical vaults and five foothills. The reach of the vaults is 50 m with sluice of floods. The accessory dam is of dam-weight type. An overflow was built on the sluice of the floods.

The lake is populated by many freshwater fish such as carp and catfish and the surrounding terrain supports wildlife (birds, hares), both of which are used for nature-based leisure activities and hunting and fishing. A youth hostel and a tourist restaurant provide accommodation and food for sportsmen and amateur equestrians.

Fig. 7 The remains of mining and the Jerissa village

3.8 Jebel Jerissa Mine (G8, Fig. 2)

The Jebel Jerissa is an iron ore mine and is an example of mineralization related in large part to a fossil reef facies where the palaeogeographical factors have contributed to controlling mineralization and the development of the mine. The iron ore has been exploited since 1907. At the beginning, the exploitation was of surface materials but since 1960 ore has been mined from quarries or from underground. Since 1974, the Jebel Jerissa mine is the most important quarry operating in Tunisia.

The hematite of the iron ore has replaced the carbonates in the bioclastic limestones of the Serdj Formation that are composed of fragments of rudists, orbitolines, molluscs and algae alternating with oolitic layers.

The rocks hosting the mineralization are intersected by a NE-SW oriented zone of transverse faults along which there has been replacement of marl limestone by iron minerals. The mineralization is in lenticular clusters. From 1908 to 1974, clusters of goethite, siderite and oligiste (hematite) have been exploited, after which the siderite beneath the hydrostatic level was worked. Other deposits of El Kef area were exploited to provide ores of lead and zinc as the deposits of Sakiet-Sidi-Youssef, Touiref, Nebeur, Bou Grine (blende, galena, calamine, barite, fluorite, smithsonite) (Sainfeld 1952). Jebel Slata consists also of iron ores in which a new mineral species, the cesarolite (lead manganate), was first discovered. The remains of mining and the Jerissa village are now an industrial archaeological Park (Fig. 7). This heritage site has already been largely surveyed and assessed, and a geo-mining circuit can be established.

The region also has deposits of phosphates in the lower Eocene (Ypresian) as at Kalaat Khasba or Sra Ouertane. In many quarries limestone is being extracted, as in Jebel Houd, or used for establishing industries such as cement manufacture in Oum El Klil in the Tajerouine area.

4 Discussion and Conclusions

El Kef region, located in the northwest of Tunisia, has a rich and varied geological, palaeontological and cultural heritage. The geology of the area contains sedimentary formations deposited on the southern fringe of the Tethys Ocean. These rocks, most of which are fossiliferous, cover a time period from the Triassic to the Pleistocene.

The economic aspects of this area deriving from the applied geology, thermal springs and mineral waters, dams, mining, phosphate ore mining, and other economic materials, make it an economically viable region. The region also reflects a unique relationship between the geological, natural, and cultural heritages as it tells a story of the settlement of men on this site since prehistoric times, e.g., the Sidi Zin Paleolithic site and Neolithic caves of Sidi Mansour.

The geological heritage, the landscapes, and the rocks and fossils are an attraction for tourists and can serve as a basis for development of scientific and cultural tourism activities. Offering geotours, along the cited geosites, will provide a framework for the development of an eco-sustainable tourism and will be a significant added value to the socio-economic infrastructure of the region.

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Use of Website and GIS Databases for Enhancement of Geosites in Algeria

L'utilisation du Web et des bases de données SIG pour la valorisation des géosites en Algérie

استخدام مواقع الويب ونظم المعلومات الجغرافية لتعزيز قواعد البيانات بالجزائر

A. Bendaoud, M.C. Chabou, O. Kolli, O. Bouzidi, S. Djemaï, and H. Kaabeche

Abstract

Algeria is the largest country in the African continent. It contains a large number of sites with geological and geomorphological interest but, so far, the Algerian geological heritage is poorly known and needs to be protected and enhanced for education, tourism and scientific purposes. A "GeoAl" project has been initiated to compile an inventory of those major geosites with exceptional geological features in Algeria, to create a GIS database, and to promote Algerian geoheritage using the new technologies of information and communication. This database will be open access and will be beneficial to the public and researchers. The database also will allow users, through maps, to geologically explore the entirety of Algeria, identifying and investigating important sites with all the available information, including photos and scientific literature. The database will evolve gradually with the inventory and will also be used as a tool for the identification and the promotion of areas with high geological potential that could be managed as geoparks. These later areas constitute one of the most appropriate instruments for both protection of natural resources and creation of economic activities. Ideally, the database will benefit the development and the promotion of geotourism as a means for sustainable development in different remote areas in Algeria, and of craft and small businesses through the creation of activities necessary for the functioning of the concept.

Résumé

L'Algérie est le plus grand pays africain et contient un grand nombre de sites ayant un intérêt géologiques et géomorphologiques. Cependant, ce géopatrimoine est peu connu et nécessite d'être protégé et valorisé pour des buts scientifiques, touristiques et éducatifs. Le projet "GéoAl" a été initié pour inventorier les géosites algériens montrant des caractéristiques géologiques exceptionnelles, créer une base de données sous SIG et promouvoir le géopatrimoine algérien en utilisant les nouvelles technologies de l'information et de la communication. Cette base de données sera à accès libre et bénéficiera aux chercheurs et au public. Elle permettra aux utilisateurs, à travers des cartes, d'explorer géologiquement

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l'Algérie pour identifier et connaître les sites les plus importants avec toutes les informations disponibles, incluant des photographies et la littérature scientifique. La base de données évoluera graduellement avec la progression de l'inventaire et sera utilisée comme outil pour la localisation et la promotion des régions ayant un grand potentiel géologique qui pourront être géré en tant que géoparcs. Ces derniers constituent l'un des outils les plus appropriés pour protéger les ressources naturelles et créer des activités économiques. Idéalement, la dissémination de cette base de données contribuera à la promotion du géotourisme comme moyen pour le développement durable de régions reculées en Algérie, et la création de petites entreprises dans les activités nécessaires au fonctionnement de ces géoparcs.

ملخص

تعتبر الجزائر أكبر بلد افريقي، ويحتوي على عدد كبير من المواقع ذات الأهمية الجيولوجية والجيومورفولوجية. ومع ذلك فإن هذا الجيوتراث غير معروف بشكل أفضل، ويحتاج إلى حماية وتقييم لأغراض علمية، سياحية وتعليمية. لقد أُحْدِثَ مشروع "جيوال" لجرد الجيومواقع الجزائرية ذاتِ الخصائص الجيولوجية الإستثنائية، وإنشاء قاعدة بيانات بتوظيف نظم المعلومات الجغرافية وتعزيز الجيوتراث الجزائري باستخدام التكنولوجيات الحديثة للمعلومات والاتصال. قاعدة البيانات هذه سوف تُتِيحُ حرية الحصول على المعلومة المفيدة للباحثين والجمهور. وسيسمح للمستخدمين، من خلال الخرائط، اكتشاف جيولوجيا الجزائر لتحديد والتعرف على أهم المواقع مع كل المعلومات المتاحة، بما في ذلك الصور والمنشورات العلمية. وستتطور هذه البيانات تدريجيا مع تقدم عملية الجرد، وستستخدم كأداة لتحديد وتعزيز المناطق ذات إمكانية جيولوجية كبيرة، والتي يمكن إدارتها كجيومنتزهات. هذه الأخيرة تشكل واحدة من أكثر الأدوات المناسبة لحماية الموارد الطبيعية ولخلق أنشطة اقتصادية. فإن نشر قاعدة البيانات هذه ستساهم، بطريقة مثالية، في تعزيز الجيوسياحة كوسيلة لتحقيق التنمية المستدامة بالمناطق النائية بالجزائر، وإحداث مقاولات صغرى لإدارة أنشطة ضرورية لتشغيل هذه الجيومنتزهات.

Keywords

GIS database • "Geoal" project • Algerian's geosite

Mots-lés

Base de données SIG • "Projet geoal" • Géosites algériens

الكلمات الرئيسية

قاعدة بيانات نظم المعلومات الجغرافية • مشروع "جيوال، • جيومواقع جزائرية

1 Introduction

Algeria, the largest country in Africa with an area of 2,381,741 km^2; contains a wide variety of geological and geomorphological sites which are among the most significant on the continent (Fig. 1). The aesthetic quality of these geosites makes their preservation as well as their promotion for geotourism a major objective for the geoscientific community. Geoscientists have a great responsibility to help decision-makers and local communities become aware of the potential of these geosites. The sustainability of these georesources will have long-term consequences for scientific as well as recreational activities.

In the last few years, the creation and management of computer-based geological databases have become an urgent requirement for both fundamental and applied research such as mining geology, management of natural hazards, and preservation of geological heritage. Databases, which allow thematic mapping, involve a big amount of data (text, images, tables,…). Their advantage is that the user can make complex requests and have immediate results. They can be very useful for public authority, economic sector, scientific research, students and teachers (for these laters as pedagogical resources).

There is an exponential growth of data related to the geology of Algeria produced by different organizations, universities, geological surveys and research centers. The digitisation of these data allows a better organization for their management which results in a substantial saving for retrieval rates of specific information. Similarly, the use of New Information and Communication Technology, i.e., the publication online of these databases, helps to enhance Algeria's national and international profile. However, at this time, there is no such database, neither in public domain nor among the university community, allowing access to even the most important information on Algerian geosites.

After describing several sites, the objective of this paper is to provide a better sense of the quality and the geographical extent of the Algerian wealth of geological treasures. A secondary objective is to use the GeoAl project in order to compile an inventory of the geological and geomorphological sites of outstanding value in Algeria, to create a dynamic database, and to identify potential areas that could be promoted as geoparks. An additional aim of this paper is to promote the creation of Geoparks which are one of the most appropriate tools to protect Algerian geoheritage, and to enhance selected areas through the development of geotourism.

A Geopark is defined globally as a territory that includes a significant number of geological heritage sites i.e., geosites, because of their scarcity or aesthetic appearance. These Earth heritage sites are part of an integrated concept of protection, education and sustainable development. Contrary to legislation which exclusively aims to protect a site, a Geopark achieves its objectives through a three-pronged approach: "conservation, education and geotourism" (UNESCO 1999). This allows not only the direct involvement of the public authorities that create the legislation to preserve natural resources, but also the local communities, educators, universities, and non-government organisations (NGOs).

2 Description of Some Algerian Geosites

In this part of the paper, some areas with exceptional geological sites, which are part of the selected sites for inclusion in GeoAl database, will be described. These areas are suitable to be enhanced into Geoparks. This list is not exhaustive but the selected regions consist of outstanding geosites that give an overview of the Algerian geoheritage.

2.1 The Eocene-Quaternary Volcanism of Hoggar Massif

Eocene-Quaternary volcanism of Hoggar massif, covering an area over 10,000 km^2 is one of the magmatic districts among the most important in North Africa (Girod 1971; Dautria 1988). This intraplate volcanism cross-cuts an old Precambrian crust composed of granulite and amphibolite (Bendaoud et al. 2004) mainly of Paleoproterozoic age, with few Archaean fragments (Peucat et al. 2003; Bendaoud et al. 2008), and Pan-African granite (Liégeois et al. 2003). It crops out in various regions, including Egéré (2,800 km^2),

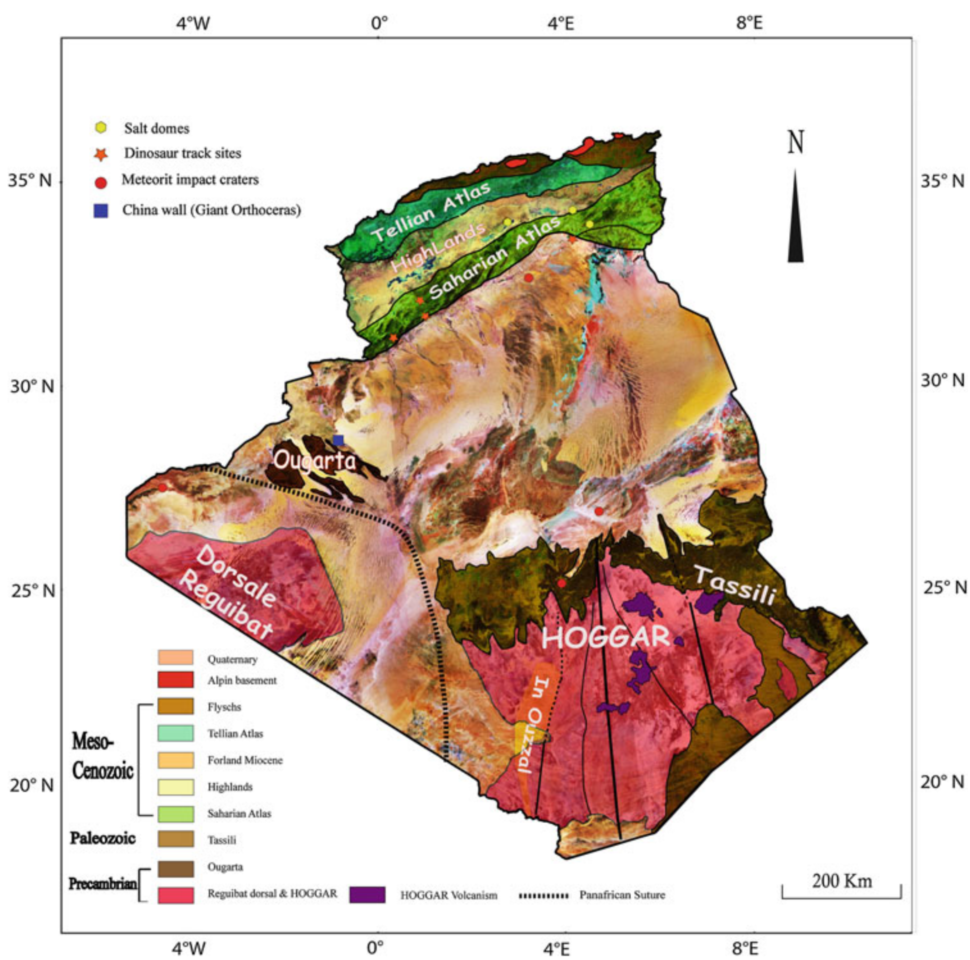

Fig. 1 Satellite image of Algeria (Landsat 7 ETM+) showing the main geological domains and location of several exceptional geosites

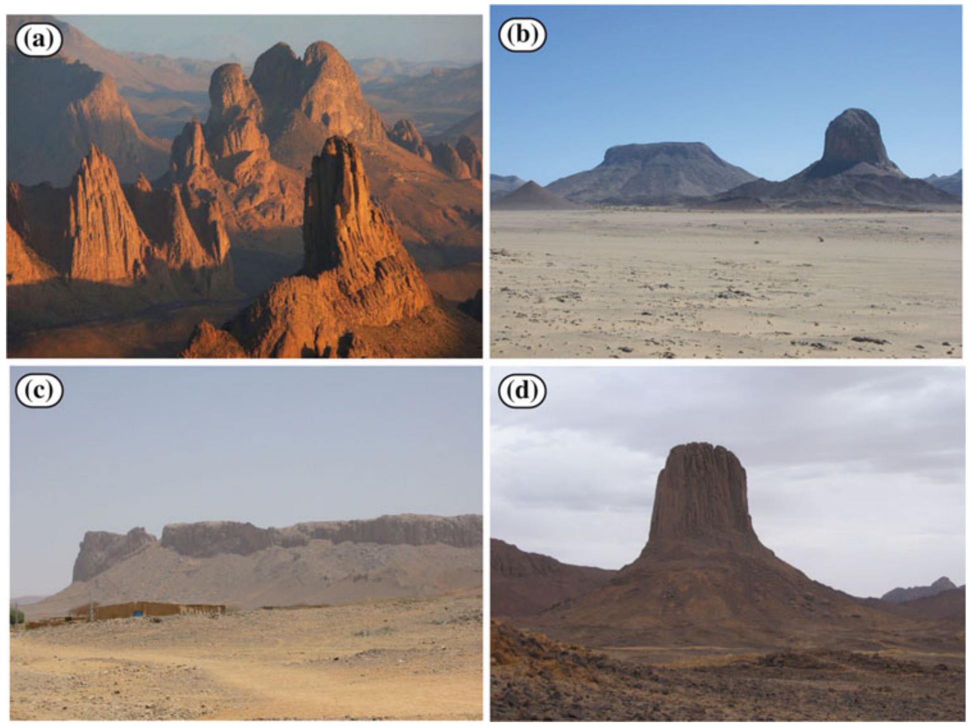

Fig. 2 The Eocene-Quaternary volcanism of Hoggar. **a** Panoramic view of Assekrem in the Atakor massif. **b** Iharen phonolitic plug with a phonolitic plateau background; **c** Hadriane trachytic plateau; **d** Trachytic plug near Tamanrasset

Adrar N'Ajjer (2,500 km^2), Atakor (2,150 km^2), Tahalra (1,800 km^2), Manzaz (1,500 km^2), Anahef (400 km^2), Teria (100 km^2), Djanet (50 km^2), and in Ezzane (800 km^2). According to Liégeois et al. (2005), the total extent of this volcanic episode exceeds 1,650 km^3. One of the most beautiful geosites with basaltic cones and a phonolitic plateau is the Atakor massif, which culminates at 3,003 m; it includes the Assekrem (Fig. 2a) where the hermitage of "frère" Charles de Foucault and his successors is situated. The volcanic activity of this district is Late Eocene-Early Oligocene (35–30 Ma), (Aït-Hamou et al. 2000) and has persisted to post-Neolithic times. Tuareg people tell stories about eruptions that their ancestors have witnessed.

The Atakor massif is an exceptional site that presents geological, cultural and educational interests. It includes the highest peak in Algeria, Mount Tahat that reaches 3,003 m; secondly, this massif constitutes an impressive natural museum for a diversity of igneous rocks (Girod 1971). Over an area of 2,150 km^2, there are a dozen varieties of igneous rocks, some of which are rare in the geological record; the most important igneous rocks are basalts, basanites, tephrites, hawaiites, mugearites, benmoreites, phonolites, trachytes and rhyolites (Girod 1971) (Fig. 2a–d). The area is also an important site because of the morphological diversity of the volcanic landforms (volcanic dome, strato-volcanoes, strombolian cones, necks, dikes, sills, lava flows with much contrasted morphologies due to erosion). In addition silicified wood dating from the Oligocene and lower Miocene has been reported in the Atakor massif (Rognon et al. 1983); and finally, from a cultural perspective, in Assekrem this massif houses the hermitage of Charles de Foucault and his successors, built in 1910 and located at 2,780 m above sea level.

2.2 Djanet and Tassili Massifs

Tassili is an extensive sandstone massif, some 750 km in length and 60–100 km wide covering 120,000 km^2. Consequently, it is considered to be the second-most important national park in Algeria and one of the most important in Africa because it extends beyond Algerian borders into Libya and Niger. It was carved into varied relief by fluvial erosion and wind action (Fig. 3a–c).

The highest uplands, with an altitude of up to 2,000 m, are dissected by canyons bordered with spectacular cliffs that reach 700 m in height. Occasionally, the rocks of the highlands, initially sculptured exquisitely by wind are covered completely by aeolian sands. The area hosts one of the most important groupings of prehistoric rupestral engravings. Thousands of drawings and engravings can be traced back to 10,000 BC recording changes in the climate, fauna and flora in this part of the Sahara (Fig. 3e, f). These interesting national resources have been listed among the World Heritage sites since 1982, and have been classified as a Biosphere Reserve in 1986.

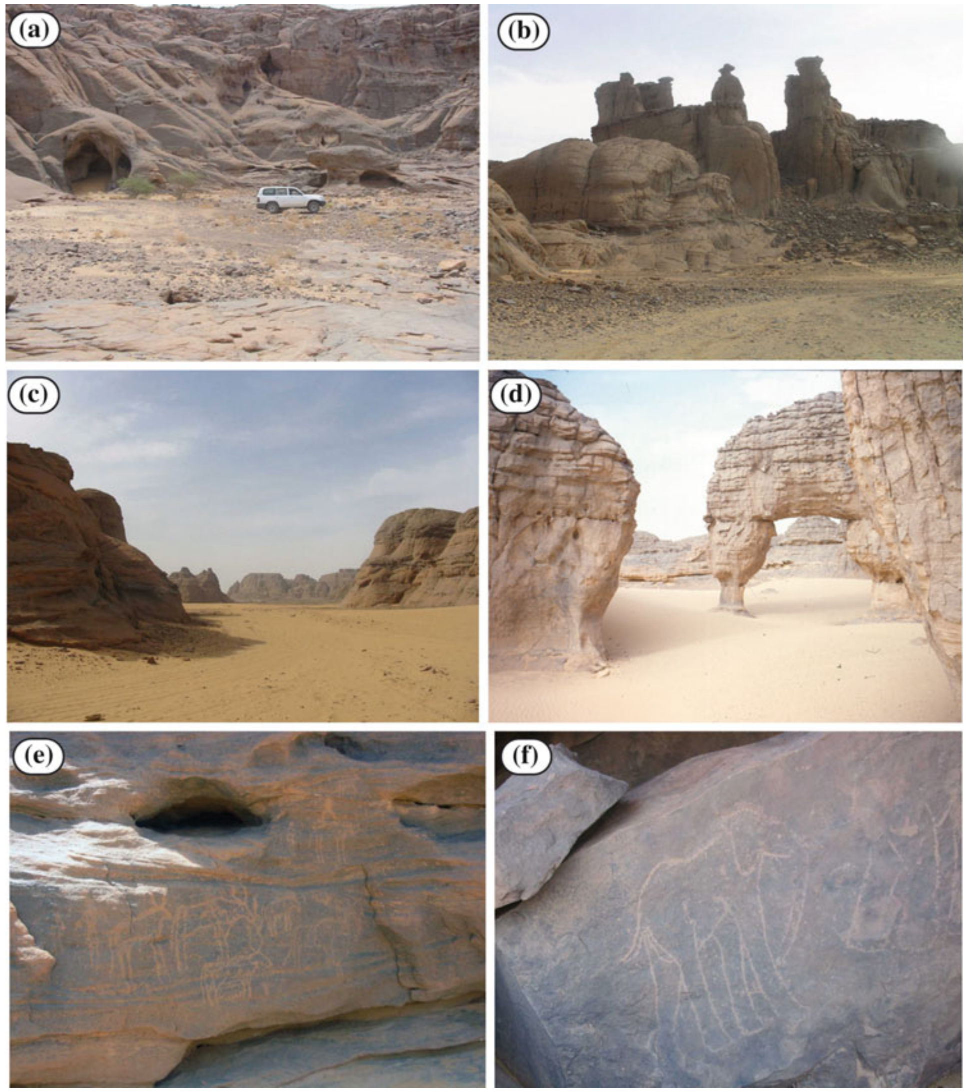

Fig. 3 Tassili **a**–**d** Various geomorphological types of Tassili sandstone (**a** Cliffs with grottoes; **b** "Cathedrals Walls", **c** Canyon, **d** Sculptures of elephants); **e** and **f** Tassili rupestral engravings (**e** Shepherd leading his flock and **f** Elephants)

Some of the important geosites that should be highlighted are as follows (Perret 1935):

(i) the canyon of Djaret wadi; its average width is about 200 m and its depth is *ca* 150 m; faults in the wadi extend over 60 km of length;

(ii) the canyon of Iherir wadi, resistant rock units have resulted in the preservation of the steep cliffs; at the bottom of deep gorges there is a wonderful oasis named Iherir;

(iii) among the most surprising rock formations of Tassili are the "stone forests" or *irrekanes* of Tuareg; they are huge sandstone outcrops standing on sandy wadis, like the bow of a ship; their landscapes, eroded and sculpted by the wind, sand and water, present a combination of weathering and erosion features; these 'stone forests' house the main rock painting sites; and

(iv) Djanet, the capital of Tassili, located in the northwest of Hoggar, is a city where the oldest part, now in ruins, is built on blocks of Pan-African granites; in the Valley of Idjeriou River is a beautiful oasis bounded by spectacular cliffs.

2.3 The Northern In Ouzzal Massif

Located in western Hoggar, the In Ouzzal terrane forms an elongated N-S trending block more than 450 km long and 80 km wide around the In Hihaou massif. It contains the oldest rocks in Algeria (2.7–3.2 Ga) (Peucat et al. 1996). It is an example of Archaean crust remobilized during very-high-temperature metamorphism related to the Paleoproterozoic orogeny (2 Ga). It is composed of two Archaean units, a lower crustal unit composed essentially of enderbites and

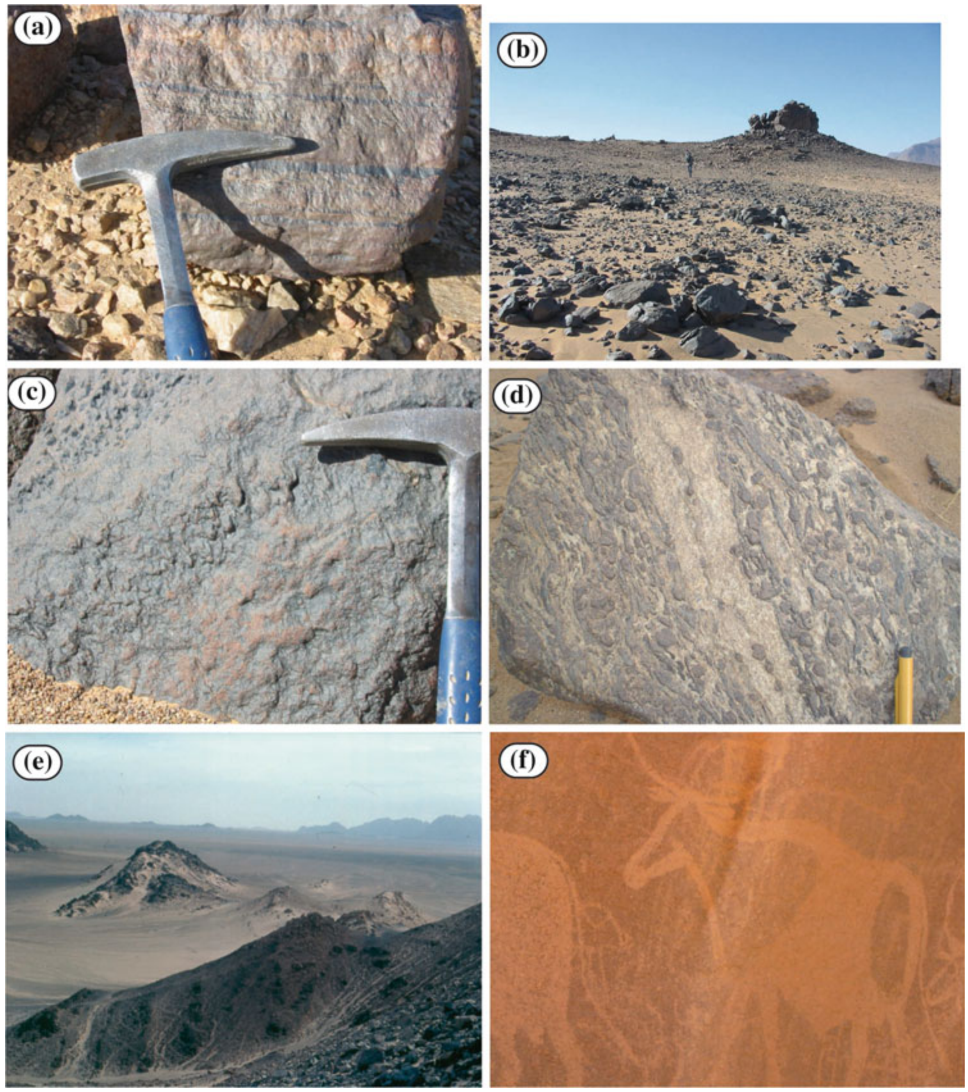

Fig. 4 North In Ouzzal Terrane: **a** Tin Tchik Tchik charnockitic TTG (dated at 3.2–2.7 Ga); **b** Alouki Greenstone belt; **c** Alouki Al–Mg granulites showing an ultrahigh temperature paragenesis; **d** Tekhamalt migmatitic Al–Fe granulites showing a ultrahigh temperature paragenesis; **e** Ihaouhaouène carbonatitic hills; **f** In Eher rupestral engravings

charnockites, and a supracrustal unit of quartzites, banded iron formations, marbles, Al–Mg and Al–Fe granulites commonly associated with mafic (metanorites and garnet pyroxenites) and ultramafic (pyroxenites, lherzolites and harzburgites) lenses (Ouzegane et al. 2003), greenstone belts (Fig. 4b–d). The continental crust, represented by the granulitic unit of In Ouzzal, was formed during various orogenic reworking events spread between 3,200 and 2,000 Ma. The formation of a continental crust, composed of tonalites and trondhjemites, took place between 3,200 and 2,700 Ma (Fig. 4a). Towards 2,650 Ma, extension-related alkali-granites were emplaced. The deposition of sediments (later to become metasedimentary protoliths) between 2,700 and 2,650 Ma, was coeval with rifting. The youngest Archaean igneous event at 2,500 Ma includes calc-alkaline granites resulting from partial melting of a predominantly tonalitic continental crust (Peucat et al. 1996; Ouzegane et al. 2003).

The Paleoproterozoic ultra-high temperature metamorphism associated with the Paleoproterozoic orogeny in this region (Ouzegane et al. 2003) is currently considered as one of the most extreme in world literature (Harley 2008; Kelsey 2008). In the late stage of this metamorphism, carbonatitic magmas were emplaced (Bernard-Griffiths et al. 1988; Fourcade et al. 1996, Fig. 4e). These carbonatites exposed in the Ihouhaouene area are special for several reasons: (i) Archaean and Paleoproterozoic carbonatites are rare in the world; (ii) they are the only ones that occured in such geodynamic context during the decompression phase after a prograde stage of a regional granulitic metamorphism (Ouzegane 1987; Fourcade et al. 1996); and (iii) they contain minerals, such as apatites which exceed 20 cm and are extremely rich in rare earth elements (Ouzegane, *personal communication*).

These geological sites mentioned above include a multitude of small archaeological sites with paintings and engravings (Fig. 4f), mostly on small Pan-African granitic massifs exposed in the region or in alkaline orthogeneiss; workshops for arrowheads and tumulus occur occasionally in this terrane.

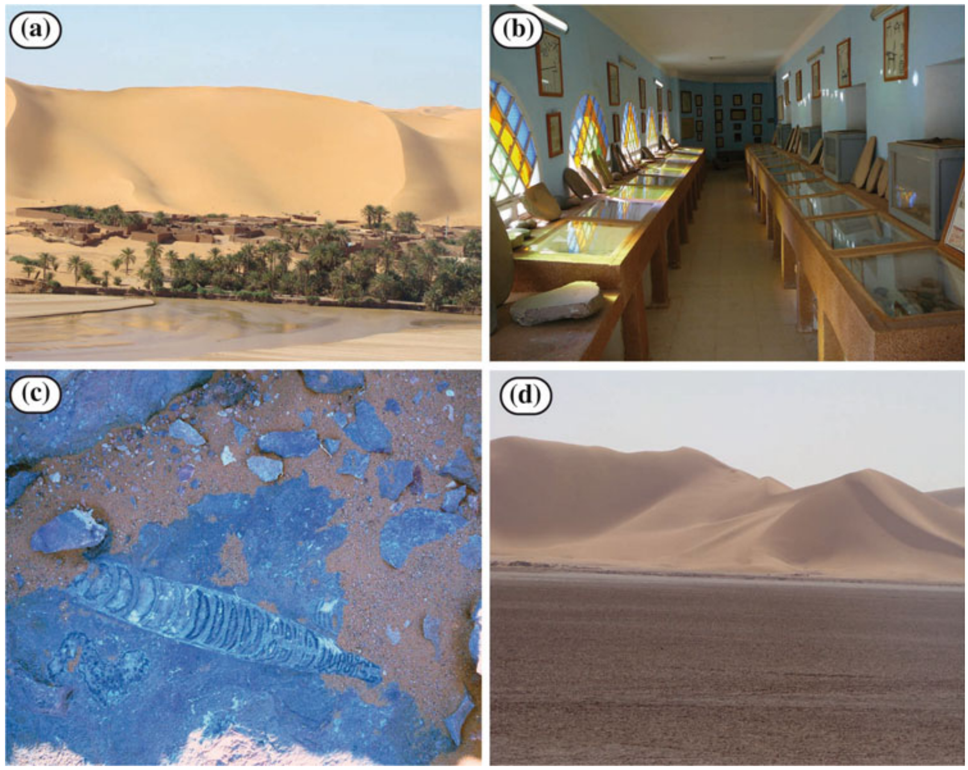

Fig. 5 Ougarta range **a** Beni Abbes Oasis; **b** Geological museum of Beni Abbes; **c** Devonian giant Orthoceras from "Muraille de Chine"; **d** Dunes from occidental Erg

2.4 The Ougarta Range

The Ougarta range, located in South-western Algeria, is a set of high ground oriented SE-NW about 250 km long and 100 km wide. It contains thick Paleozoic rocks (Cambrian to Devonian) that rest on a Precambrian basement. These series, deformed during the Hercynian orogeny, are folded into domes and synclines (Joly et al. 1991). The Ougarta is interesting because this is one of the few regions in Algeria where continuous exposure of Paleozoic series more than 7,000 m thick can be found. In this series, the entire tectono-sedimentary sequences from Cambrian to upper Devonian can be traced to the south-west across Algeria. It is also the only region in the Algerian Sahara where Hercynian tectonics is defined through well-exposed folded structures. Ougarta range includes, among others, the following geosites:

(i) two important exposures in the oasis of Ougarta (Fig. 5a) of the Ordovician-Silurian transition, marked by tectonic events and traces of the great glaciation that affected the Sahara during this period (Nedjari 2007a); in addition, this oasis is an important prehistoric site where hundreds of prehistoric tools were discovered (Vinot 1947);

(ii) the small town of Beni Abbes, houses a small geological museum (Fig. 5b) which belongs to "l'Unité de Recherche sur les Zones Arides (URZA)" created in 1942. Through this center, Beni Abbes became an important site for geological research activities (Chikhi-Aouimer 2007);

(iii) "La muraille de Chine", located 30 km from Beni Abbes it shows an outcrop of bioclastic limestone of 10 m thick; the limestone is an important stratigraphic benchmark in the Saharan platform (Nedjari 2007b); this limestone, early Devonian age (Emsian), it is well known for their giant *Orthoceras* (Fig. 5c), and currently is a protected site; and

(iv) the dunes of the Great Western Erg, constituting a real sandy sea (Fig. 5d) that covers an area of 80,000 km^2; the height of the dunes varies from a few dozen meters to over 300 m; these dunes constitute a major tourist attraction.

In addition to the above, the Ougarta hosts several sites with prehistoric carvings. The most important are those of Tahtania near Taghit which are the oldest in the Sahara (Alimen 1966).

2.5 The Impact Craters

Impact craters are geological structures formed when large meteoroids or asteroids collide with the Earth's surface. To date, 182 meteorite craters are known on Earth. Algeria is one of the Arab and African countries that contain most craters; four were identified in the Algerian Sahara: Amguid, Maadna, Ouarkziz and Tin Bider (Koeberl 1994). These craters are amongst the most well-defined in the world and

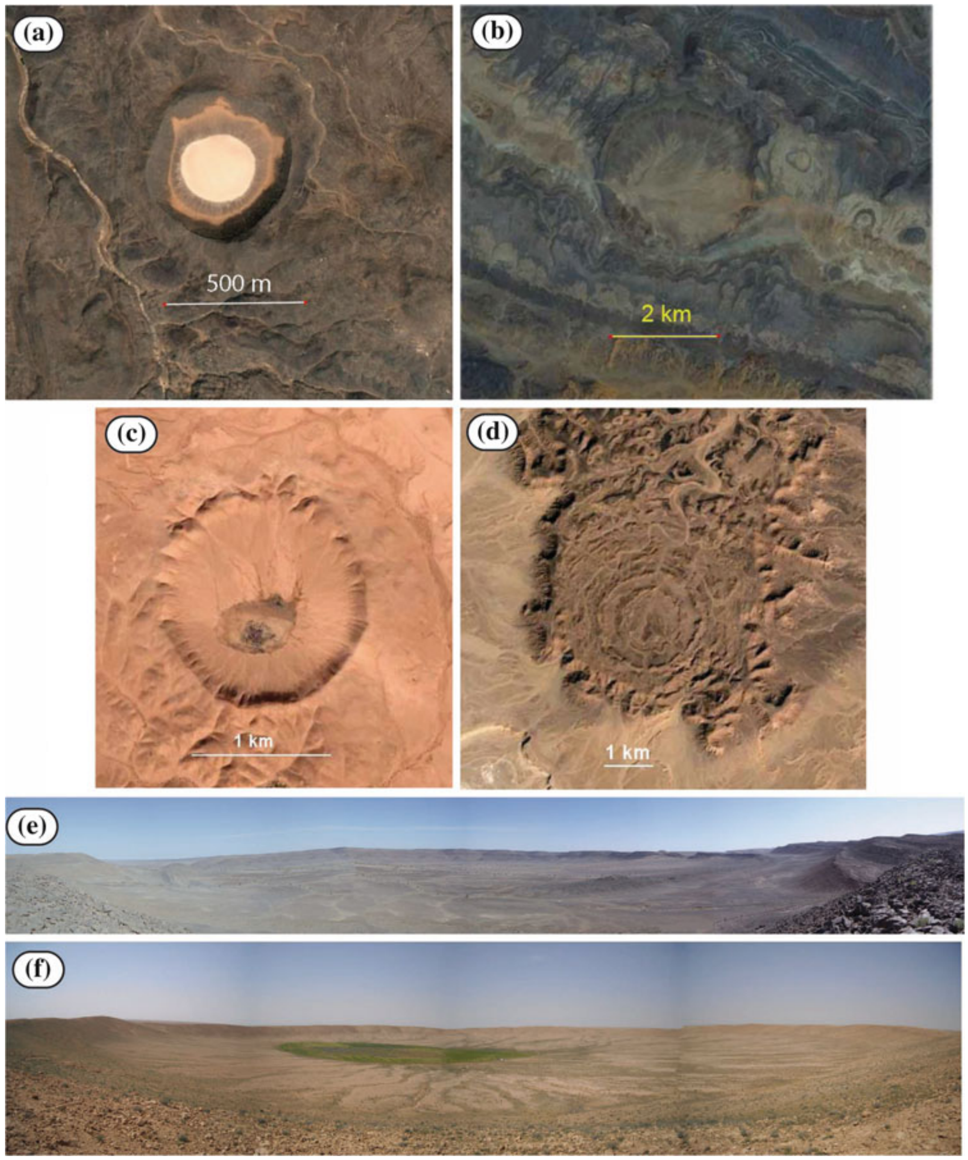

Fig. 6 Algerian craters **a** Satellite view of Amguid crater; **b** Satellite view of Ouarkziz crater, **c** Satellite view of Talemzane crater, **d** Satellite view of Tin Bider crater; **e** Panoramic view of Ouarkziz crater; **f** Panoramic view of Talemzane crater

the best preserved despite the absence of any protective measures.

The Amguid crater is a fresh, circular cavity about 550 m in diameter, affecting Lower Devonian sandstones (Fig. 6a). It has an elevated rim up to 65 m above the crater floor. The flat center of the crater is filled with very bright and fine-grained compacted aeolian silts. The age of the crater was estimated to be 100,000 years considering its near perfect state of preservation (Koeberl 1994).

The Ouarkziz crater (Fig. 6b, e) is located close to the Algero-Moroccan border, 170 km in the NE of Tindouf. The crater is a deeply eroded circular ring structure about 3.5 km in diameter, affecting Carboniferous limestones and shales.

The Talemzane crater (Fig. 6c, f), also known as “Daiet El Maadna”, is located about 120 km ESE of Laghouat. It is a simple, bowl-shaped depression of approximately 1,750 m in diameter. The crater was emplaced in Cretaceous-Tertiary limestones and has a raised rim up to 75 m above the crater floor.

The Tin Bider structure (Fig. 6d) is situated about 265 km ENE of In Salah and appears as a series of at least three concentric annular ridges 2, 3.5 and 6 km in diameter, respectively. The structure affects the Upper Cretaceous clay and limestone formations, and Lower Cretaceous sandstones.

2.6 The Saharan Atlas Mountains

With the use of satellite images and *Google Earth*, aerial views have become readily available and, as such, great and spectacular geological structures can be observed. Over 85 % of the Algeria territory has almost no vegetation which provides exceptional definition of lithologies, outcrops and geological and geomorphological structures.

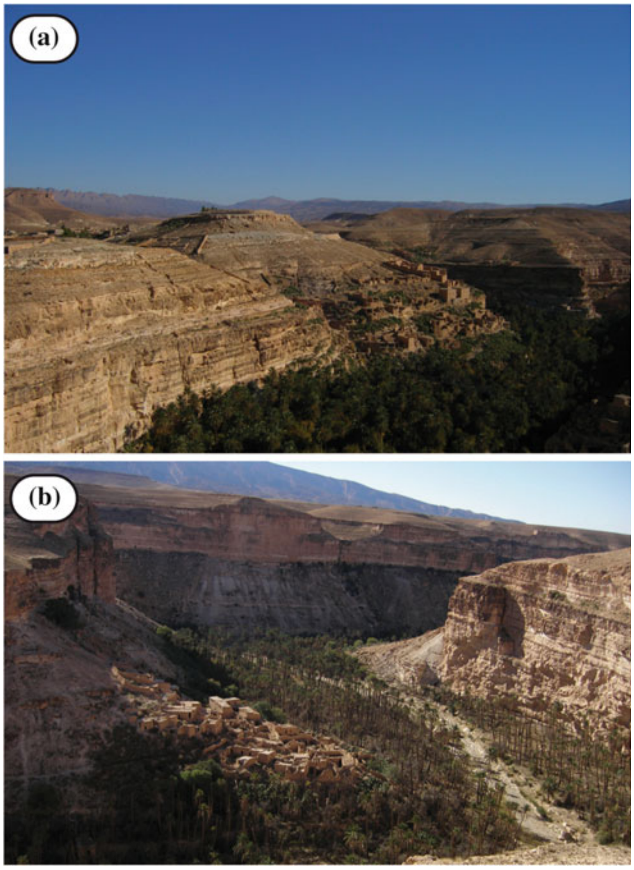

Fig. 7 **a** and **b** The balconies of Ghoufi with villages on the cliffs above the oasis

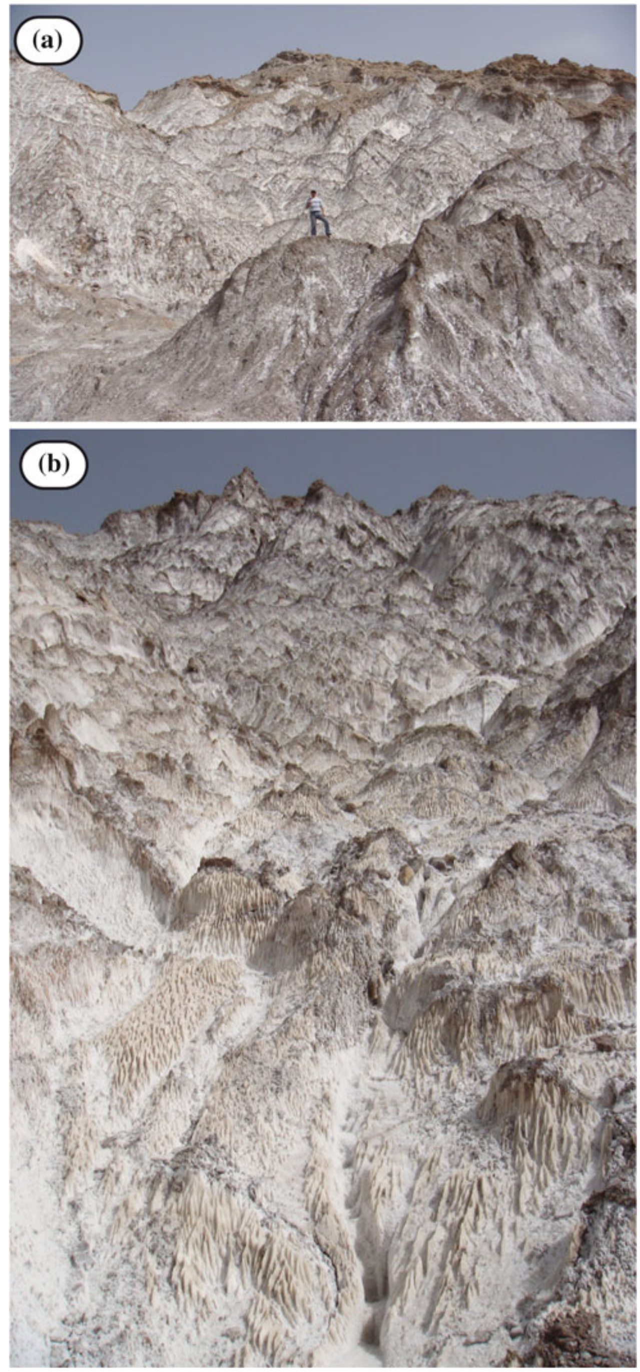

Fig. 8 **a** and **b** The Djelfa Salt mountain (scale is given by the geologist in the photo **a**)

With satellite imagery, one of the most wonderful structures to be observed are the Saharan Atlas mountains that are a Tertiary intracontinental chain trending NE-SW and bounded by two major fault lines: the North and South Atlas Faults. The Saharan Atlas mountains consist of Mesozoic sequences which are of 3–4 km thick, exceeding 6 km in some places. This chain is characterized by large folded anticlines and synclines. The structures are elongated in a NE-SW direction in the western part and E-W in the eastern part (Bettahar 2009). These structures are both spectacular and educational. Furthermore, the Saharan Atlas is very rich in geosites of considerable interest, but relatively few are known in detail. Some of the geosites are described briefly below.

The Rhoufi balcony (Fig. 7a–d), located in the Aures Massif, is a region with an interesting stratigraphic sequence from Jurassic to Quaternary (6,000 m thick) in age. The El-Abiod wadi has carved a spectacular canyon and its cliffs provide a beautiful view of the small oasis. The terraces of Ghoufi, cut into the rock waterfalls, is a location offering an unusual vista; on each terrace is perched an uninhabited village which was built 4 centuries ago; the site was declared a national heritage site in 1928 and in 2005. The Salt mountains, which are three mountains composed entirely of salt, are located in the Saharan Atlas (Gautier 1914): El Outaya rock between El Kantara and Biskra is considered to be the most important one in North Africa (6 km long, 3 km wide and 300 m high); the Djelfa rock salt (1,500 m in diameter, Fig. 8a–d) situated 25 km north of Djelfa, and Metlili rock (less than 500 m in diameter) located 30 km

Fig. 9 Graphic user interface of GeoAl database

north-west of El Kantara; these formations are Triassic outcrops (diapirs).

As mentioned previously, this list is not exhaustive. Other historical geosites exist in Algeria, such as the old Roman mines, dinosaur tracks (Chabou et al. 2015), etc.

3 GeoAl Project

Some of the natural resources described in this paper are in danger of irreversible damage and are in urgent need of protection. For this reason, we initiated project GeoAl to create software (Fig. 9) to integrate a database that will be published free online (see Appendix 1).

The objectives of the GeoAl project are to index and classify the maximum number of geosites that will be published online. This database will be collaborative: other research groups can bring their contributions online. This database and the website will be interactive, continually updated, and enhanced gradually with the progress of the inventory.

The database will be posted on the website for public access. The users will have access to the entire geological map of Algeria with all the information concerning the geosites listed in the inventory, including photos and available scientific literature. The database thus is an effective decision-making tool for national geoconservation programmes and for the identification of areas with high geological potential to be protected and valorised.

The structure of the GeoAl is centered on 22 attributes within the database which form the specific and pertinent information to use with every geosite in Algeria. These attributes were selected as defined in the BRGM models (BRGM 2007).

While there is an existing database that lists current geosites, the GeoAl database allows scope for the user to add new geosites and information on those geosites. When a user adds a new geosite, they should define its geographic coordinates (longitude, latitude, altitude). Thus, each geosite will be located, described in terms of its geology, described in terms of its administrative and legal attributes, and then evaluated based on scientific, aesthetic, educational and legal criteria. Consequently, the goal is to make the most remarkable geosites known according to a set of objective criteria. For each region, experts will be assigned to act as local adjudicators. Among the prioritised pre-selected geosites, priority will be given to potentially sensitive sites where information is lacking. Their insertion into the database provides them with some visibility to attract the attention of government and educational institutions.

To select and describe these geosites, the following methods have been adopted in order to benefit from the experiences made in a number of countries (e.g. BRGM 2007; Fuertes-Gutierrez and Fernandez-Martinez 2010; Joyce 2010). Thus:

1. Name of the geosite, e.g., Greenstones bassin of Alouki, carbonatites of Ihouhaouene.
2. Name of the region where the geosites are located, e.g., In Ouzzal (for Carbonatites of Ihouhaouene).
3. The location of the sites: geographical and administrative boundaries;
4. Description of the site;

5. Status of the site, e.g., managed by Ahaggar National Park.
6. Geological interest of the geosite, e.g., the Paleoproterozoïc metamorphism of In Ouzzal is considered as one of the most extreme in the world (international interest).
7. Educational interest: e.g., knowing the various types of volcanic rocks, to recognise a dome and basins structures typical of the Archaean.
8. Schedule Interest: e.g., panafrican granitic circular massif in In Ouzzal.
9. Touristic and cultural interest: e.g., volcanic landscapes beauty, the hermitage of Charles de Foucauld, presence of prehistoric engravings and paintings…
10. Vulnerability and threats, e.g., the destruction of several outcrops of carbonatites…

Criteria 6–10 are evaluated by scoring from 0 to 4 in order to show the importance of the geosite. Consequently, 20 is the highest score possible for a geosite (i.e., 4 is the maximum score given to each criterion x5 number of noted criteria).

In addition to this descriptive sheet, the database includes satellite images, geological and topographic maps, photo gallery of the site, and as exhaustive bibliography as possible (list of publications and scientific books).

Later, the desktop application will be able to be used directly from the web with the same graphic user interface, so that the users can make all the operations from the web mode in the same way they know in the desktop mode. This technology will host the application on the web, and offers the users the possibility for use from their web-browser when requested. In this case, the speed and reactivity of the execution depends on the Internet speed flow.

4 Conclusions

Algeria contains unique geological and geomorphological sites that merit being known and protected. They could also be a real vector of local and national development. The list of geosites included in this paper is not exhaustive; they account for only a small proportion of geological and geomorphological treasures of the country.

It has been clear for some time that the Algerian government have realized the importance of preserving sites as national natural heritage (Bouzidi and Rabhi 2011). However, these sites can also be an economic stimulus with the development of geotourism that will promote local products and create sustainable small businesses. In our view, the establishment of Geoparks is one of the most appropriate tools in order to achieve these objectives. The involvement of local people in such projects will help to preserve Algerian geoheritage and enhance socio-economic development in remote areas.

The scientific community must have a role to play in this endeavour, and for that reason GeoAl project was initiated. The GeoAl project refers to the creation of a general inventory by use of an internet database and should be made available as broadly as possible. This database could become, in collaboration with the largest number possible of contributors (as the required work is large), a reference tool, allowing the Algerian public authorities to have the fullest possible knowledge of the exceptional geological sites that exist in Algeria, tourists to have a guide to visit the most beautiful and most educational places, and students to have a list of the most educational sites for their training. This project is also a tool for intelligent and efficient management of geosites, ensuring their protection and allowing regional economic growth and well-being of local populations.

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5 Appendix 1

The algorithm projection used by the GeoAl program combines between the screen pixels and the map's pixels used for the projection. In fact, it's a mathematical function coded to run in real time in a way to convert a screen pixel into a geographic coordinates according to the dimensions of the used map, and vice versa. The user adds information on the geological attributes of the sites, its administrative and legal attributes, and so on.

The actual version of software (GeoAl v1.0 beta, downloadable at http://www.geolalg.com/setup.exe—without the databases) is constituted of an executable file running under Windows. The application is ready to use as a 1 Mb auto-installable desktop program. The minimal recommended configuration to guarantee a good running is a Windows XP edition or later, under an Intel Pentium 4 with a 128 Mb free memory and 50 Mb of free disk space.

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Dinosaur Track Sites in Algeria: A Significant National Geological Heritage in Danger

Les sites des empreintes de pas de dinosaures en Algérie: un patrimoine national en danger

مواقع أثار أقدام الديناصورات بالجزائر: جيوتراث وطني هام في خطر

M.C. Chabou, M.Y. Laghouag, and A. Bendaoud

Abstract

Numerous dinosaur track sites are known in Algeria. Most of them are located in the Saharan Atlas, in addition to one site in the Djurdjura Mountains with small footprints assigned to *Rotodactylus*, one of the earliest members of the dinosaur lineage. Two sites have been known for a long time: (i) the Amoura site, located in the Cenomanian layers at Djebel Bou Kahil, eastern Saharan Atlas; It is one of the oldest known scientific references to dinosaur tracks in the world and contains theropod footprints; and (ii) the Tiout site located at the Triassic-Jurassic boundary layer near Ain Sefra, Ksour Mountains, western Saharan Atlas; this site also contains theropod footprints. Recently, several sites have been discovered in Lower Cretaceous strata in the El Bayadh area (western Saharan Atlas). These sites contain many tracks which include both theropod and sauropod footprints, some of which are exceptionally large and well preserved. Regrettably, this invaluable world geological heritage is now facing dramatic decay if no serious actions are undertaken to protect and conserve it.

Résumé

La plupart des sites à empreintes de pas de dinosaures connus en Algérie sont situés dans l'Atlas saharien, mis à part un site localisé dans le Djurdjura avec de petites empreintes attribuées à *Rotodactylus*, l'un des premiers membres de la lignée des dinosaures. Deux sites sont connus depuis longtemps: (i) le site d'Amoura, situé dans les couches du Cénomanien du Djebel Bou Kahil (Atlas saharien oriental); c'est l'un des premiers sites à empreintes de dinosaures au monde à être cité dans une publication scientifique et contient des empreintes de théropodes; (ii) le site de Tiout, près d'Aïn Sefra, dans les monts des Ksour (Atlas saharien occidental), est localisé dans une couche d'âge Trias-Jurassique; contenant également des empreintes de théropodes. Récemment, plusieurs sites ont été découverts dans la région d'El Bayadh (Atlas saharien occidental) et sont situés dans des couches du Crétacé inférieur. Ces traces comprennent à la fois des empreintes de pas de théropodes et de sauropodes ainsi que de nombreuses pistes. Certaines traces sont exceptionnellement grandes et bien préservées.

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Malheureusement, ce patrimoine géologique mondial d'une valeur inestimable est aujourd'hui voué à la dégradation si des mesures sérieuses ne sont pas prises pour le protéger et le conserver.

ملخص

إن معظم مواقع أثار أقدام الديناصورات المعروفة بالجزائرمتواجدة بالأطلس الصحراوي، باستثناء موقع واحد متواجد بجبال "جرجورة" يضم آثار أقدام صغيرة صنفت ضمن جنس "*روتوداكتليس*"، الذي يعد واحدا من أول أعضاء سلالة الديناصورات. هناك موقعين معروفين منذ فترة طويلة، هما : (أ) موقع "عمورة"، الواقع بطبقات "*سينومانيان*" بجبل "*بوكحيل*" (شرق الأطلس الصحراوي) ؛ ويُعَدّ واحدا من المواقع الأولى لأثار أقدام الديناصورات في العالم التي ورد ذكرها في إصدارات علمية، ويحتوي على آثار أقدام ديناصورات ذوات الأقدام، و(ب) موقع "تيوت" قرب "*عين الصفراء*" بجبال القصور (الأطلس الصحراوي الغربي)، وهو متواجد بطبقة العصرين الترياسي والجوراسي، ويحتوي أيضا على آثار أقدام ديناصورات ذوات الأقدام. وقد تم، في الآونة الأخيرة، اكتشاف عدة مواقع بمنطقة "*البياض*" (الأطلس الصحراوي الغربي) والمتواجدة بطبقات العصر الطباشيري السفلي. وتشمل هذه الآثار في الوقت نفسه آثار أقدام ديناصورات ذوات الأقدام والصوربودات بالإضافة إلى العديد من المسارات. بعض هذه الآثار كبيرة بشكل استثنائي ومحفوظة بطريقة جيدة. لكن للأسف، هذا الجيوتراث العالمي الذي لا يقدر بثمن، معرض الآن للتدهور إذا لم تتخذ أي إجراءات جدية لحمايته والحفاظ عليه .

Keywords

Dinosaur footprints • Saharan atlas • Djurdjura • Algeria • Geological heritage

Mots-clés

Empreintes de pas de dinosaures • Atlas saharien • Djurdjura • Algérie • Patrimoine géologique

الكلمات الرئيسية

آثار أقدام الديناصورات • الأطلس الصحراوي • جرجورة • الجزائر • جيوتراث

1 Introduction

Until recently, dinosaur track sites were rarely known in Algeria. Only two sites were known in the past; one located in Amoura (Djebel Bou Kahil, eastern Saharan Atlas) and another one in Tiout, near Ain Sefra (Ksour Mountains, western Saharan Atlas). Dinosaur footprints of Amoura, located in Cenomanian layers, were discovered in 1880 and are the first documented dinosaur tracks found in North Africa (Le Mesle and Peron 1880). Those of the Tiout site are known since 1971 and are located in the Triassic-Jurassic boundary layer (Bassoullet 1971). Lately, numerous sites of dinosaur footprints were discovered in the Cretaceous of El Bayadh region in the western Saharan Atlas (Mahboubi et al. 2007; Regagba et al. 2007; Taquet 2010; Le Loeuff et al. 2012). These discoveries have restored interest in the study of dinosaur tracks in Algeria, and opened debate on their vulnerability as geosites.

The aim of this paper is to provide an overview on the known dinosaur footprint sites in Algeria and to emphasise the urgent need for their protection and their valorisation for scientific, educational, cultural and touristic purposes.

2 Location and Geological Context

Dinosaur footprint sites in Algeria are mainly located in the Saharan Atlas, except for one site found in the Djurdjura Mountains in northern Algeria (Fig. 1). The Saharan Atlas is an intracontinental chain, uplifted during the Cenozoic that includes to the west the Ksour Mountains, to the centre Djebel Amour, and to the east, the Oulad Nail Mountains and the Zibans, and continues into the Aures Mountains, in the north-east (Herkat 2009). It contains a thick succession of shallow marine or continental sedimentary rocks of Mesozoic age (3,000–4,000 m thick). In the Ksour Mountains, the dinosaur footprints of the Tiout site were discovered in beds of Triassic-Jurassic age. In Djebel Amour Mountains, dinosaur tracks sites of El Bayadh and Brezina regions were identified at Lower Cretaceous levels, while in Ouled Nail Mountains, footprints at the Amoura site are located in the Upper Cretaceous (Cenomanian).

The Djurdjura Mountains belong to the so-called "dorsale calcaire" (limestone chain) and are the sedimentary cover of the basement of the Internal Zones of the Maghrebides, the Maghrebides orogenic system being a segment of the Alpine

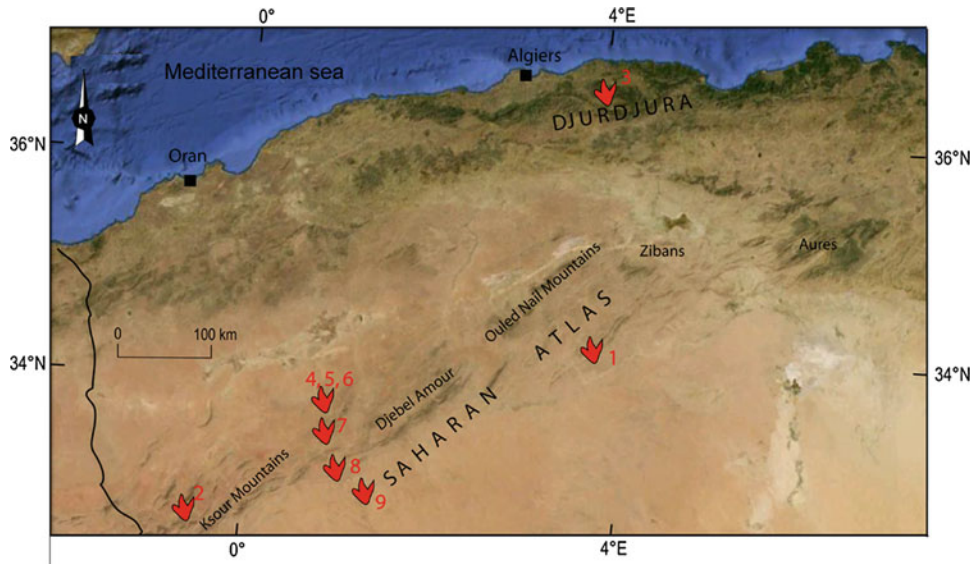

Fig. 1 Location of Dinosaur track sites in Algeria. *1* Amoura; *2* Tiout (Ain Sefra); *3* Belvedere-Akherdous (Djurdjura); *4*, *5*, *6* El Bayadh; *7* Ouafeg El Hamra; *8* El Mezioud (Brezina); *9* Daiet Sidi El Arbi

belt that runs from southern Spain and Gibraltar to Northern Sicily and Calabria. In Algeria, it comprises, from the south to the north, the following zones (Durand-Delga 1969): (i) the External zones, or Tellian domain, which represent the inverted African palaeo-margin consisting of Mesozoic and Cenozoic sedimentary rocks that overthrust the Atlas foreland; (ii) the flyschs units, made up of Upper Cretaceous to Eocene units (Massylian and Mauretanian flysch), and younger, Oligocene to Aquitanian silici-clastic series (Numidian Flysch); and (iii) the Internal zones, made up of crystalline Hercynian or older basement, and their sedimentary cover, the "dorsale calcaire", mainly formed by Mesozoic carbonate slices, and characterized by a thick limestone formation of early Liassic age. The flysch domain and the Internal zones are overthrusting the External zones.

The "dorsale calcaire" of the Djurdjura Mountains are subdivided, from north to south, into three structural and paleogeographic units (Flandrin 1952): the internal (Kouriet), the middle (Haizer-Akouker) and the external (Tikjda and Tamgout) units.

Assemblages of dinosauromorph footprints were discovered by Kotañski et al. (2004) in the Middle Triassic of the Haizer-Akouker units near the locality of Belvedere-Akherdous in the Djurdjura Mountains.

3 Dinosaur Track Sites in Algeria

Four sites are described below, namely, the Amoura footprints site, the Tiout footprints site, the Belvedere-Akherdous (Djurdjura) footprints site, and the El Bayadh footprints sites.

3.1 Amoura Footprints Site

Amoura is located in the Wilaya of Djelfa, approximately 300 km south of Algiers (Fig. 2). This village is perched on the southern side of Djebel Bou Kahil in the southern part of Ouled Nail Mountains. Djebel Bou Kahil is located in a syncline, with Turonian sediments in its core, located near the South Atlas Front. In Amoura, the outcrops consist of limestone-marl series of Cretaceous age (Albian to Turonian). The Amoura site is of major geological and heritage interest due to the presence of dinosaur footprints. From a historical perspective, this is one of the oldest sites in the world which is known for dinosaur tracks. Those dinosaur footprints found on a limestone slab, were first reported in 1880 by Le Mesle and Peron who thought they were bird footprints. At the time of this discovery, only the famous footprints in the red sandstone of the Connecticut Valley in USA were known. For this reason the Amoura site is of major historical interest since it was the first dinosaur tracks site discovered in North Africa and the second in the world (Taquet 2010). Popular legend attributes the footprints to a large ostrich (Naama in arabic), that belonged to Marabout Sidi Ali Ben Allouche, the saint of the village. Bellair and Lapparent (1948) reported the legend with the following sentence: "This ostrich, running on the rock, leaping over the ravine that separates the two groups of footprints, jumping and landing, would have marked the track of his feet on the rock". During our on-site visit, we noticed that this legend is still current among many people in the village. It was Gaudry (1890) who suggested for the first time that the Amoura footprints belong to dinosaurs and not to giant birds.

Fig. 2 View of Amoura village

The Amoura dinosaur footprints are located on the top of a Cenomanian limestone slab containing mud cracks. Bellair and Lapparent (1948) discovered 140 tridactyl footprints that are divided according to size into three groups: (1) the first group includes the largest and most numerous footprints (Fig. 3); the length of a footprint of this group is 24 cm, the width is 17 cm, and the stride length is about 80 cm on average; (2) the second group is rarer; it includes small tridactyl tracks (10 cm in length); and (3) the third group includes even smaller tridactyl footprints (8 cm in length) with digits more spread apart than digits of the other groups. These tracks were attributed to a theropod dinosaur *Columbosauripus amouraensis* (Taquet 2010).

Recently, Mammeri et al. (2011) made a new discovery of dinosaur footprints in the Cenomanian at Amoura, about 20 m stratigraphically below the surface on which the previously known dinosaur tracks are located. Thirty new large tridactyl footprints were reported, with an average length of 61 cm and an average width of 49 cm (Mammeri et al. 2011). These tracks are much larger than previously described, and are attributed to a large theropod.

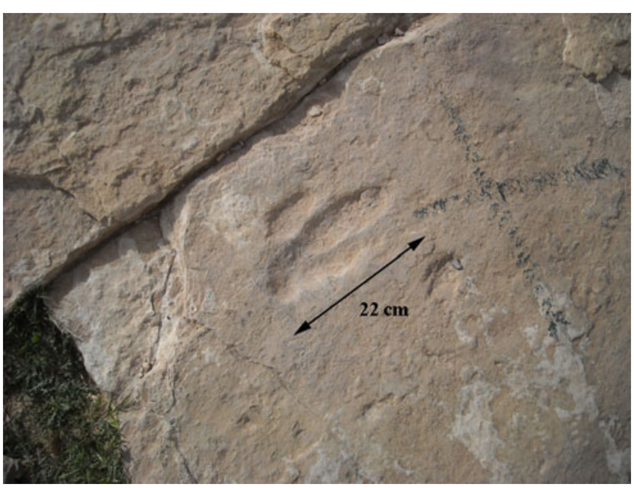

Fig. 3 Theropod footprint at Amoura track site

In addition to the presence of dinosaur tracks, the Amoura site has an excellent and very educational Cretaceous stratigraphic cross-section, with layers ranging from Barremian to Turonian without any gap (Figs. 4 and 5). This section was described in brief by Bellair and Lapparent (1948) and in detail by Emberger (1960).

In addition to this geological treasure, Amoura is also an old ksar (fortified villages) with beautiful gardens. It is also worth mentioning the presence of an old sundial in the village (Fig. 6). Undoubtedly, with all these geological, historical and cultural features, Amoura site is a good candidate for geoheritage status.

3.2 Tiout Footprints Site

The Tiout Oasis is located in the Ksour Mountains (Saharan Atlas), about 540 km southwest of Algiers and 12 km west of Ain Sefra, in the Wilaya of Naama. Near the Tiout bridge, at 1.75 km south-east of Tiout, Triassic-Jurassic (Rhetian-Hettangian) rocks crop out along a major fault, which is underlain by Triassic basalts and marls (Fig. 7). The Triassic-Jurassic rocks consist of rhythmically bedded dolomitic limestones and dolomites. In this outcrop, Bassoulet (1971) discovered about ten tridactyl footprints, which appear on a vertically uplifted dolomitic limestone slab. The tracks are located on 1 m^2 bedding surface. The length of the footprints varies from 9 to 13 cm with a maximum width of 6 cm (Fig. 8). These theropod tracks were attributed to *Grallator variabilis* (Bassoulet 1971).

Tiout Oasis is also famous for its oldest known Prehistoric rupestrian carvings in North Africa, discovered in 1847. These paintings depict elephants, buffaloes, ostriches that lived in the area 7,000 years ago (Fig. 9). A petrified forest near Tiout has also been recently discovered. Unfortunately, this unique geological and historical site is nowadays totally dilapidated.

3.3 Belvedere-Akherdous (Djurdjura) Footprints Site

In 1983, the third historical discovery of dinosaur footprints in Algeria was made by Polish geologists in the Djurdjura Mountains. In the middle unit of the “dorsale calcaire” of the Djurdjura Mountains (Haizer–Akouker), the full Triassic sequence, from the Anisian to Rhaetien, is well represented in the Belveder-Akherdous locality. The Lower Triassic is partly preserved and composed of few meters of clastic deposits (yellow and red sandstones), the middle Triassic strata are represented by up to 200 m of carbonate sediments

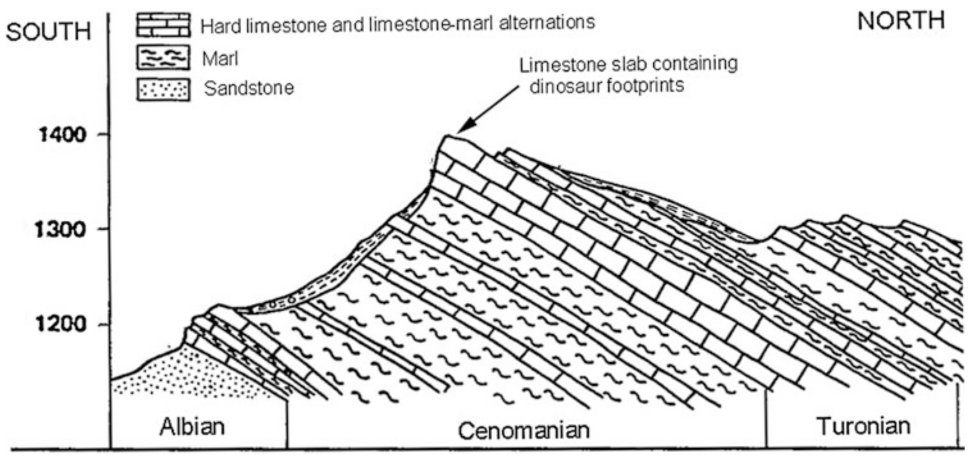

Fig. 4 Cretaceous cross-section at Amoura and location of dinosaur footprints

Fig. 5 Panoramic view of the top of the Cretaceous cross-section at Amoura

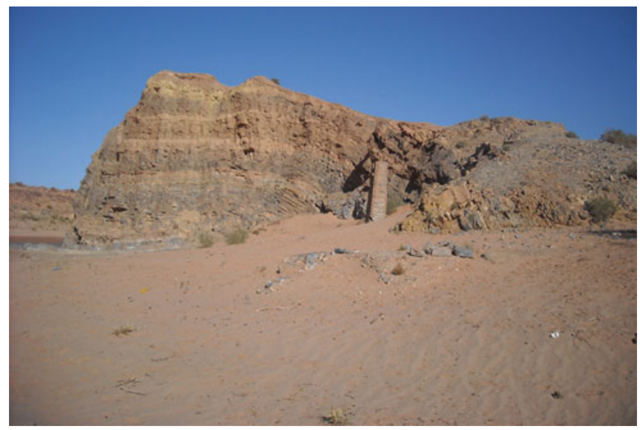

Fig. 7 Outcrop of Triassic-Jurassic (Rhetian-Hettangian) rocks near the oasis of Tiout containing dinosaur tracks

Fig. 6 An old sundial in the village of Amoura

Fig. 8 Theropod footprint at Tiout track site

Fig. 9 Prehistoric rupestrian carvings that are the oldest known in North Africa in the oasis of Tiout

that consist of dolomites and vermicular limestone, whereas the Upper Triassic strata are composed of 300 m of red sandstones and conglomerate (red beds formation) (Flandrin 1952). In the uppermost part of the vermicular limestone of Middle Triassic there are 2–3 m of continental sediments (fine-grained quartz sandstones) containing tracks of small reptiles (Kotañski et al. 2004). These footprints were discovered in 1983 preserved on the underside of a small slab of fine-grained grey-yellowish sandstone. A total of 12 footprints were observed with an average length of 2 cm. The tracks at this site are pentadactyl with the impressions of four clawed digits in addition to a reverted digit. These footprints are assigned to *Rotodactylus* which is regarded as one of the earliest members of the dinosaur lineage (e.g. Kotañski et al. 2004).

3.4 El Bayadh Footprints Sites

El Bayadh city is located about 380 km southwest of Algiers, in Djebel Amour, central Saharan Atlas. The region of Djebel Amour consists of a series of NE-SW trending tight anticlines separated by broad flat-bottomed synclines. The El Bayadh area constitutes one of these synclines with thick sedimentary layers of Early Cretaceous age. The succession includes marly limestone formation (Valanginian-Hauterivian) and predominantly sandstones series (Barremian-Aptian) (Cornet 1952). In the last 10 years, large numbers of dinosaur footprints of Early Cretaceous age have been found around and south of El Bayadh town (Bensalah et al. 2005; Mahboubi et al. 2007; Regagba et al. 2007; Bessedik et al. 2008; Mammeri et al. 2009). The main sites are described below.

3.4.1 Footprints Sites Around the Town of El Bayadh

Around the locality of El Bayadh, three dinosaur track sites have been found. Two sites (sites 1 and 2) are located 2 km northeast of El Bayadh, and a third (site 3) 1 km west of that locality.

Site 1 is located near the road that connects El Bayadh to the village of Rogassa. At this site, two track levels were recognized on lumachel limestone slabs of Valanginian age, in an area of about 1 km^2. About 100 tridactyl footprints with clawed digits of theropod dinosaurs forming 12 separate trackways were discovered (Figs. 10 and 11). The tracks are in a good state of preservation and their average dimensions are 50 cm in length and 40 cm in width (Fig. 10). About twenty half-moon-shaped footprints related to sauropod dinosaurs, 22 cm in length and 25 in width on average were also found at this site.

Site 2 is located 500 m east of the site 1 and shows two track levels on greenish micritic limestone slabs of Valanginian age. About 50 isolated footprints, including about thirty tridactyl tracks with clawed imprints of small sizes, and about 40 half-moon-shaped footprints were found (Fig. 12).

Site 3 is located 1 km west of locality of El Bayadh, on the left bank of Oued Merires. In this site, about 10 tridactyl footprints of theropod dinosaurs were found on the surface of a steeply dipping limestone slab.

3.4.2 Ouafeg el Hamra Footprints Site

Ouafeg El Hamra track site is situated 30 km south of the locality of El Bayadh. The track level is on a steeply dipping bedding surface of sandstones of the Continental Intercalaire (Barremian-Aptian-Albian) (Fig. 13). At least 40 footprints, including oval-shaped and tridactyl tracks (Figs. 14 and 15), are gathered on an area of about 30 m^2 (Mammeri et al. 2009). The footprints are in an excellent state of

Fig. 10 Theropod footprint at El Bayadh track site 1

Fig. 11 Theropod trackway at El Bayadh track site 1

preservation. The oval-shaped sauropod footprints are more abundant, with an average of 48 cm in width and 65 cm in length (Fig. 14). Tridactyl theropod tracks are 32 cm long and 28 cm wide in average, and exhibit distinct claw impressions (Fig. 15).

3.4.3 El Mezioued Footprints Site

The dinosaur track site of El Mezioud is situated near the oasis of Brezina, 60 km south of El Bayadh. The site shows tridactyl impressions of theropod dinosaurs on two sandstone slabs of Lower Cretaceous age (Mahboubi et al. 2007). At least 40 footprints are preserved on an area of about 300 m^2. The first slab shows three trackways with 30 large and small tridactyl footprints (Fig. 16). The second slab

Fig. 12 Theropod and sauropod footprint at El Bayadh track site 2

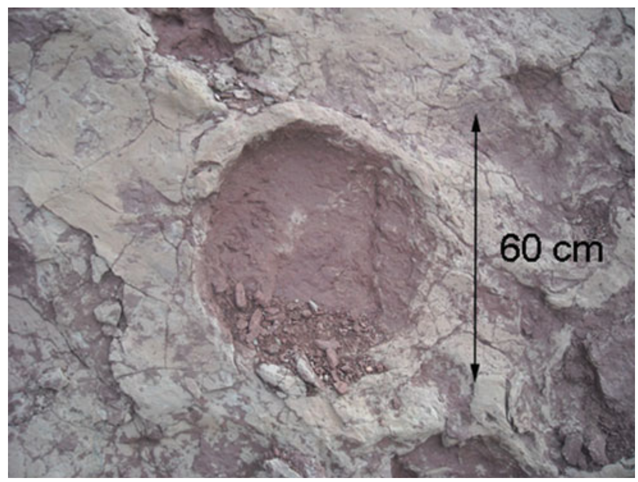

Fig. 14 Oval-shaped sauropod footprint at Ouafeg El Hamra track site

Fig. 13 Bedding surface of sandstones containing dinosaur footprints at Ouafeg El Hamra track site

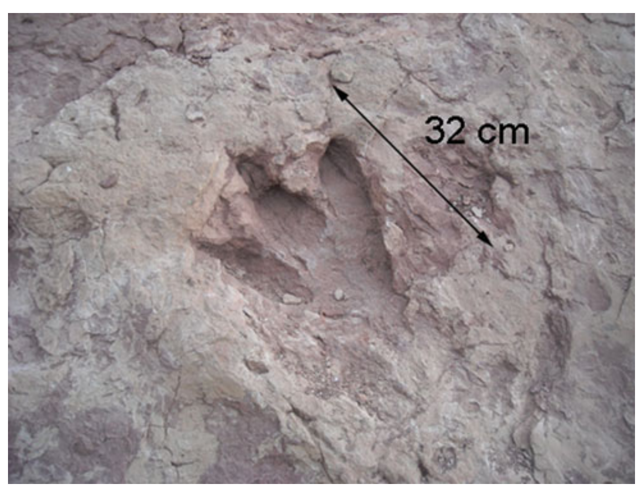

Fig. 15 Tridactyl theropod footrpint with claw impressions at Ouafeg El Hamra track site

Fig. 16 Theropod trackway at El Mezioued track site

Fig. 17 Informative panel near the El Bayadh track site 1

contains large footprints that exhibit 2 trackways and 4 small isolated footprints.

3.4.4 El Kohol Daiet Sidi el Arbi Footprints Site

El Kohol Daiet Sidi el Arbi track site is situated south of El Bayadh at the top of the sandstones of the Continental Intercalaire. The tracks are located on a bedding surface of 50 m^2, and comprise oval-shaped and tridactyl footprints (Mammeri et al. 2009). The oval-shaped footprints of sauropod dinosaurs are very large, with an average length of 120 cm and a width of 110 cm; those that are best preserved show claw impressions. These footprints are among the largest in the world. The tridactyl tracks are also large, 60 cm long and 52 cm wide in average, and show separate digits with claws. They are assigned to large theropod dinosaurs.

4 Discussion

Although the existence of dinosaur footprint sites in Algeria has been known for a long time (the Amoura site is one of the oldest known in the world), because of the rarity of these sites and the lack of interest shown in them by the scientific community, these sites largely have been abandoned. The discovery of new track sites over the past ten years in the region of El Bayadh, and the media coverage given to these findings has revived the study of dinosaur footprints in Algeria and raised awareness of the need for their protection.

After this later discovery, the local authorities issued a decree for the protection of these sites (Mahboubi et al. 2007). An information panel was erected near site 1 indicating that the site is protected against any act of vandalism (Fig. 17). Since then, no other protective measures have been taken and the site has been damaged at several locations. Site 2, located north of El Bayadh, is missing following the floods that occurred in autumn 2011. It is necessary that the authorities implement serious protective measures to preserve these footprint sites, especially those located south of El Bayadh, knowing that many of them are among the largest dinosaur footprints in the world. As in many countries in the World, these sites should be considered a global geoheritage site and declared as a natural monument (Santos et al. 2008).

Furthermore, El Bayadh area is a good candidate for a geopark designation. Indeed, in addition to the hundreds of dinosaur footprints, the region has a large number of fossil dinosaurs, hundreds of prehistoric rupestrian carvings, Triassic diapirs, hot springs, extraordinary geological cross-sections and geological structures of the Saharan Atlas, an exceptional outcrop of the “South Atlasic Fault” near the locality of Brezina, caves, and beautiful sandstone buttes. The creation of a geopark can also enhance the local economy and tourism in this region, which is among the less-developed and poorest regions in Algeria.

The other sites reported in this paper, Amoura, Tiout and Djurdjura, have never been the subject of protective measures. At Amoura, the tracks have been weathered, and damaged due to human activity. Several tracks have been erased and some limestone slabs containing footprints have been removed (Fig. 18). From the 140 footprints identified by Bellair and Lapparent (1948), only about 50 still exist. Protective measures must be taken as soon as possible to protect and to conserve what remains. Amoura site is among the best candidates for designation as a geosite. Indeed, in addition to the dinosaur footprints that are among the oldest known scientific references to dinosaur tracks in the world we have already reported that this site has an excellent Cretaceous cross-section which can act as a study site for scientists and students. Amoura is also located near the “South Atlasic Fault” which separates the two major geological and structural domains of Algeria, i.e. the stable Saharan domain to the south, and the Alpine/Atlas folded

Fig. 18 Amoura track site. At *right*, a limestone slab containing footprints have been removed

belts to the north. The contrast between the two domains can be easily observed from this location. Amoura is also a site of historical cultural heritage, with its old ksars (fortified villages), gardens, old sundial and the presence of an archaeological site near the village. Given its scientific, educational and cultural significance, it is urgent that the Amoura site be declared a protected area and a geological heritage site.

The dinosaur track site of Tiout is less well known and the presence of dinosaur footprints at this site is hard to locate by non-experts given the small number of these tracks and their small size. The location of these footprints on a vertically uplifted limestone slab protects them from climate hazards. However, the site remains unknown to the authorities and the lack of reporting of its presence could lead to its destruction, e.g. from limestone mining. Consequently, it is extremely important and necessary to report the presence of the site in the very near future and to classify it as a protected natural site.

In Djurdjura, slabs containing dinosaur footprints have been removed and are now in the Geological Museum of the Polish Geological Institute (Poland). No study has been undertaken since the discovery of this site; therefore, a new field investigation should be carried out in order to find any new tracks within the lithological level where the first discoveries were made. Further, given the rarity of these dinosaur footprints attributed to *Rotodactylus* which is among early members of the dinosaur stem lineage (Brusatte et al. 2011), this exceptional site deserves more attention.

The protection of these tracks sites and their transformation into outdoor geological and palaeontological museums (geosites) is crucial in the development of local tourism and can contribute to the improvement of the local economy of these regions. In addition, some of these sites, such as many others in the world, are valuable for geoscience popularization and promotion of Earth Science education (Santos 2008).

5 Conclusion

About 10 dinosaur track sites are known in Algeria. Among them is the Amoura site in Djebel Bou Kahil, eastern Saharan Atlas, which is one of the oldest known scientific references to dinosaur tracks in the world. Numerous sites have been identified in recent years in the El Bayadh area (Western Saharan Atlas); these contain theropod as well as sauropod footprints and trackways. Some of them are exceptionally large and are very well preserved. These sites are mostly abandoned and no serious action has yet been taken to protect and conserve them. Some of these sites are in an advanced state of decay. Geoconservation measures should include: (i) the protection of these sites through the establishment of geological protected areas; (ii) providing facilities for scientific, educational, cultural and touristic purposes; and (iii) the creation of geoparks, notably, in the region of El Bayadh.

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Dinosaur Footprint Sites in Arhab Area: An Aspiring Geopark in Yemen

Les sites à traces de pas de dinosaures d'Arhab : un géoparc potentiel au Yémen

مواقع آثار أقدام الديناصورات بمنطقة أرحب، مقترح لإنشاء أول منتزه جيولوجي في اليمن

M. Al-Wosabi and A.A. Al-Aydrus

Abstract

The Arhab area in Yemen possesses a cultural and natural heritage that needs to be enhanced and protected. Dinosaur footprints represent the most important geological heritage features in the region and in the Arabian Peninsula. They are distributed within an area of 200 km^2. The Arhab area possesses all the requirements to be a geopark; these include a large area, the occurrence of geological and paleontological features of regional and international importance, several archaeological sites, willingness of the local community to be involved in a geopark project, a society in need of socio-economic development, elements of scientific and cultural tourism, and ease of access to the region. Establishing a geopark in the region will safeguard and preserve the geological, paleontological and archaeological heritage and improve the quality of life for the local communities. The local Government of Yemen, the local council of Arhab area, and international communities should work together to promote, support and establish that project.

Résumé

La zone d'Arhab au Yémen possède un patrimoine culturel et naturel qui mérite d'être valorisé et protégé. Les traces des dinosaures représentent le plus important élément du patrimoine géologique dans la région et dans la péninsule arabique. Elles sont réparties sur une superficie de 200 km^2. La zone d'Arhab possède toutes les conditions pour devenir un géoparc à savoir une grande superficie, la présence d'éléments géologiques et paléontologiques de signification régionale et internationale, plusieurs sites archéologiques, la volonté de la communauté locale de s'impliquer dans un projet de géoparc, une société dans le besoin d'un développement socio-économique, des éléments de tourisme scientifique et culturel et la facilité d'accès à la région. La création d'un géoparc dans la région permettra de sauvegarder et de préserver le patrimoine géologique, paléontologique et archéologique et d'améliorer la qualité de vie des populations locales. Le gouvernement local du Yémen, le conseil local de la zone Arhab et la communauté internationale devraient travailler ensemble pour promouvoir, soutenir et mettre en place ce projet.

ملخص

تمتلك منطقة أرحب باليمن تراثا ثقافيا وطبيعيا يستحق أن يحظى بالتقييم والحماية. وتُمَثِّلُ آثار الديناصورات، موزعة على مساحة تقدر بـ 200 كم^2، أهم عنصر للتراث الجيولوجي بالمنطقة وبشبه الجزيرة العربية. تتوفر منطقة أرحب باليمن على جميع المتطلبات التي تؤهلها لتصبح جيومنتزها، كالمساحة الشاسعة، ووجود العناصر الجيولوجية والحفرية ذات الأهمية الإقليمية

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والدولية، والعديد من المواقع الأثرية، وإرادة المجتمع المحلي في الانخراط في مشروع خلق الجيومنتزه، ومجتمع في حاجة إلى تنمية سوسيو اقتصادية، وعناصر السياحة العلمية والثقافية وسهولة الوصول إلى المنطقة. إن إحداث جيومنتزه بالمنطقة من شأنه حماية التراث الجيولوجي والاستحاثي والأثري والمحافظة عليهم، وتحسين مستوى عيش الساكنة المحلية. ولتعزيز ودعم وتنفيذ هذا المشروع ينبغي على الحكومة المحلية باليمن والمجلس المحلي لمنطقة أرحب والمجتمع الدولي العمل معا لتعزيز ودعم وتنفيذ هذا المشروع.

Keywords
Dinosaur tracksites • Palaeontological heritage • Geopark • Geotourism • Arhab • Yemen

Mots-clés
Pistes de dinosaures • Patrimoine paléontologique • Géoparc • Géotourisme • Arhab • Yémen

الكلمات الرئيسية
مسارات الديناصورات • تراث استحاثي • جيومنتزه • جيوسياحة • أرحب • اليمن

1 Introduction

Fossils are excellent records of life on Planet Earth since its creation, as well as they are a major attraction for Earth Scientists, researchers and general public interested in Earth history and the stages through which life has evolved. Dinosaurs are among the most attractive creature, through their skeletal remains and ichnofossils, worldwide, whether in scientific researches, education or entertainment such as science fiction movies.

More and more countries are compiling inventories of their sites of geoheritage significance that can be used for educating the general public in Earth history, environmental matters, demonstrating sustainable development, and illustrating methods of site conservation thereby recalling that rocks, minerals, fossils, soils, landforms and landscapes are all the products and record of the evolution of our planet Earth and, as such, form an integral part of the natural world (Eder and Patzak 2004).

In the last five decades, several countries sought to protect their geoheritage, whether it was fossils, rocks, minerals or combinations of certain different geologic phenomena. This activity clearly emerged in UK, USA, Australia, European and some Asian countries. In Africa, and Middle East countries, there has been an urgent need to address and rectify the depletion of natural resources and destruction of a large proportion of features of geological heritage but, unfortunately, up to 2010, the protection, conservation and management of these features are still marginalized and neglected. In 2011, the organization of the First International Conference on African and Arabian Geoparks in El Jadida (Morocco), by the African Geoparks Network (AGN) provided an opportunity to begin to define and introduce geoheritage into African and Middle East regions, and to promote sites of geoheritage significance through the establishment of geoparks (Errami et al. 2012).

This paper introduces the dinosaur footprints as features of geoheritage significance in the Arhab area to the international community, highlighting the necessity for their urgent protection and valorization, and to promote the establishment of a geopark in the region.

The study area is situated in the Arhab district, 47 km northeast of Sana'a, the capital of Yemen (Fig. 1). It is located in the central plateau where the altitude ranges between 1,941 and 3,017 m above sea level. The region is linked to the capital by the main road leading to Al-Jawf Governorate (Fig. 1). A network of asphalted and paved roads branches from the main road to many villages and to neighboring regions. This region is characterized by a mild climate throughout the year, but it tends to be slightly cool in winter. The rainy season is between the onset of the spring (March) and winter (October); though it may not rain for consecutive years.

2 Geological Setting

The Arhab area is located in the central plateau of Yemen which is covered by the limestone of the Amran Group and the Tertiary and Quaternary volcanic rocks (Fig. 2). The Amran Group in Yemen and its equivalent in Arabia is one of the most interesting research areas due to its geologic setting and economic importance. These rock units host the large oil reservoirs in the Middle East and in the world. In Yemen, this group represents the source reservoir and the cap rocks of the oilfields in Marib–Shabwa (Sab'atayn) Basin (Bosworth et al. 2005). Rocks of the Amran Group are mainly of yellowish to beige limestone and greenish marl containing various invertebrate fossils such as bivalves, brachiopods and echinoderms with a dominance of gastropods and foraminifera. Gastropods are represented by the

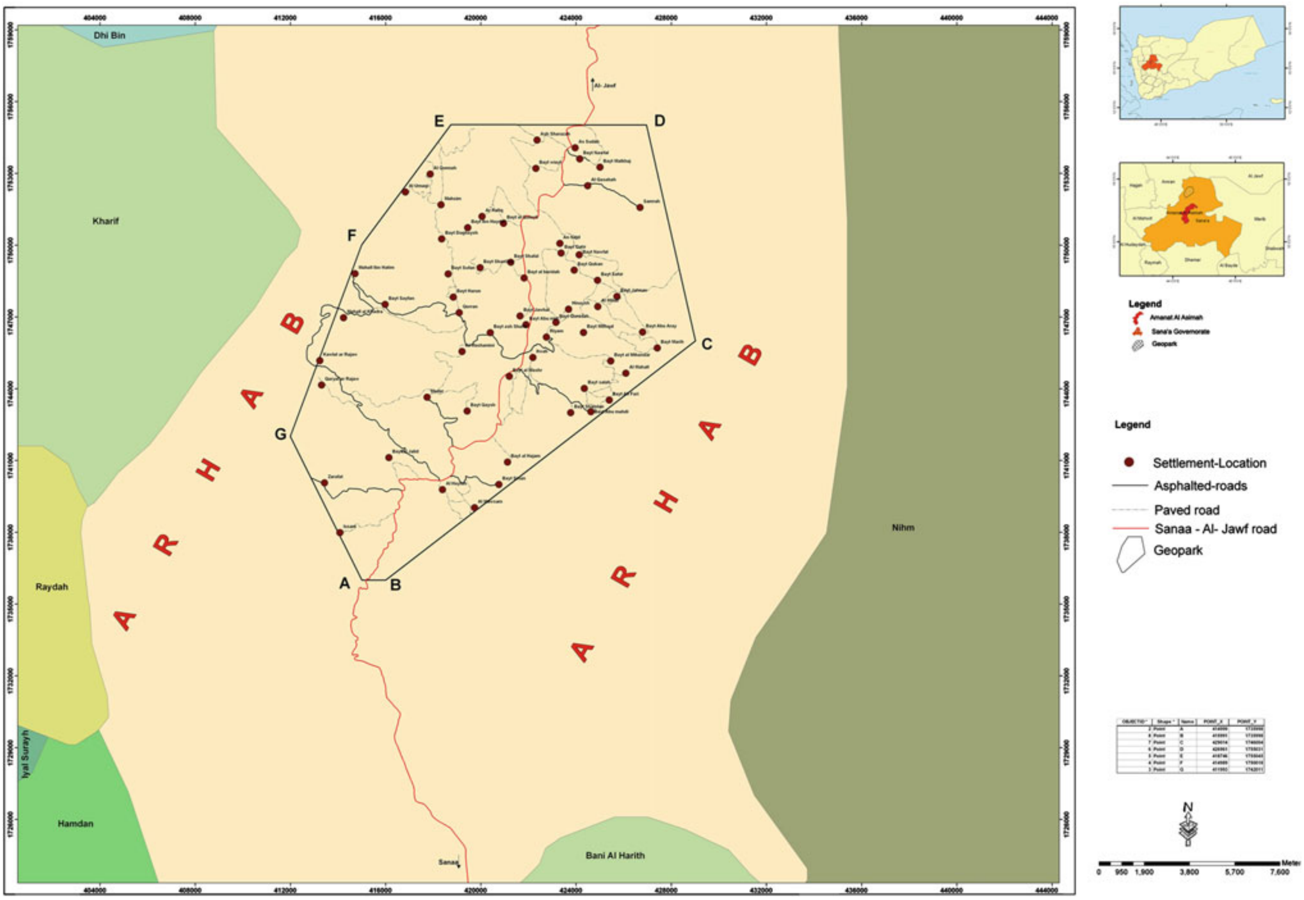

Fig. 1 Location map of the proposed geopark

genus *Nerinia*, an index fossil of the upper Jurassic (Clarkson 1993) (Fig. 3). Many species of foraminifera were described in these formations; these include *Kurnubia plastiniensis* Henson, *Nautiloculina oolithica* Mohler and *Bramkampela arabica* Redmond, which indicate Kimmeridgian–Berriasian ages (Al-Wosabi 2001) (Figs. 4, 5 and 6).

The geologic setting of the Amran Group (sedimentology, paleontology, stratigraphy and paleoenvironment) has been described and discussedby many researchers (Botez 1912; Lamare 1923; Lamare et al. 1930; Basse et al. 1954; Beydoun 1964, 1966, 1991, 1997; Geukens 1966; Beydoun and Greenwood 1968; El-Anbaawy 1984; Al-Thour 1988, 1992, 1997; El-Nakhal 1990; Le Nindre Y et al. 1990a, b; Al-Ganad 1991; Al-Ganad et al. 1993; Simmons and Al-Thour 1994; Al-Sharhan and Nairn 1997; Howarth and Morris 1998; Bosence 1997; Al-Wosabi 1993, 2001, 2005, 2009; Al-Matary 2007; Al-Matary and Ahmed 2011).

The Amran Group is of Bathonian or Callovian–Berriasian age and it has been subdivided into four formations: Shuqra (?Bathonian/Callovian–Oxfordian), Madbi/Sabatain (Kimmeridgian–Middle Tithonian) and Naifa'a (Late Tithonian–Berriasian) (Schulp and Al-Wosabi 2012). The dinosaur tracks are within the Madbi Formation, assigned to the *Alveoseptа jaccardi* biozone (Al-Wosabi 2001). This biozone is of Kimmeridgian age (Ascoli 1988; Williams et al. 1990; Al-Thour 1992; Simmons and Al-Thour 1994; Al-Wosabi 2001). However, the presence of *Nerinia* spp. and *B. arabica* Redmond and the study of (Beydoun et al. 1998) extend the Madbi Formation to the Middle Tithonian. We assign the age of the Serwah trackways to the Kimmeridgian-Middle Tithonian (Schulp and Al-Wosabi 2012). These sections occurring at Jabal Riyam and Jabal Al-Nadef were deposited in a shallow marine environment and the dinosaur footprints have been preserved in the sediments of a restricted platform (Al-Ammari 2011) (Fig. 7a, b).

3 Dinosaur Tracksites

The first bipedal dinosaur trackway in the Arabian Peninsula was discovered in 2003 in the Serwah site (Madar village, Arhab area). In 2007, searches for dinosaur trackways were expanded to include adjacent areas by a collaborative project between Yemen Geological Survey and

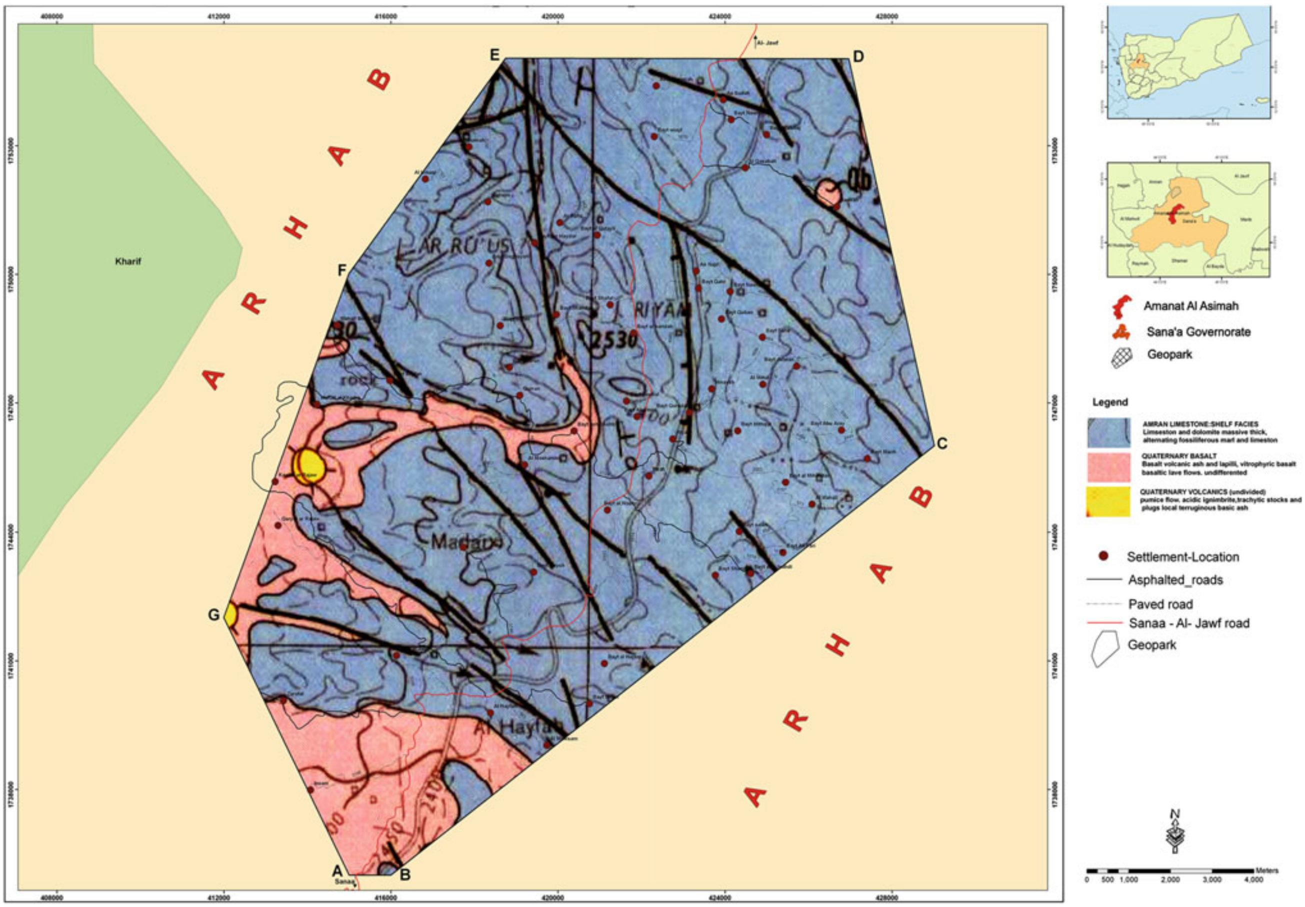

Fig. 2 Geologic map of the proposed geopark

Fig. 3 "*Nerinia*" the abundant gastropod indicated to the upper Jurassic age

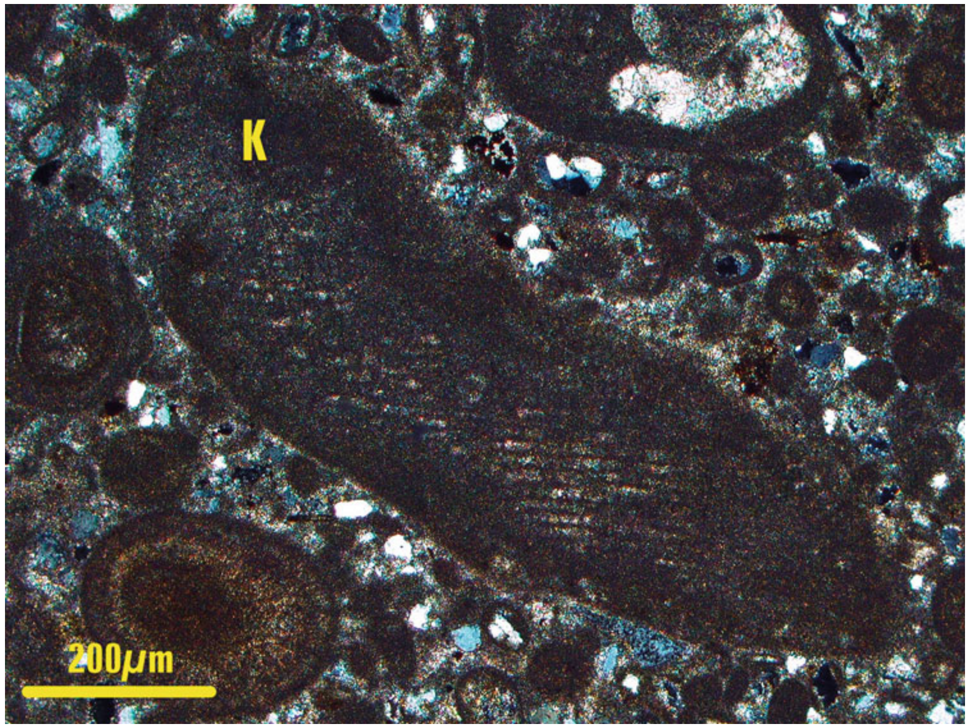

Fig. 4 *Kurnubia plastiniensis* Henson (K), a foraminiferal species indicated to middle-upper Jurassic

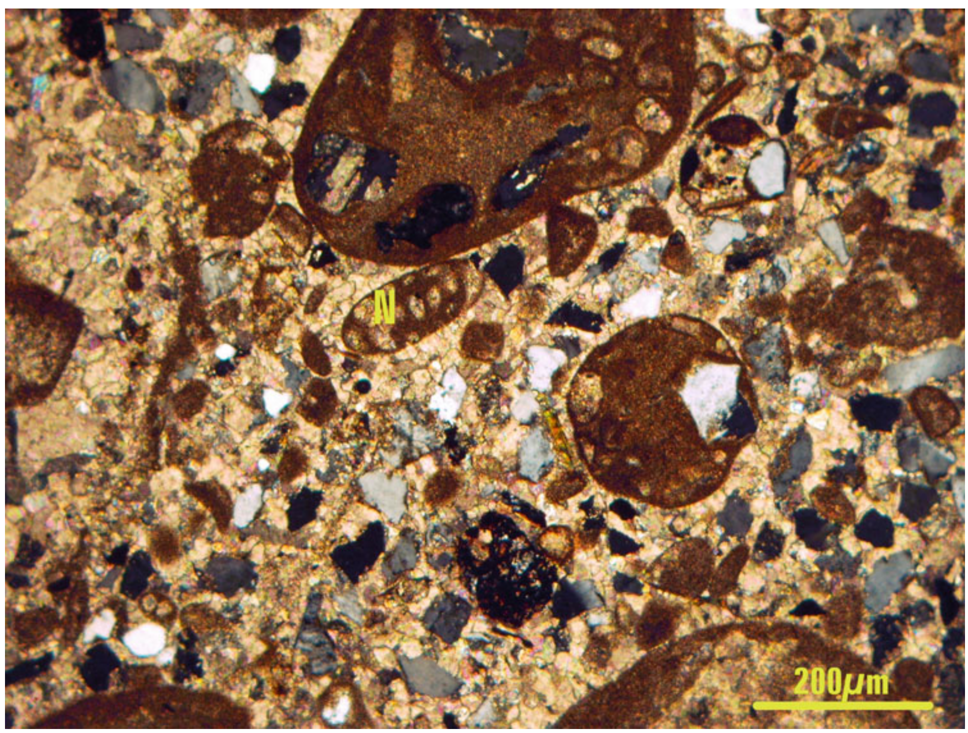

Fig. 5 *Nautiloculina oolithica* Mohler (N), a foraminiferal species indicated to the upper Jurassic

Mineral Resources Board (YGS), Sana'a University and externally by Maastricht Natural Museum (Netherlands) and Ohio University (USA). This collaboration culminated in the publication of the first paper on the subject (Schulp et al. 2008).

By the end of 2010, 40 dinosaur tracksites had been recorded over a vast area covering 200 km^2. These tracksites contain bipedal, quadrupedal and strange bipedal dinosaur footprints that may be metatarsal prints according to Kuban (1989).

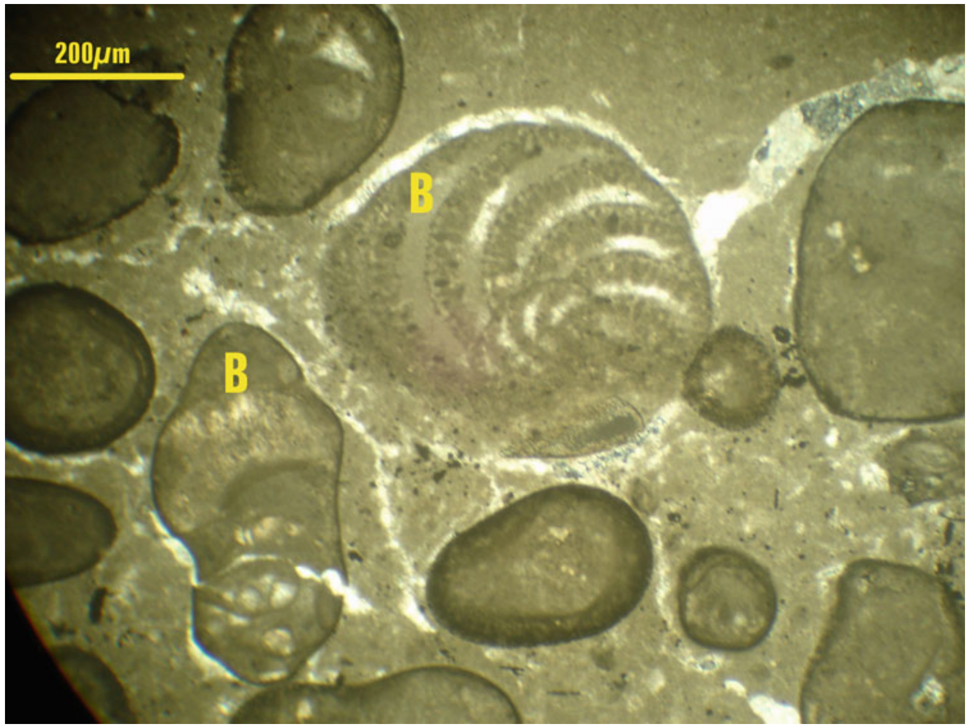

Fig. 6 *Bramkampella arabic*a Redmond (B), a foraminiferal species indicated to the Berriasian age

Only the best-known tracksites located in Madar and Bait Sha'afal villages will be described below, while general information about the other geosites are given in Table 1.

3.1 Geosites of Madar Village

In 2003, the first dinosaur footprints were discovered in many sites near Madar village (Fig. 8) in a distinctive yellowish fossiliferous limestone layer, except for the Al-Nadef site where they appear at different stratigraphic levels (Fig. 7b). Below is a review of the first discovered footprints sites within Madar Village at the Serwah geosite.

The Serwah geosite consists of the first and main discovery of bipedal dinosaur footprints in Yemen and in the Arabian Peninsula. It is accessible via an unpaved road from Madar village. Schulp et al. (2008) described this trackway as the first discovery of a bipedal tridactyl series spanning 14 m; it shows 15 consecutive tracks directed SSW. These footprints were referred to ornithopods (Schulp and Al-Wosabi 2012). This geosite was fenced in 2006 by the YGS (Fig. 9a, b).

At the same site, eleven trackways were discovered next to the first bipedal trackway; these are quadrupedal dinosaur tracks belonging to the large dinosaurs "Sauropod" (Schulp et al. 2008) (Fig. 10a, b). They preserve evidence of large and small quadrupedal animals traveling together in a herd. The longest trackways currently preserves 16 consecutive footprints. As with the bipedal trackway, potential exists for discovering additional tracks by further exposing the layer along the northern edge of the site. We refer these quadrupedal tracks to neosauropods based on the anteroposteriorly short, u-shaped manus impressions suggesting an arc-shaped articulation of metacarpals, as observed in the Neosauropoda. The quadrupedal trackways at Arhab are relatively narrow-gauge, with the left and right pes tracks touching [but not overlapping] the trackway midline, unlike the wide-gauge trackways typically associated with titanosauriforms. Given this narrow-gauge stance, together with a more derived, arc-shaped manus impression, quadrupedal tracks at Arhab were likely made by nontitanosauriform neosauropods. Additional tracks have been recognized nearby, within Bait Al-Washr village (Fig. 11), 4 km south of Serwah site.

3.2 Geosites of Bait Sha'afal Village

This is the most remote area of recorded dinosaur footprints in the proposed geopark area. The tracks within this village are easily accessible from the main road linking the capital Sana'a and Al-Jawf District at coordinates 0421775 and 1749626 (Fig. 8). Several geosites were discovered around this village such as Jern Bait Derhem, Masqa Al-Jerbah, Al-Saleel, Ad Darb, Bait Al-Muslem and Haid Eraij (Fig. 1 and Table 1). The famous geosite in Bait Sha'afal is Masqa Al-Jerbah which is a part of the track of 150 m linking the main road and Bait Sha'afal village (Fig. 12). Many bipedal and quadrupedal trackways have been recorded here, though most are poorly preserved. The longest bipedal trackway is

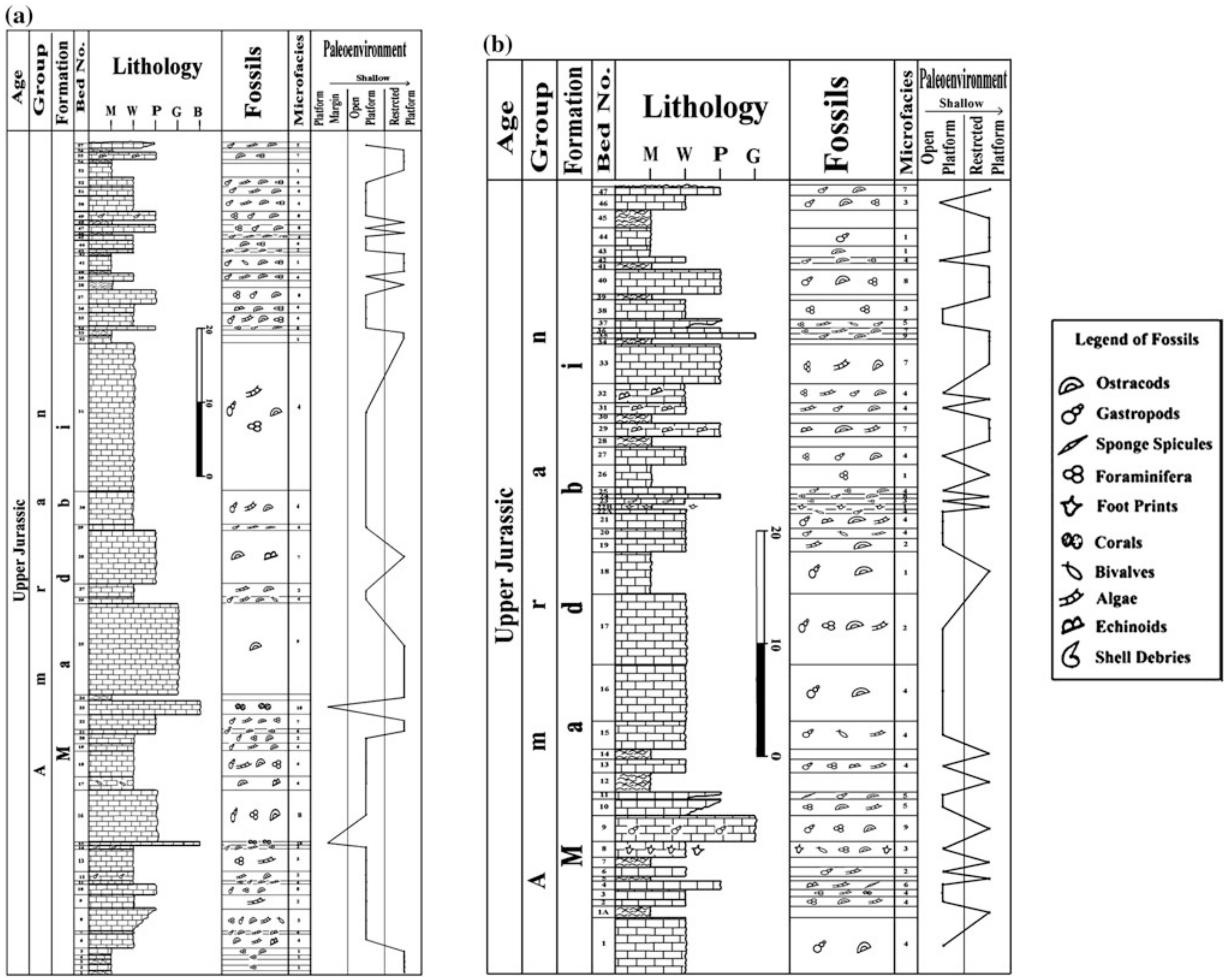

Fig. 7 **a** Lithic log, fossil content and depositional environments of the Madbi Formaion in Riyam section (After Al-Ammari 2011). **b** Lithic log, fossil content and depositional environments of the Madbi Formaion in Al-Nadef section (After Al-Ammari 2011)

175 m consisting of 102 footprints and contains the largest footprint in the region (82 cm length and 80 cm width) (Figs. 13 and 14). This geosite, used as a road for vehicles, chariots and people, is very vulnerable and is subject to degradation. According to Marty et al. (2004), the trackway in this geosite will be the fourth longest trackway and the second in Sauropod footprint number in the world.

4 Archaeology of the Region

The proposed geopark area consists of many archaeological sites such as the Madar, Riyam and Itwah villages. Many of them are still in a good state of preservation and, although as such, they are scavenged for building stones. During our visits to the area, we noticed that there are many archaeological artifacts in the houses of the local populations such as statuettes and inscriptions. Al-Hamadani (1981) described in his famous book "*Al-Ekleel*" many archeological sites in these three villages which relate to Pre-Islamic and Islamic periods. Bafakih et al. (1985) provided a detailed description supported by photographs of many archeological artifacts that were dated back to the covenants of the Sheba and Hemiar Kingdoms. Many of the relics have been stolen or broken and the remains need to be explored by the relevant government bodies. There are many of these monuments, artifacts and inscriptions in foreign museums.

5 Risks and Protection Status

Fossil occurrences across the world are endangered by development, construction, collecting, and vandalism, even though many outstanding examples have been protected as

Table 1 Locations and types of tracksites of dinosaur footprints in the region

NO	Site	X	Y	Trackways	
1	Zarafat	413610	1739690	A bipedal trackway, 21print	
2	Bait Hatem	414591	1648897	A bipedal trackway	
3–28	M a d a r sites	Serwah (A)	418623	1744778	A bipedal trackway, 16 print
		Serwah (B)	418571	1744821	11 Quadrupedal trackways & 3 bipedal trackways
		As Serar	418793	1744406	A bipedal & several Quadrupedal trackways
		Al-Khashabi	417780	1745466	A bipedal & several Quadrupedal trackways
		Al-Nadef (A)	416030	1744293	A bipedal trackways
		Al-Nadef (B)	416102	1744468	A bipedal trackways
		Jabal Hared	417509	1745348	Quadrupedal trackways
		Al Bakri	417410	1744921	Quadrupedal trackways
		Saqiat Al-Qail (A)	417780	1743942	Bipedal trackways
		Saqiat Al-Qail (B)	417680	1744074	
		Saqiat Al-Qail (C)	417525	1744115	
		Saqiat Al-Qail (D)	417161	1744164	
		At Tannor	417204	1743315	Bipedal trackways
		Shea'ab Bait As Shami	416902	1743383	Bipedal trackways
		Saqiat Al-Mashannah	416977	1743364	Bipedal trackways
		Hadhirat Bait Hajeb	416191	1743871	Bipedal trackways
		Al-Nejr (A)	415531	1744042	Bipedal trackways
		Al-Nejr (B)	415491	1744048	Bipedal trackways
		Al-Nejr (C)	415329	1744079	Bipedal trackways
		Al-Nejr (D)	415148	1744271	Bipedal and Quadrupedal
		Al-Nejr (E)	415560	1744265	Bipedal trackways
		Al-Nejr (F)	415736	1744158	Bipedal trackways
		Al-Nejr (G1)	415706	1744362	Long heeled Strange bipedal ``metatarsal'
		Al-Nejr (G2)	415662	1744434	Bipedal trackways
		Al-Nejr(H)	415546	1744506	Bipedal trackways
		Ghawl Al-Khanjar	0417685	1742842	Long heeled Strange bipedal ``metatarsal'
29	Al-Mashamin- Bait Sailan	419222	1745594	Bipedal and Quadrupedal	
30	Al-Mashamin- Bait Farhan	419208	1745556	Bipedal trackways	
31	Bait Saifan – Jern of the village	416073	1747643	Bipedal trackways	
32	Bait Saifani- Mirat Thua'a	415899	1747694	Bipedal trackways	
33	Bait Al-Washr	421208	1744530	Quadrupedal trackways	
34	Bait Shandag-Jern Bait saeed	420014	1749002	Bipedal	
35–40	Bait Sha'afal sites	Jern Bait Derhem	421509	749354	Bipedal and Quadrupedal
		Masqa Al-Jerbah	421409	1749444	Bipedal and Quadrupedal
		Al-saleel	421358	1749169	Bipedal and Quadrupedal
		Ad Darb	421569	1748743	Bipedal and Quadrupedal
		Bait Al-Muslem	420341	1749164	Bipedal trackways
		Haid Eraij	420547	1749027	Bipedal trackways

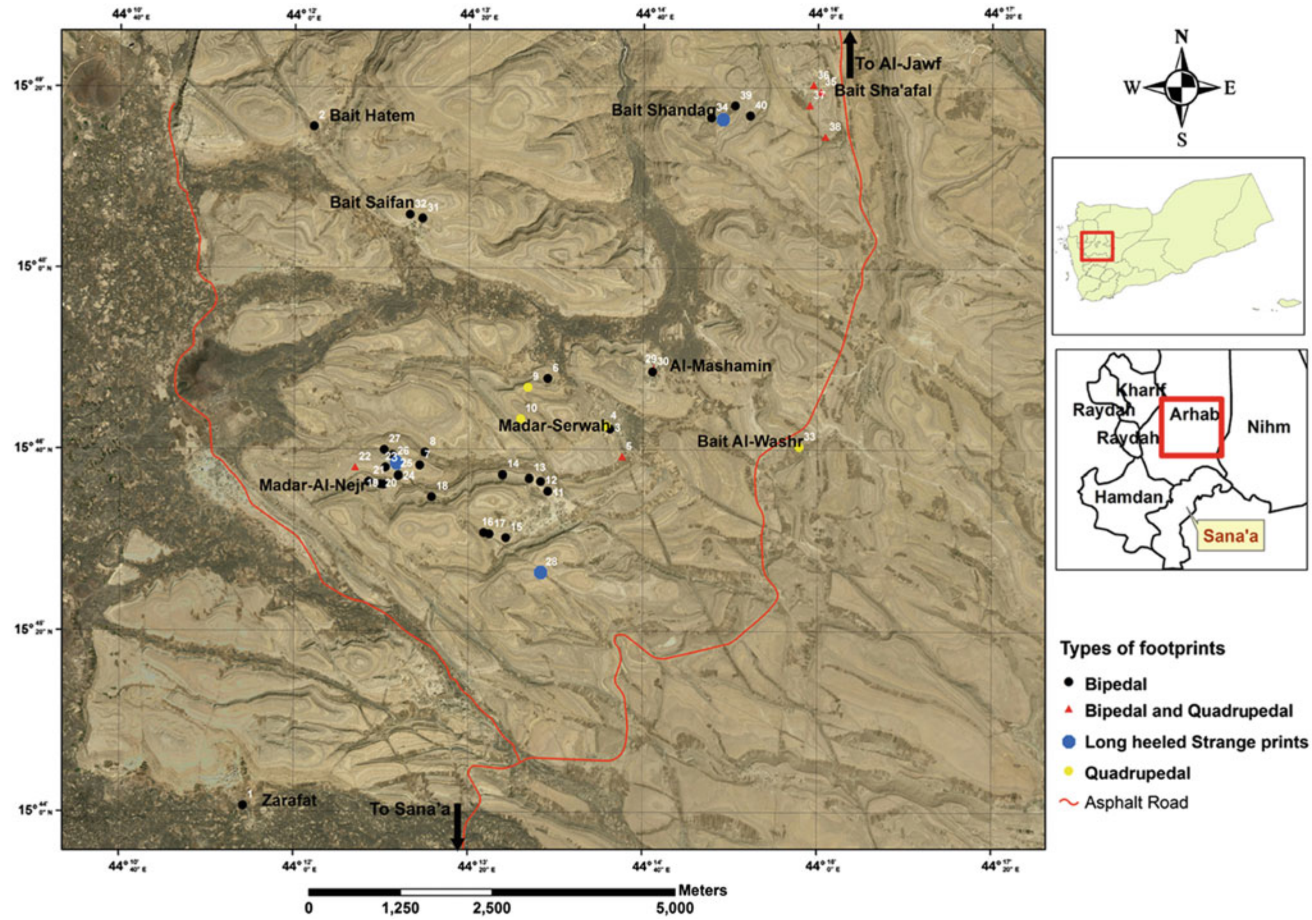

Fig. 8 Distribution of tracksites in the proposed area

Fig. 9 The first discovered tracksite in Sarwah site, Madar village: **a** Before fencing 2003 and **b** After fencing

World Heritage Sites, national parks, monuments and reserves, state and provincial parks. The International Palaeontological Association (IPA) established a PaleoParks Initiative to protect endangered fossils sites as a primary source of scientific data, educational opportunities and recreational activities, as well as key places protecting “living

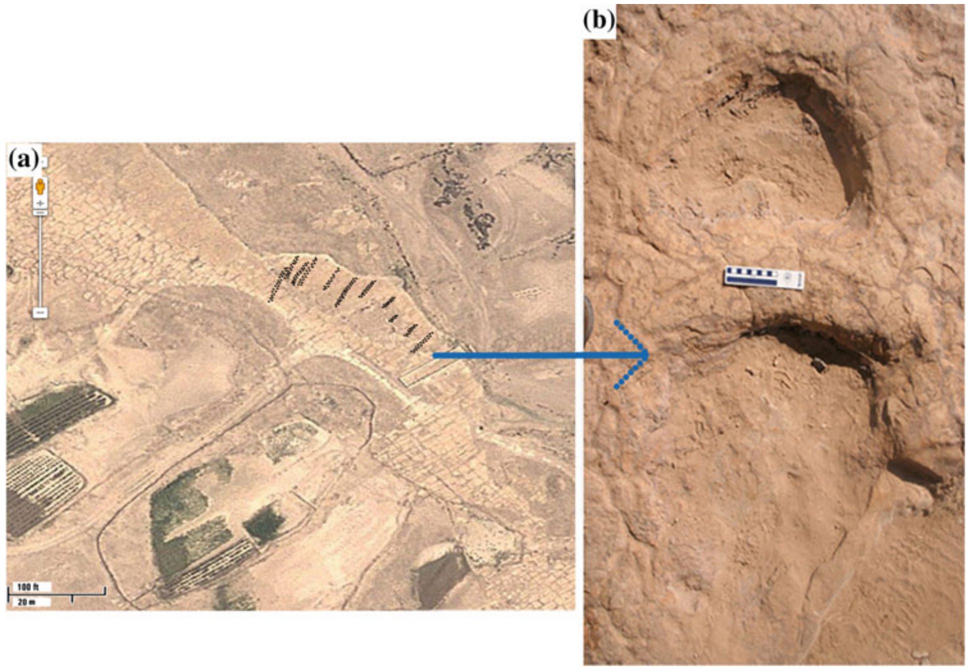

Fig. 10 Sauropods trackways in Serwah site, **a** trackways in the site (Google Earth 2014 with modification) and **b** Sauropod *left* manus and pes print (After Schulp et al. 2008). Source: https://www.google.com/maps/place/Al+Hayfah,+Yemen/@15.7740764,44.247151,802m/data=!3m1!1e3!4m2!3m1!1s0x16016dcafb7b967d:0x34ce9ebe2671bcd8

Fig. 11 Tracksite of quadrupedal dinosaur at Bait Al-Washr site

fossils" (Lipps 2009). Erosion or natural weathering is the main threat to tracksites. If not protected, the tracksites will disappear (Winkler 1987).

In the studied area, there is no protection of any of the described geosites except a simple fence, which was built by the YGS around the first discovered track site in Serwah area (Fig. 9b). The footprints in these geosites may be degraded and destroyed by misuse by local populations and visitors, and by the impact of natural hazards.

5.1 Human Impacts

The human impact on the geoheritage values of the dinosaur trackways is significant and results generally from lack of awareness. Local residents use some track sites as a threshing floor during harvest time and/or as sheds for animals (Fig. 15), and/or as roads/tracks for cars, animals and people (Figs. 12 and 16). Some locals and visitors fill the footprints with water to make them photographically

Fig. 12 Masqa Al-Jerbah location at Bait Sha'afal

Fig. 13 The longest bipedal trackway at Masqa Al-Jerbah, Bait Sha'afal

prominent for filming and viewing (Fig. 17). This causes growth of plants on the edges the prints as well as accelerating the process of decomposition of the host limestone. In addition, limestone is the main source of building stone in the region, therefore; limestone sites are vulnerable to the removal of stone (Fig. 18a, b).

5.2 Natural Processes and Hazards

Natural processes and hazards such as weathering and erosion accelerate the degradation of some geosites. Rain and flooding have led to the chemical decay of limestone rocks bearing the dinosaur footprints (Fig. 19). These latter are

Fig. 14 The largest bipedal footprint in the geopark region at Masqa Al-Jerbah, Bait Sha'afal

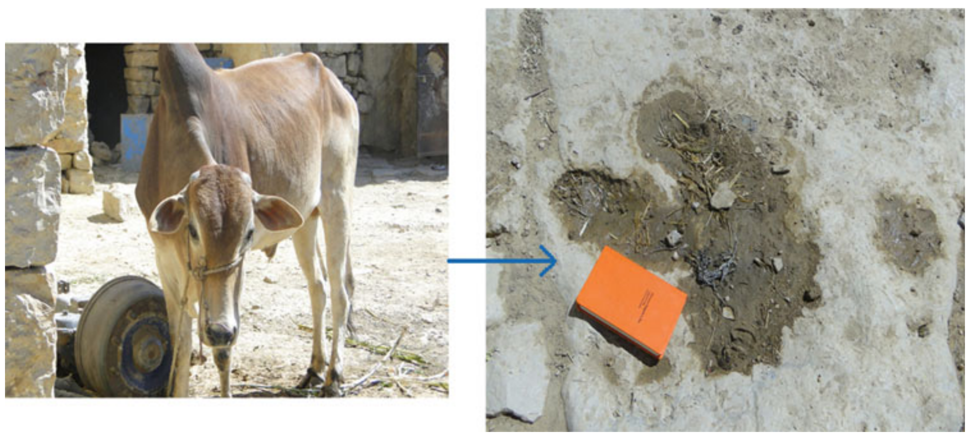

Fig. 15 Using tracksites as cowsheds for the animals

Fig. 16 Some of tracksites represent roads between the villages and used by cars, animals and humans

sometimes covered or abraded by the debris carried by water during rainfall seasons or by wind (Fig. 20). The growth of grasses, herbs and plants in beds containing footprints led to further cracks in the beds bearing the footprints and increase the rate of weathering and the rapid disintegration of these beds (Fig. 21).

Fig. 17 Footprints filled with water to be clear for photography

Fig. 18 **a** Rock layers containing the prints for the purposes of construction (ruler = 20 cm). **b** Limestone rocks are a major source of building stone in the region

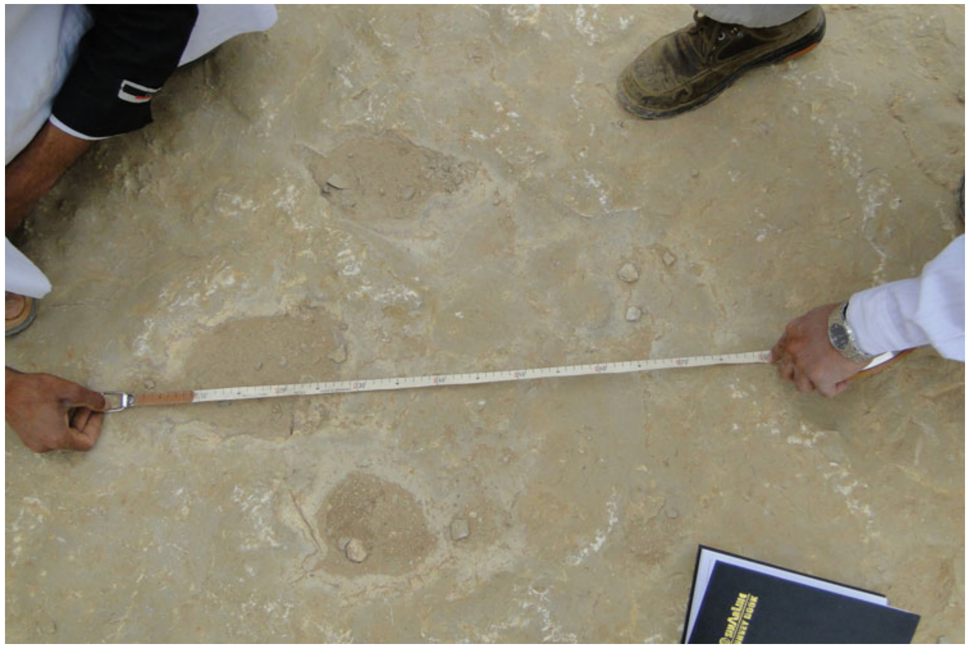

Fig. 19 Decay of limestone rock as a result of the interaction between water and limestone beds

Fig. 20 Many of the tracks covered or abraded by soil during rainfall or wind

6 Discussion and Conclusions

The Arhab tracksites are the first and only discovered dinosaur tracksites in the Arabian Peninsula. They consist of footprints of bipedal "Ornithopods" and quadrupedal "Sauropods". These sites, of global importance, provide a great opportunity for future generations interested in palaeontology and archaeology in Yemen to continue fieldwork and excavations for further discoveries.

However, these sites, of geoheritage importance, are located in open areas in and/or around villages (Fig. 8). Some of them are still in a good state of preservation, while others are degrading under many natural hazards threats (weathering, erosion, climate changes, etc.), as well as misuse by local populations, all of which will probably lead to their loss. Therefore, it is imperative to set up management plans to protect and valorize these sites. At this stage, the only action that has taken place is that the YGS fenced the first discovered sites in Madar village.

Fig. 21 Growth of grasses, herbs and plants in beds containing footprints after rainy seasons

These dinosaur footprints are attracting a large number of visitors. Many broadcasters, local and international television (such as Yemeni and BBC television), and school pupils from different areas in Yemen are visiting these geosites, either for purposes of science or leisure. Inscribing the region as a geopark will augment these activities and contribute to promote sustainable tourism.

Establishing a geopark in the Arhab area will help in developing a detailed inventory of the sites of geoheritage significance, building a management plan for their promotion and protection, promoting local manufactured products, and improving the infrastructure of the area by increasing the living standard of local populations through geotourism. Such a project needs the involvement of local communities and local authorities, the YGS, the Ministry of Higher Education (Museum of sciences), Ministry of Education (National Commission for Education, Science and Culture), Ministry of Tourism, Ministry of Culture (General Authority for Antiquities and Museums).

The proposed geopark in the Arhab area supports a local total population of about 17,000, with a variable density from a village to another due to the migration to neighboring cities. The targeted area is not far from Sana'a, so there are main public services available such as the presence of asphalted roads, power station, primary and secondary schools, and a branch of the faculty of education of Sana'a University. The most common activity in the region is agriculture. The Arhab area consists of many archaeological sites. The local populations are in urgent need of socio-economic development in many fields, and establishing a geopark in this area will help to preserve and promote its geological and cultural heritages for scientific, educational and geotouristic uses, and the return of many crafts and local industries that have ceased or have started disappearing, and will encourage reverse migration.

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Geomorphological Features of the Manengouba Volcano (Cameroon Line): Assets for Geotourism and Other Anthropogenic Activities

Caractéristiques géomorphologiques du volcan Manengouba (ligne du Cameroun): Atout pour le géotourisme et autres activités anthropiques

الخصائص الجيومورفولوجية لبركان مانينكوبا (خط الكاميرون): رصيد للجيوسياحة وأنشطة بشرية أخرى

G.T. Zangmo, A.D. Kagou, D.G. Nkouathio, P. Wandji, and M.D. Gounté

Abstract

Mount Manengouba, a volcanic complex emplaced between 1.5 and 0 Myr, occurs in the Cameroon Line, about 120 km NE of Mount Cameroon, Cameroon. Mount Manengouba culminates at 2,411 m and is characterized by important geomorphological features (geomorphosites), namely, two nested sub-circular calderas (Elengoum and Eboga), broken cones, crater lakes (Female, Male and Beme), and domes and basin (Djeu-Seh). These geomorphosites constitute an asset for geotourism and other anthropogenic activities. The scientific values (rareness, representativeness, integrity…) and additional values (aestheitic, ecological, economic…) Mount Manengouba geomorphosites constitute an enterprise for geotourism. The fertility of the soil favours farming in the downslope areas of the volcano, with the main products being coffee, maize, bananas, fruit and tubers. Hunting and fishing are practiced by craftsmen throughout the year in the forests and Female Lake, respectively. Vegetation cover fosters the practice of animal breeding (beef and sheep) in both calderas and their vicinities. The presence of pyroclastic cones are utilised for quarrying in the region. Pozzolana is the main product that is used as road aggregates, and in the manufacture of concrete, bond-stones and cement. Excursions and research programs are carried out by universities for educating the public about the geological and geomorphological heritage of

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Mount Manengouba. Currently, in the Mount Manengouba region, tourism is not well developed, but it is recommended that, roads be improved to facilitate the accessibility to the geomorphosites, and interpretative panels, guide books and postcards be produced to inform tourists about the geology of the region.

Résumé

Le Mont Manengouba est un complexe volcanique qui s'est mis en place entre 1,5 et 0 Ma, le long de la Ligne du Cameroun, à environ 120 km au NE du Mont Cameroun (Cameroun). Le Mont Manengouba culmine à 2,411 m et se caractérise par d'importants géomorphosites, à savoir, deux caldeiras sub-circulaires emboitées (Elengoum et Eboga), des cônes égueulés, des lacs de cratère (Femme, Homme et Beme), et des dômes et bassin (Djeu - Seh). Ces géomorphosites constituent un atout pour le géotourisme et d'autres activités anthropiques. Leurs valeurs scientifiques (rareté, représentativité, intégrité…) et additionnelles (esthétique, écologique, économique…), confèrent au Mont Manengouba une entreprise pour le géotourisme. La fertilité du sol favorise l'agriculture au piedmont du volcan dont les produits principaux sont le café, le maïs, la banane, les fruits et les tubercules. La chasse et la pêche sont pratiquées toute l'année par les paysans; respectivement dans les forêts et le lac de la Femme. Le couvert végétal favorise la pratique de l'élevage dans les deux caldeiras et leurs environs. La présence de nombreux cônes pyroclastiques donne lieu à l'ouverture de carrières dans la région. Les pouzzolanes, produits principaux, sont utilisés dans les revêtements routiers et dans la fabrication du mortier, des parpaings et du ciment. Les excursions et les programmes de recherche sont exécutés par les universités dans l'optique d'éduquer le public sur le patrimoine géologique et géomorphologique du mont Manengouba. Comme le tourisme n'est pas bien développé dans le Mont Manengouba, il est recommandé d'améliorer les infrastructures routières pour une bonne accessibilité aux géomorphosites, de produire les panneaux interprétatifs, des documents et des cartes postales pour informer les touristes sur la géologie de la région.

ملخص

جبل مانينكوبا هو مجمع بركاني تكون ما بين مليون ونصف سنة إلى الوقت الحالي، على طول خط الكاميرون، وعلى بعد حوالي 120 كلم شمال شرق جبل الكاميرون (الكاميرون). يبلغ علو جبل مانينكوبا 2411 مترا، ويتميز بخصائص جيومورفولوجية هامة، وهي اثنتين من الكالديرا شبه دائرية ومتداخلة، مخاريط مكسورة، بحيرات فوهة البركان، القباب والحوض (دجو – سه). تشكل هذه المواقع الجيومورفولوجية رصيدا للجيوسياحة وأنشطة بشرية أخرى. فجودتها العلمية والجمالية وطابعها الاستثنائي يجعل من جبل مانينكوبا مُنْشَأَةٌ للجيوسياحة. تشجع خصوبة التربة الزراعة بسفوح البركان، ومن منتجاتها الرئيسية هناك القهوة، والذرة، والموز، والفواكه والدرنات. ويُمَارَسُ القنص وصيد الأسماك على مدار السنة من قِبَلِ الفلاحين، على التوالي بالغابات وببحيرة المرأة. الغطاء النباتي يشجع على ممارسة تربية المواشي بالكالديرتين والمناطق المحيطة بها. إن وجود العديد من مخاريط بيروكلاستية يؤدي إلى فتح مقالع بالمنطقة. ويستخدم البوزولانا، المنتوج الرئيسي، في الطرقات وتصنيع الكتل الخرسانية والاسمنت. يتم تنظيم الرحلات وبرامج البحث من قِبَلِ الجامعات بهدف تثقيف الجمهور حول التراث الجيولوجي والجيومورفولوجي لجبل مانينكوبا. وبما أن السياحة ليست متطورة بجبل مانينكوبا، فإنه ينصح بتحسين البنية التحتية للوصول بشكل أفضل إلى المواقع الجيومورفولوجية، وانتاج لوحات تفسيرية ووثائق وبطاقات بريدية لإرشاد السياح حول جيولوجية الموقع.

Keywords

Geomorphosites • Anthropogenic activities • Calderas • Mount Manengouba • Cameroon

Mots-clés

Géomorphosites • Activités anthropiques • Caldeiras • Mont Manengouba • Cameroun

الكلمات الرئيسية

مواقع جيومورفولوجية • أنشطة بشرية • كالديرا • جبل مانينكوبا • الكاميرون

1 Introduction

Cameroon is crossed by a structure called Cameroon Line (CL), which is an oceano-continental axis, comprised of volcanic and plutonic rocks (Fig. 1). It is oriented N30°E and stretches from Gulf of Guinea to Lake Chad (Tchoua 1974). Although there is sporadic occurrence of natural phenomena (Kling et al. 1987; Sigurdsson et al. 1987; Nana 1991; Evans et al. 1993; Tanyileke 1994; Wandji et al. 1994, 1998, 2001; Tchoua et al. 1998, 2001; Njilah et al. 1999; Bardintzeff et al. 2001; Ghogomu et al. 2001; Kagou Dongmo et al. 2005; Zangmo Tefogoum et al. 2009, 2011a, 2012a; Nechia Wantim et al. 2012), these structures represent numerous assets for educational and cost-effective activities. Thus, multi-ethnic populations migrated there; moreover, it is an attraction for national and international researchers, and visitors. In spite of the economic potential of the volcanoes, serious geoheritage studies have not yet been carried out along the CL. Among these volcanoes, Mount Manengouba has been selected for this study. It is characterized by an equatorial climate of the Guinean type, dominated by about 7 months of precipitation in June–October (with an average of 2,742 mm/year) and a dry season of 5 months' duration, with temperatures ranging from 21 to 24 °C (Olivry 1986). Mt Manengouba constitutes a geological heritage dominated by numerous geomorphological features.

The objective of this paper is to identify and study the potential geomorphosites of the Mt Manengouba, this will give an overview on: (1) the touristic potential of the studied area; and (2) impacts of the geomorphosites on farming, breeding, hunting (main income sources for local inhabitants), and educational activities. This will be an important

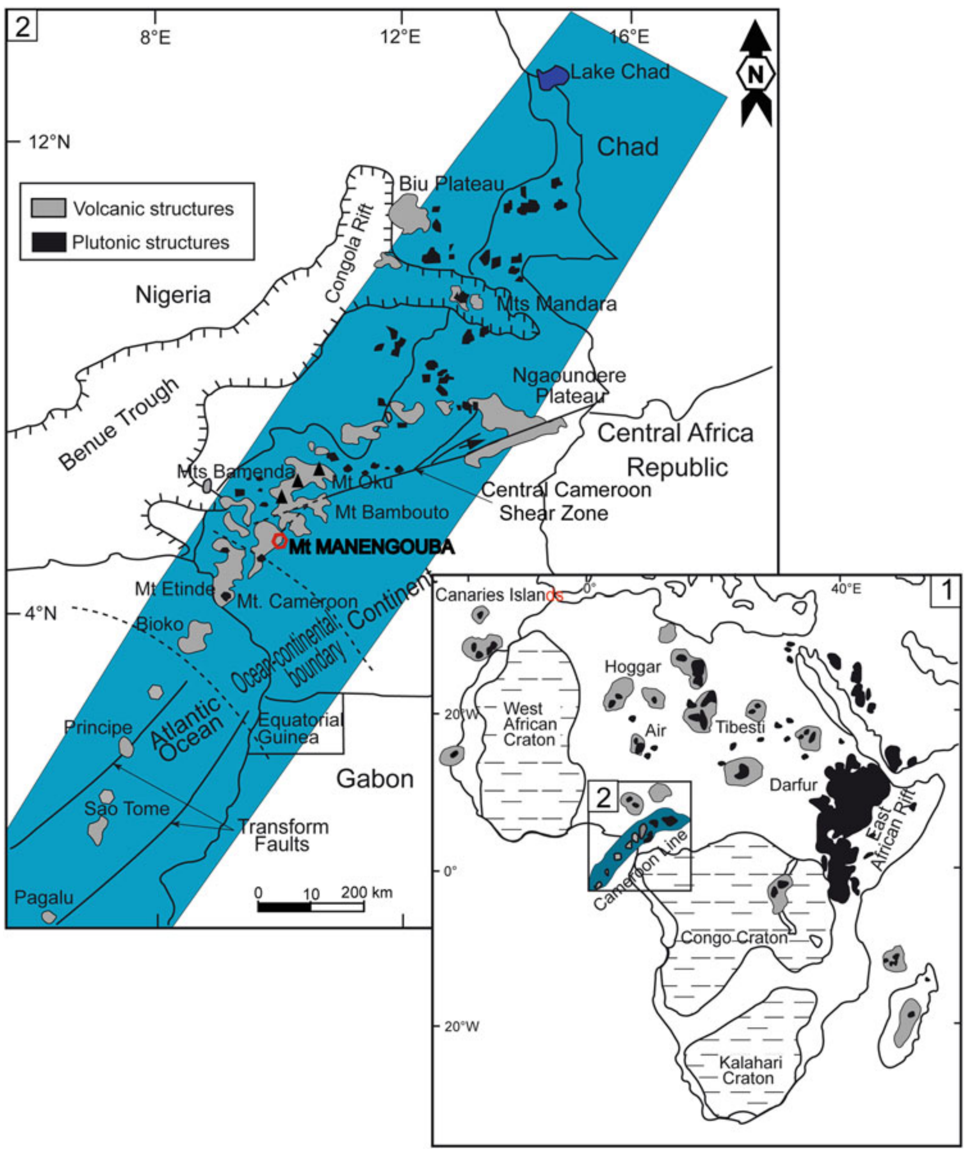

Fig. 1 Cameroon Line (CL) in Africa (*1*); location of Mt Manengouba in the CL (*2*) (from Nkouathio et al. 2008, modified)

contribution in increasing the awareness of the local population about their geoheritage and the necessity for its management for local sustainable development.

According to Grandgirard (1997), Reynard (2005), a geomorphosite is any part of the Earth's surface that is important for the knowledge of Earth, climate and life history. Panizza and Piacente (1993, 2003) and Quaranta (1993), defined geomorphological sites as geomorphological landforms and processes that have acquired a scenic/aesthetic, scientific, cultural/historical and/or a social/economic value due to human perception of geological, geomorphological, historical and social factors.

2 Geological Context

Mt Manengouba was developed by successive emplacement, from 1.55 to 0 Myr, on a 800 m uplifted granite-gneiss substratum of two volcanoes, Elengoum and Eboga, and is situated at about 120 km NE of Mount Cameroon. Mt Manengouba covers an area of 500 km^2 and occurs between the Tombel and Mbo grabens, precisely between longitude 09°42′ and 10°10′ East and, latitude 04°49′ and 05°15′ North (Kagou Dongmo et al. 2005). The maximum height of the whole volcano is 2,411 m and it is located at the south-eastern external slopes of the Eboga caldera.

Mt Manengouba is surrounded by plutono-tectonic units expressed geomorphologically as the Ekomane cliffs to the north (1,685 m), Mount Bakossi to the west (1,678 m), Mount Koupé to the south-west (2,064 m) and Mount Nlonako to the south-east (1,825 m).

Mt Manengouba was characterized by adventive fissural volcanism that gave rise to more than 70 strombolian cones; some of them were initiated by phreato-magmatic explosive events (Kagou Dongmo et al. 1998). Numerous rocks occur at Mt Manengouba such as basalts, hawaiites, mugearites, benmoreites trachytes, dolerites and pyroclastic ejecta (scoria) (Figs. 2 and 3). The outcrop expression of these rocks results in several geomorphological units that comprise the uneven topography of Mt Manengouba.

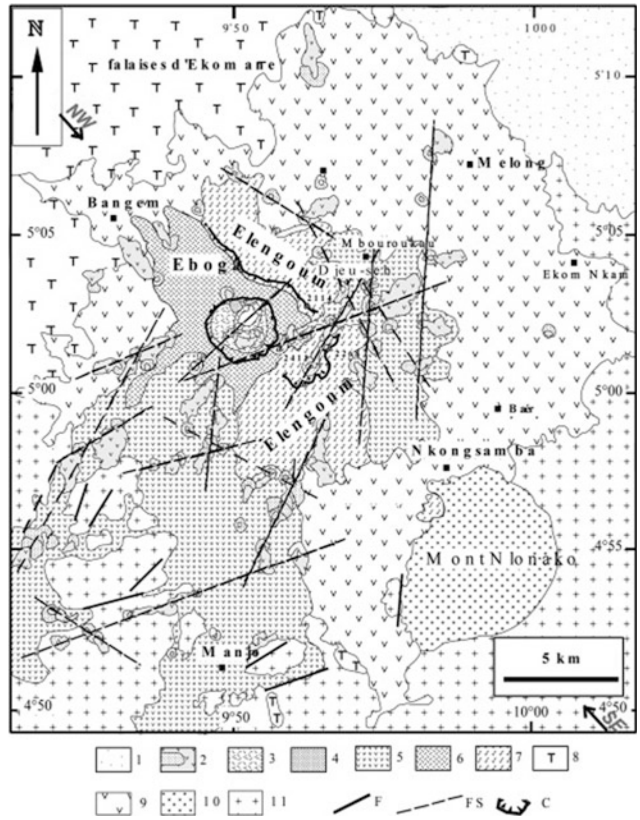

Fig. 2 Geological map of Mt Manengouba. *1* alluvium; *2* recent adventive strombolian volcanoes, with cones and basaltic flows; *3* diatremes-related hyaloclastites in the Eboga caldeira and at Djeu-seh; *4* mugearite extrusions in the Eboga caldeira; *5* piles of basalt and hawaiite flows of the Eboga middle and lower flanks; *6* mafic to intermediate lavas and tephras of the Eboga central edifice; *7* intermediate to acidic (trachytes) lavas of the Elengoum volcano emplaced before the Eboga; *8* old trachytic outpourings, mainly ignimbritic; *9* relative substratum made of Mio-pliocene basaltic plateau flows; *10* pre-volcanic Cenozoic intrusion of syenite; *11* Precambrian granito-gneissic shield; F, fault; FS, fissural system; C, caldera scarp. (From Kagou Dongmo et al. 2005)

2.1 The Geomorphological Features of Mt Manengouba

The high geodiversity (lithological diversity) and the tectonics in this area have been the main influence in developing its distinctive geomorphological features (Meireles et al. 2002; Pereira et al. 2004a, b). In Mt Manengouba, as well as in other volcanoes along the CVL, tectonic events have been underlined by eruptive events (Tchoua 1972; Marzoli et al. 2000; Zangmo et al. 2011b; Gountie et al. 2011). These events created four major volcanic landforms, namely, cones, domes, cliffs and lava plateau (Wandji 1995; Kagou Dongmo et al. 2010), as in the volcanic terrains in the Park of Fogo Island, Cape Verde (Costa 2011). To assess the Mt Manengouba landforms, we undertook a review of the criteria to determine intrinsic values (scientific) and additional values (ecological, aesthetic, economic and cultural) used by Gray (2004), Pereira et al.(2006, 2007), Reynard et al. (2007), Reynard (2008), Ilies and Josan (2009), Pereira and Pereira (2010), Maillard and Reynard (2011) and Reynard and Coratza (2013). The geomorphosites that characterize Mt Manengouba are calderas, broken cones, crater lakes, domes, plug, and basin.

2.1.1 Calderas

Mt Manengouba stands as an example of a Hawaiian shield. At the summit, there are two sub-circular nested calderas: Elengoum and Eboga (Fig. 4). The larger one is the Elengoum caldera, some 6–7 km in diameter, but its margins appear diffuse. The floor of Elengoum is occupied by the

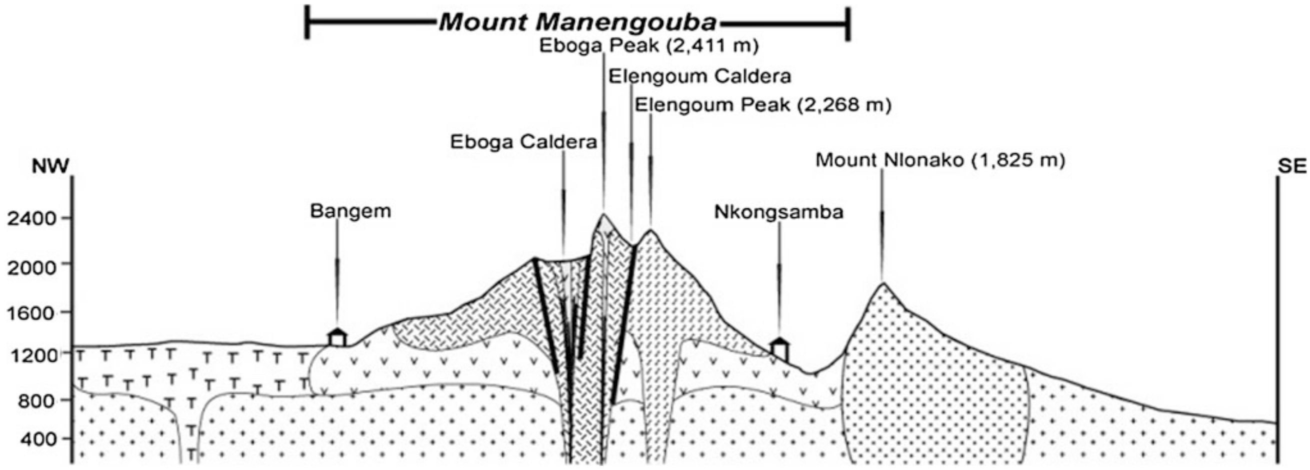

Fig. 3 Geological cross section of the Mt Manengouba (symbols are same as in Fig. 2)

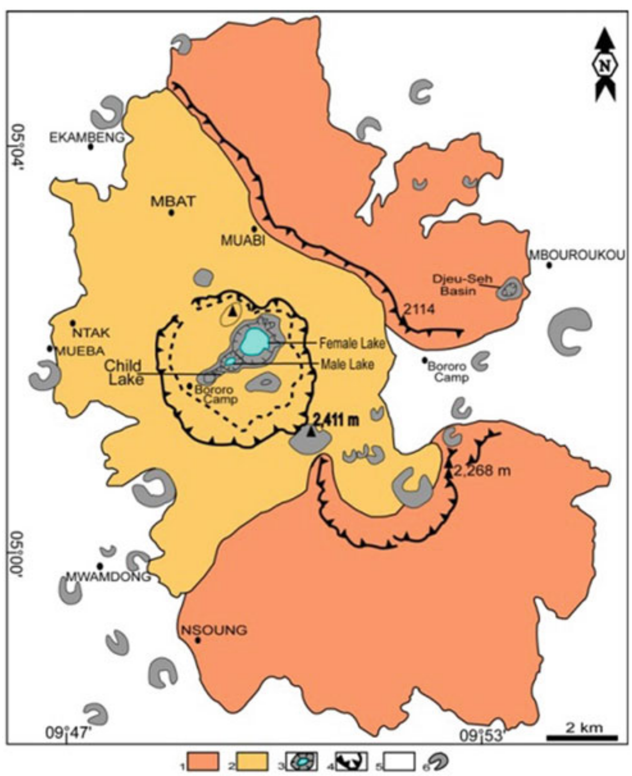

Fig. 4 The Mt Manengouba summit. *1* Elengoum volcano and its caldera; *2* Eboga volcano and its caldera; *3* Crater lakes; *4* Caldera boundaries; *5* Adventive phase flows; *6* Broken cones

smaller Eboga caldera, which is well shaped and 4–5 km in diameter. The floor of the Eboga caldera is slightly flat and approximately 1,900 m in relative relief.

2.1.2 Cones

Volcanic cones result from the accumulation of bombs, ashes and lavas, ejected from the vents of a pre-existing scoria cone (Costa 2011). Mt Manengouba has around 70 cones (Kagou Dongmo et al. 1998) three-quarters of which are broken (Figs. 5 and 6). Broken cones result from lavas that have erupted downslope of the pre-existing cones composed of volcanic ejecta (bombs, cinders, scoria etc.). The slope of a cone will slide under the influence of the loose state of the volcanic ejecta (Kagou Dongmo 1998).

2.1.3 Crater Lakes

The Eboga caldera is characterized by two major crater lakes (Female Lake and Male Lake). Female Lake (Fig. 7) is the larger one of the two, some 22 ha in area and 168 m deep. Male Lake (Fig. 8) is 2 ha in area and 92 m deep (Kling 1988). The temperature of the waters lakes varies from 19.2 to 20.6 °C and from 16.8 to 21 °C, respectively (Tanyileke 1994).

Beside both lakes, in a SW–NE direction lays Child Lake (Fig. 9). This lake is shallow and seasonal. It is recharged during the rainy season. During the dry season, the lake floor is inhabited by natural herbage. Child Lake is not closed like Female Lake and Male Lake, and its outlet is visible in the NW side of Fig. 9.

In the Beme village (NW of Mt Manengouba), there is an important circular crater lake (Fig. 10). This lake is the largest in the region, some 60 ha in area and 14.5 m deep (Kling 1988). It is characterized by steep rims that make accessibility difficult.

2.1.4 Dome and Basin

Mt Manengouba slopes are characterized by several extrusive domes (Kagou Dongmo 2006) that have uneven topography. The most scenic is the mugearite dome called Mboriko (2,067 m altitude), situated in the Eboga caldera (Fig. 11). There is also a spectacular basin called Djeu-Seh (approximately 300 m in diameter and 70 m deep), located on the eastern external slopes of the Elengoum caldera. While this basin is not a lake, its bottom is swampy (Fig. 12).

Fig. 5 Two cones located in the south-western bottom of the Eboga caldera

Fig. 6 Ekambeng broken cone; situate on the north-western flank of Mt Manengouba

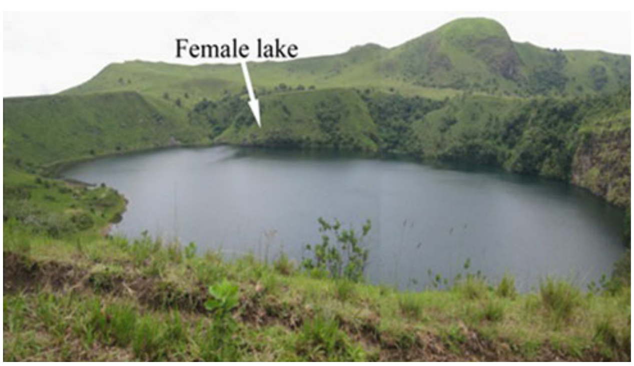

Fig. 7 The female lake in the Eboga caldera

Fig. 8 The male lake in the Eboga caldera

2.2 The Influence of Geomorphology on Anthropogenic Activities

The geomophosites of Mt Manengouba give rise to numerous sustainable anthropogenic activities such as geotourism, agriculture, breeding, animal building, fishing, hunting and education.

2.2.1 Geotourism

Geotourism focuses on the geological and geomorphological heritage of an area (Gavrila et al. 2011). In Mt Manengouba geotourism sites were selected according to five criteria used by Pereira et al. (2009) in the Portugal National Park. These

Fig. 9 The child lake in the Eboga caldera. There is the outset of water accumulation in the beginning of the rainy season

Fig. 10 The Beme Lake

Fig. 11 The Mboriko dome in the Eboga caldera

criteria are: value, vulnerability, accessibility, visibility and spatial distribution. The scientific quality, the aesthetic appeal and the uniqueness of Mt Manengouba geomorphosites such as calderas, crater lakes, broken cones, domes and basin (Zangmo Tefogoum et al. 2012b), constitute an enterprise for geotourism that can be led by foreign and local tourists (Figs. 13 and 14).

In Mt Manengouba, there are several locations that enable tourists to have a panoramic view of the landscape. Geomorphosites of Mt Manengouba have a local, national and international relevance, and this annually attracts more than 600 local and foreign tourists. The local tourists include mainly researchers from the universities, and students from the colleges in Manengouba neighborhood towns and other

Fig. 12 The swampy Djeu-Seh basin

Fig. 13 Tourists (*1*, *2*) in the Eboga caldera

Fig. 14 The excursion of secondary school students in the Eboga caldera

regions of Cameroon. Every year, the tourism activities in Mt Manengouba occur from December to April, and are focused on the Eboga caldera that presents the most interesting features with well-defined rims that exhibits the Mboriko dome, and has three broken cones covered by natural lawn. Female Lake for instance, has a swimming facility, and plays a leading role in craftsmen fishing and traditional ritual issues (Fig. 15).

To facilitate tourism activity in the region and limit the variations of the routes of visitors, Kagou Dongmo et al. (1999), have proposed the following trails:

1. tourists with off-road vehicles can pass through Bangem (NW of Mt Manengouba) to obtain direct access to the caldera;
2. tourists on foot pass through Mbouroukou, and, after 3 h walking on the NE flank of the caldera, they arrive at a

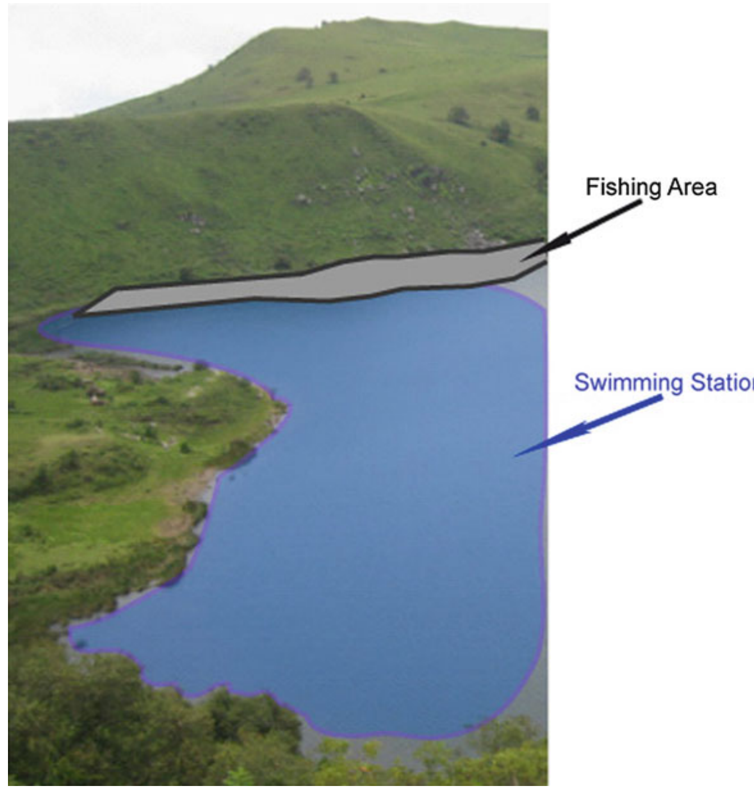

Fig. 15 Swimming and fishing area in the female lake

location where they have a panoramic view of the whole caldera;
3. the third trail for tourists on foot passes through Mouanguel, when, after one and half hour's walking, they arrive on the eastern flank of the caldera;
4. the fourth trail for tourists on foot passes through Nsoung, and, after two and a half hours' walking on the uneven track, arrive on the southern flank of the caldera.

According to Reynard et al. (2003), Pralong (2006), geosites should possess original (or primary) and derived (secondary) tourist attractions. In this region, the original attraction is the geology (rocks, crater lakes, volcanoes, domes, etc.) and the derived attraction is the set of infrastructures, goods and services that are offered to tourists to facilitate their visit. As presented above, the Mt Manengouba geomorphosites are the primary attraction in the region. The secondary attractions are not well developed, nevertheless there are infrastructures such as accommodation in the closest village to the calderas (Zangmo Tefogoum et al. 2012b), and two degraded shelters in the Eboga caldera. One of the limits of the derived tourist attractions is the lack of guide books and interpretative panels.

2.2.2 Farming, Breeding and Hunting

In several cases geomorphosites provide the basis for human occupation and biodiversity (Ferreira et al. 2001; 2003; Alves et al. 2004). However, while biodiversity encourages human activities, it can be threatened by them. The geological and biological diversity of Mt Manengouba has attracted a multi-ethnic active population (Mbo, Bakossi, Bamileke, Bamenda and Bororo) who settled there to undertake agriculture, animal breeding and hunting.

Farming The Manengouba volcano is underlain by Ando soils developed on basic volcanic rocks (mainly basalts and pyroclastic ejecta) that contain fertilizing elements (Kagou Dongmo et al. 1999). This promoted the practice of farming that is well developed in the downslope areas of Mt Manengouba. More than ten types of crops are grown: coffee, cacao, plantains, bananas, melons, tubers (manioc, yam, and tarot), maize, potatoes, beans, fruit (avocado, sugar cane, pineapple) and pigments (Fig. 16). These products are marketed in some of the villages near the volcano.

Breeding and hunting Mt Manengouba geomorphosites are strewn by vegetation comprised mainly of forests and meadow as natural herbage (Fig. 17). The latter supports animal breeding at the summit of the volcano. Stock raising (cattle and sheep) is practiced in the calderas (Fig. 18). The annual income from this activity is about USD 290,000 (ZangmoTefogoum et al. 2011b).

There are two categories of forest: gallery forests located in the Eboga caldera, and forest reserves (Bakaka, Manehas, Mekombé and Eko) that are mainly distributed in the

Fig. 16 Crops harvested in Mt Manengouba. *1* Plantains and bananas; *2* pineapples; *3* sugar canes; *4* tarots; *5* maniocs; *6* gingers; *7* yams; *8* potatoes; *9* avocadoes; *10* palm oil; *11* cocoa; *12* coffee; *13* dry manioc for many purposes; *14* mangoes

Fig. 17 The Northern rim of the Eboga caldera that highlights a primary school enclosed by a natural marvelous lawn

Fig. 18 The breeding activity highlighted by sheeps flock (*1*) and cattle herd (*2*)

Fig. 19 The forest reserve in the Beme village

Elengoum caldera and on the external slopes of the whole volcano (Fig. 19). Both forest types, due to the richness of their fauna, support hunting; however, hunting is the less-developed activity in the region.

2.2.3 Civil Engineering Works

Mt Manengoubais is composed of several rocks types (Kagou Dongmo et al. 2005; Zangmo Tefogoum 2007; Zangmo Tefogoum et al. 2011a). The most widespread is pyroclastic ejecta that formed the numerous cones in the volcano, and consists mainly of pozzolana that reacts with lime to form the cement (Wandji and Tchoua 1988). As such, pozzolana is used for the local manufacture of cement and for civil engineering works which led to the opening of several quarries by local councils and residents on the flanks of Mt Manengouba (Fig. 20). Moreover, the friability of pozzolana renders it useful in manufacturing bond-stones and concretes, and in the surfacing of roads and terraces (Fig. 21). Blocks of volcanic rocks are also used for the building of foundations and the surfacing of walls and road embankments.

The greatest threat to the geodiversity in this region is probably the ignorance about the potential impacts and activity (Gray 2008). Quarrying is the main threat to the Mt Manengouba geomorphosites. More than three quarries are deserted, but they now represent an anthropogenic landscape that plays a scientific and educational role in geotourism (Gavrila et al. 2011).

2.2.4 Education

Mt Manengouba geomorphosites are important assets for research and science. Due to its geological history, petrographic variability, structure and geomorphology, many field studies are carried out by secondary schools and universities and other research institutions. Young scientists undertaking Masters and Ph.D. degrees are increasingly focusing their research in this region (Fig. 22).

There are several tens of streams and four thermo-mineral water springs in this region. The major streams are the collecting zone of smaller streams and are very useful for local purposes. The thermo-mineral water springs are found in Baré, Ngol, Nsoung and Bangem (Tchoua 1974; Kagou Dongmo et al. 1999). Thermo-mineral water springs (Figs. 23 and 24) are a post-volcanic product in Mt Manengouba. Thus, they are helpful in the training of scholars in the volcanic processes along the CL.

Fig. 20 Some opened quarries in Mt Manengouba surrounding villages: *1* Njombé, *2* Njom, *3* Ndom and *4* Ekoh

Fig. 21 Coating of road with the pouzzolana in the Njom Village

Fig. 22 Students fields work in Mt Manengouba

3 Discussion and Conclusions

Mt Manengouba is one of the most popular volcanoes along the CL. It constitutes a geomorphological heritage of a volcano emplaced between 1.5 and 0 Myr. It has some important assets that foster numerous cost-effective educational and economical activities. To that end, several active local populations (Mbo, Bakossi, Bamileke, Bamenda and Bororo) are still migrating and settling there.

Mt Manengouba geomorphosites are characterized by fertile soils and diversified vegetation. The fertile soils promote the farming of several crops that are marketed in the village near the Manengouba volcano. The meadow and

Fig. 23 The reddish thermo-mineral water spring in the Ndibse village. There is a colorless fresh water stream that is quite close to the hot spring

Fig. 24 The thermo-mineral water spring in the Baré village

forest vegetation of the region underpin animal breeding and hunting respectively. The competition for the green space gave rise to tribal conflicts that led to the settlement of animal breeders on the summit and crop farmers on the downslope areas of the volcano.

The geomorphological features of Mt Manengouba consist of two nested sub-circular calderas, three permanent lakes, basin, domes and broken cones, and natural herbage (Fig. 25). The uniqueness of the geomorphological features and the thermo-mineral water springs in the region gives Mt Manengouba its local, national and international importance. Accordingly, every year, local and foreign tourists visit the area, though their number is still insignificant. The main threats to Mt Manengouba tourist assets are the opening of quarries on pyroclastic broken cones, the over-grazing of pastures, the deteriorating state of the roads and the lack of shelters in tourist sites. The geomorphosites of the summit of Mt Manengouba (calderas, lakes, cones and dome) are the main tourist attractions. In view of this, it is a necessity to:

1. amalgamate the stock breeders in a single location and create stock farms to avoid overpasturing;
2. control the balance between quarrying and promotion of geotourism;
3. improve and maintain the main itineraries to facilitate the accessibility to the geomorphosites;
4. create new tourism tracks in the Mt Manengouba area;
5. train local guides;
6. provide interpretative panels and adequate documentation to highlight the geological interest of the area;
7. foster cost-effective activities (handicrafts, shops, inns or hotels) to improve the local economy; and
8. establish a museum for the exhibition of rock samples, geological maps, tourist sites map, postcards etc.

Although the fact that most of geomorphosites of Mt Manengouba are well exposed and can attract mass tourism which can progressively influence their integrity in the region, there is no specific legal protection of the geosites. However, geomorphosites constitute the centre of interest of numerous research endeavours that could play an effective role in raising the awareness of the local population and

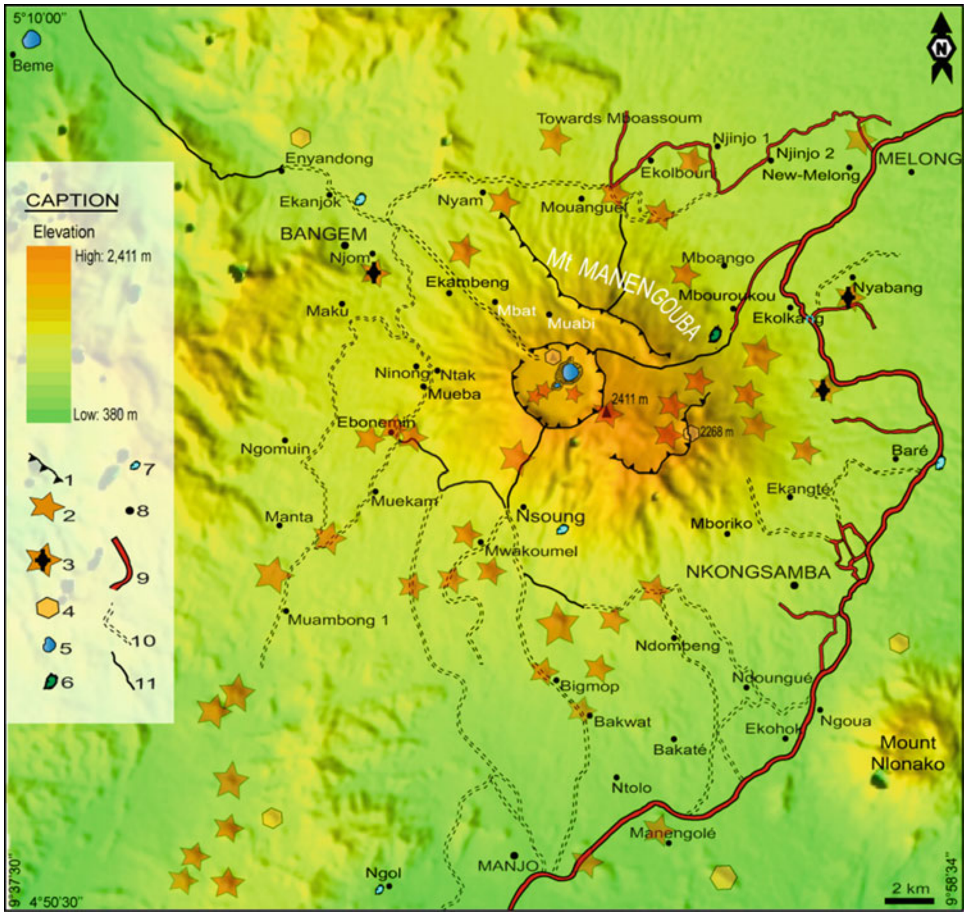

Fig. 25 Geomorphological features of Mt Manengouba of geoheritage significance. *1* Caldera boundaries; *2* cones; *3* quarries; *4* domes; *5* lakes; *6* basin; *7* thermo-mineral water springs; *8* settlements; *9* asphalted roads; *10* off-road vehicle tracks; *11* pedestrian tracks

visitors about the necessity for the protection and valorization of sites of geoheritage significance in the region. Thus, through the African and Arabian Geoparks Network which promotes geoparks in Africa and the Middle East, we hope to create the first geopark in Cameroon in the region of Mt Manengouba.

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Enhancing the Geological Heritage of the Apuan Alps Geopark (Italy)

Valorisation du géopatrimoine du Géoparc des Alpes Apuanes (Italie)

تعزيزجيوتراث جيومنتزه أبوان ألب بإيطاليا

A. Amorfini, A. Bartelletti, and G. Ottria

Abstract

The geoheritage of the Apuan Alps Geopark is represented by outstanding examples of tectonic structures, a variety of rocks and minerals, hypogean karst systems and geomorphological landforms. Archaeological investigations and historical records indicate a long history of mining and quarrying and record the sociological impacts of these activities. Long before the term 'geopark' came into common usage, the Park's Authority sought to integrate the rich geological heritage of the area with the promotion of sustainable geotourism. Three cultural and tourist attractions related to geosites of special significance and beauty were identified (the Corchia Underground System, the Karst-palaeontological Park of Equi Terme Caves, and the Archaeo-mining area of the "Bardiglio Cappella" marble). These attractions constitute the main tangible assets of the Geopark. Using Geopark's attractions and experience as a case study, this paper describes the development of projects to popularize geology through environmental education, publications, websites and partnerships with universities and agencies for research and environmental protection.

Résumé

Le géopatrimoine du Géoparc des Alpes Apuanes est représenté par des remarquables exemples de structures tectoniques, une variété de roches et minéraux, de systèmes karstiques hypogés et autres éléments géomorphologiques. Les recherches archéologiques et historiques révèlent une très longue activité dans le temps des minières et des carrières et elles enregistrent les impacts sociologiques de ces entreprises. Bien avant que le terme de "géoparc" soit entré dans l'usage commun, l'Autorité du Parc a cherché à intégrer le riche patrimoine géologique de la région dans la promotion du géotourisme durable. La même Autorité a identifié trois attractions culturelles et touristiques liées aux géosites d'importance spéciale et d'attrait particulier (le Système souterrain de Corchia, le Parc karst-paléontologique des Grottes d'Equi Terme, et le site archéologique des carrières du marbre "Bardiglio Cappella"). Ces attractions constituent les principales activités tangibles du Géoparc. En utilisant ces attractions et l'expérience du Géoparc comme un cas d'étude, cet article décrit le développement de projets de divulgation de la géologie à travers une éducation environnementale, des publications, des sites Web et des partenariats avec les universités et autres organismes de recherche et conservation de la nature.

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ملخص
إن جيومورروث جيو منتزه منطقة أبوان ألب مُمَثَّلٌ بنماذج بارزة من البنيات التكتونية، ومجموعة متنوعة من الصخور والمعادن، وأنظمة كارسية وتضاريس جيومورفولوجية. تَكْشِفُ الحفريات الأثرية والتاريخية عن تاريخ طويل من أنشطة التعدين واستغلال المحاجر، وتُسَجلُ الآثار السوسيولوجية لهذه الأنشطة. قبل فترة طويلة من دخول مصطلح "جيومنتزه" حيز الاستعمال الشائع، سعت الهيئة المشرفة على المنتزه إلى دمج التراث الجيولوجي الغني للمنطقة في الترويج للجيوسياحة المستدامة. تم تحديد ثلاثة عوامل جذب ثقافية وسياحية مرتبطة بجيومواقع ذات أهمية استثنائية وجمالية خاصة، (نظام تحت الأرض "كورشيا"، ومنتزه كهوف " *إكي تورم*"، ومنطقة التعدين العتيق للرخام "*باردیكليو كابيلا*")، هذه المعالم تشكل الرصيد المادي الرئيسي للجيومنتزه. وباستخدام هذه العوامل وخبرة هذا الجيومنتزه كنموذج للدراسة، يوضح هذا المقال كيف يتم تطويرُ مشاريعَ تعميمِ الجيولوجيا من خلال التربية البيئية، والمنشورات، والمواقع الالكترونية، وإقامة شراكات مع الجامعات ومؤسسات البحث وحماية البيئة.

Keywords
Geosites • Geodiversity • Geoheritage • Apuan Alps • Italy

Mots-clés
Geosites • Géodiversité • Géopatrimoine • Alpes Apuanes • Italie

الكلمات الرئيسية
جيومواقع • جيو تنوع • جيومورروث • أبوان ألب • إيطاليا

1 Introduction

The Apuan Alps Geopark, founded in 1997, belongs to the European and the Global Geoparks Networks since 2011. It comprises the Apuan Alps, an orographic mountain range in the northwest of Tuscany, in Northern-Central Italy. The Alps reach an altitude of almost 2,000 m. They are separated from the main range of the Northern Apennines to the east by the Serchio valley, and are limited to the west by the Versilia plain at a short distance from the Ligurian Sea (Fig. 1).

The outstanding environmental value of the Apuan Alps has long been acknowledged and this has allowed the area to be subjected to environmental protection under the jurisdiction of the Nature Park of the Apuan Alps, the regional authority defined by the Law No 65/1997 of the Tuscany Region. The Geopark represents, in a relatively limited area (about 500 km^2), an exceptional geological heritage (Gray 2004). The interpretation of this Apuan geoheritage provides insight into many fundamental geological processes and Earth Science concepts, such as tectonics, geomorphology, mineralogy, glaciation and glacial landforms, karst

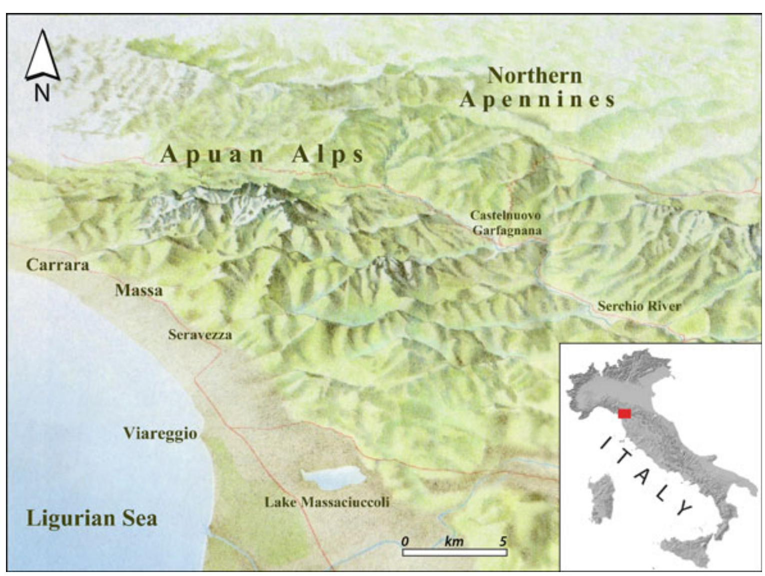

Fig. 1 Geographic location of Apuan Alps in Northern-Central Italy

hydrogeology, palaeoclimatology and geological hazards. However the Apuan Alps owe most of their fame to the beauty of their marbles as well as to the large caves of the karst underground.

This paper describes the geoheritage of the Apuan Alps, from an historical perspective of the quarrying and mining activities and the geological research into geotourism (Newsome and Dowling 2006; Hose 2012).

An important objective of this paper is to share with the aspiring geopark community the main actions taken by the Apuan Alps Geopark Authority to enhance knowledge and understanding of the Park's geoheritage. This contribution is mainly directed to territories, such as those in Africa, that are taking their first steps in establishing geoparks under the umbrella of the African Geoparks Network. For such projects that are at an early stage of development, it is important to start with clearly defined objectives consistent with the global Geopark concept.

2 Apuan Alps History: Quarrying, Mining and Geological Research

Human activity has long been closely associated with the georesources of the Apuan Alps. Indeed, quarrying of the Apuan marbles is the longest lasting such activity in the world and probably it is also one of the most fruitful in terms of the quantity and quality of the extracted ornamental stones. As far as we know, quarrying and first marble artifacts date back to the Etruscans in the second half of the 6th Century B.C. (Bruschi et al. 2004; Bartelletti and Cantisani 2011). Then, throughout the Archaic and Hellenistic ages and later, during the Roman times, Apuan marbles (known as Lunense Marble and later as Carrara Marble) provided the material for the major sculptures and civil and religious monuments that spread all over the Roman Empire (Ward-Perkins 1977; Dolci 1988; Granger et al. 2011). However, during the Renaissance, more than in any other historical period, a large number of sculptors (e.g., Michelangelo Buonarroti) turned to the Apuan Alps for their white marble. Over time, the quarrying activities have focused on almost every metalimestone, metabreccia and calcareous schist occurring in the Apuan Alps, introducing to the market many commercial varieties of stones with various names and uses (Carmignani et al. 2007).

The first exploitation of ore deposits also took place during the Etruscan and Roman periods, but it was only during the 16th century that mining flourished, mainly the working for silver-lead in the Bottino Mines (southern Apuan Alps) (Fig. 2). Industrial exploitation was active in the 19th century but mining ceased after the Second World War when production became uneconomic.

Fig. 2 Old medieval gallery in Bottino Mines in the southern Apuan Alps Geopark (photo by Stefano Pucci)

The Apuan Alps area also has long been of interest to geological researchers because of its economic resources and heritage. In the 18th century, Vallisnieri (1715) developed a new theory about the perpetual water cycle, testing the close relation between springs and karst cavities, thus demonstrating the meteoric origin of the spring waters. The first geological observations were made (Targioni Tozzetti 1752; Savi 1833) and detailed, 1:25.000 scale, geological maps were completed by the end of the 1800s (Zaccagna 1880). Stoppani (1872) and Cocchi (1872) were the first to recognise moraine deposits in the Apuan Alps and presented their findings to the scientific community as the first evidence of Quaternary glaciations in the Apennine belt. In Italy, the interpretation of nappe tectonics was introduced for the first time in the Apuan area (Steinmann 1907). This theory, suggesting the tectonic duplication of the continental margin succession (Tuscan units), was supported by Lencewicz (1917) and Tilmann (1926), and the Apuan Alps were recognised as a tectonic window. Since then, research on the geological evolution of the area has become increasingly detailed, with the identification of polyphase deformations, found to be consistent with the Cenozoic crustal movements of the western Mediterranean area.

The karst caves occurring widely in the Apuan Alps represent an exciting field of scientific investigation. Since the 18th century, the more easily accessible caves have attracted many naturalists (Spallanzani 1783). However, modern speleology is considered to begin in 1840, following the discovery of the first entrance to the Corchia Cave system, the largest in Italy and one of the biggest in Europe (more than 50 km of galleries with a depth of about 1,200 m). In the second half of the 19th and early 20th centuries, the scientific community turned to the Apuan caves specifically for their palaeontological and palaeoethnological interest (Regnoli 1867). During this period, the first true explorations of Grotta all'Onda Cave (Mt. Matanna) and Equi Cave (Lunigiana) yielded many lithic artifacts from the Neolithic to Mousterian and significant remains of extinct Würmian fauna (cave bear, lion, leopard, etc.). The first inventory of the Apuan karst caves dates back to 1913 (Brian and Mancini 1913) and since then investigations have advanced through collective explorations and systematic surveys. To date, more than 1,000 karst caves have been discovered and explored.

3 The Origins of Geotourism in the Apuan Alps

The geographical and orographic characteristics of the Apuan Alps have attracted naturalist-travellers since the 16th century, when geologists and botanists combined their excursions with the pleasure of improving their knowledge of nature. Herborists were the first to climb peaks in search of rare medicinal plants (Pichi Sermolli 1999). In the 17th century, the Dutch cartographer, Jan Janszoon, visited the area and mapped the valley of Seravezza with its sites of marble excavation and silver extraction (Fig. 3). Anglo-Saxon travelers and mountain climbers played an important role in promoting the area as a compulsory leg of the Tuscan part of the Italian "Grand Tour" (Lassels 1698). The Apuan Alps, visible from western Florence, were particularly fascinating for its citizens, who grew up surrounded by Renaissance culture and were, therefore, naturally inclined to discover nature from both the aesthetic and scientific points of view. Their visits were already numerous in the 18th century when several hikers went, often on foot, from the Tuscan city to the the Apuan Alps. Targioni Tozzetti (1752) described the Apuan rocks and minerals as well as physical landforms and fluvial erosion.

Fig. 3 Seravezza valley drawn by Jan Janszoon (1588–1664)

Systematic tourism started in the second half of the 19th century, when explorers were attracted by the unique nature of the landscape of these mountains and their inaccessibility. The Florence branch of the Alpine Club of Italy, founded in 1868, has focused its main activities on the Apuan Alps. The historical presence of hikers has led to the development of an intricate network of more than 600 km of footpaths. These paths, which are now managed by the Tuscan branches of the Alpine Club of Italy, bring hikers closer to the geological heritage, thereby making geotourism a natural feature of the hiking itineraries.

Another facet of long-standing geotourism in the area is linked to speleological exploration. After the discovery of the Corchia Cave in 1840, the Apuan Alps attracted speleologists from Italy and other European countries to the large number of caves and still unexplored karst cavities. The first speleological groups were formed after the First World War, introducing a new period of collective exploration and systematic expeditions, previously carried out by individuals. In the present day, the presence of speleologists throughout the year is usual.

4 Geological and Geomorphological Setting

The Apuan Alps define a tectonic window and provide insight into the geological evolution of the Northern Apennines, a belt of the Alpine-Himalayan orogenic system. The Northern Apennines resulted from the convergence and the subsequent collision between the European plate and the African plate. These processes thrust ophiolite-bearing oceanic-derived Ligurian Units onto the continental-derived Tuscan Units and have resulted in a complex fold and thrust belt with NE-directed tectonic transport. The Apuan tectonic window allows the observation of the crustal duplication of the continental Tuscan units (Fig. 4). The lower tectonic units (Tuscan Metamorphic Units) underwent green-schist metamorphism during the Cenozoic time and constitute the lowermost units of the structural stacking of the Northern Apennines (Carmignani and Kligfield 1990). The upper units are the corresponding unmetamorphosed sedimentary formations forming the Tuscan Nappe. The latter consists of a Mesozoic-Cenozoic succession evolving from shallow

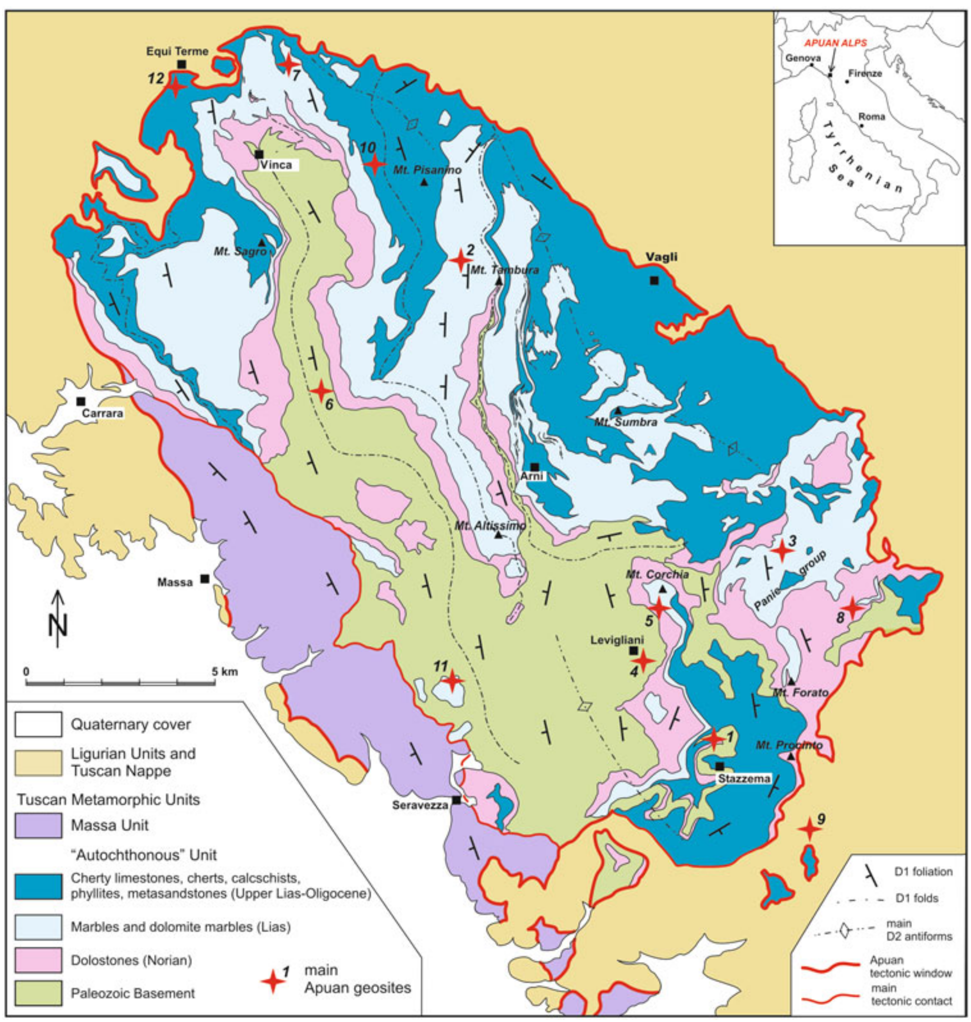

Fig. 4 Tectonic map of Apuan Alps Geopark. Modified after1 et al. (2010). Main geosites: *1*. Buca della Vena Mine, *2*. Roversi Abyss, *3*. Vetricia karren field, *4*. Quicksilver mines, *5*. Corchia cave, *6*. Forno Spring, *7*. Equi Gorge, *8*. Wind cave, *9*. Wave cave, *10*. Serenaia valley, *11*. Archaeomining area of the "Bardiglio Cappella" marble, *12*. Karst-paleontological Park of Equi Terme Caves

Fig. 5 Harsh landscape of the main ridge of the Apuan Alps

water to pelagic and ends with siliciclastic foredeep turbidites of Oligocene-lower Miocene age (Fazzuoli et al. 1994).

The Apuan Alps form an area of high relief defined by the metamorphic units, including the Dolomitic landscape and the rugged karst terrain so important to the Park and its heritage (Figs. 5 and 6). Glacial features occur, mainly on the eastern side of the range (Fig. 7). The outcrop of the sandstone and shale-dominant formations that comprise the Tuscan Nappe gives rise to smoother landforms and less strongly incised valleys surrounding the Apuan main range.

5 The Geosites of the Apuan Alps

Several years ago the Authority for the Nature Park of the Apuan Alps decided to apply for membership of the European Geoparks Network, with the main aim of enhancing the Park's geological heritage (Acta apuana 2005). With the strong support and help of local authorities and the local communities during the following years, the application dossier for membership was presented in November 2010. The Apuan Alps Geopark was formally recognised as a member of the European and Global Geoparks Network during the 10th European Geoparks Conference held in Langesund, Norway, in September 2011.

The first list of European geosites, drawn up by Wimbledon et al. (1996) for the European Association for the Conservation of the Geological Heritage (ProGEO), contained some exclusive sites from the Apuan Alps, such as the Apuan tectonic window, the Hercynian discontinuity of Mt. Corchia and the Apuan "Cipollino" Marble. Information about geosites from the Apuan Alps is also contained in the ISPRA database within the "Italian Geosites Inventory" project, launched in 2002. This project aims to create a national inventory of geological sites in order to become a useful tool for the geological knowledge of Italy, as well as for territorial planning and landscape-environment protection.

Compilation of the first systematic inventory of the Apuan Alps geosites started during the drafting of the Master Plan of the Nature Park of the Apuan Alps (2007). The inventory documented the wealth and the unique character of the geological heritage of the Apuan Alps, allowing information on their geodiversity to be spread, including a first selection of the geosites, to increase public awareness and to stimulate local communities to participate in conservation and enhancement strategies.

Subsequently a field survey was undertaken to compile descriptive and evaluation "ID cards" and to create photo reportage (Amorfini and Isola 2010). The "ID card" of each identified geosite was based on the inventory data sheet prepared by the Italian Institute for Environmental Protection and Research (ISPRA). The data sheet comprises different sections of description and assessment of the value of the geological asset. In particular, the section regarding the scientific interest documents the "degree of interest", defined as the geological significance compared to the geographical setting, also including the attribution to the disciplinary category (geomorphology, hydrogeology, structural geology, etc.).

During the inventory of Apuan geosites, the scientific value of every natural element was carefully considered, following the criteria of uniqueness, representativeness or exemplarity, but also the cultural, tourist and socio-economic

Fig. 6 Vetricia karren field in the southeastern Apuan Alps Geopark (Panie mountain group; see location in Fig. 4)

Fig. 7 The Campocatino area (northern Apuan Alps Geopark) is characterized by a glacially overdeepened basin. In the background, the Mt. Roccandagia rocky walls from which the Würmian glacier was originated; in the foreground, the lateral moraine ridge

appeal of each geosite (Reynard et al. 2007; Bruschi et al. 2011). Therefore, the Geopark inventory described not only geological and geomorphological sites but also identified areas in which geodiversity is so clearly demonstrated that it is possible to create eco-friendly tourist attractions (Mt. Corchia-Levigliani area, Equi Terme area, Serenaia Valley; Fig. 4).

5.1 Geosite Inventory Results

To date, the ongoing inventory process has led to a list of 253 geosites, almost all identified by Amorfini and Isola (2010), that represent all the degrees of scientific interest, from local to global. The geosites have been divided into 29 categories according to the main generating geological processes. According to these categories, the geomorphological sites, including karst and glacial landforms, are prevalent (79 %). The other geosites represent hydrogeological, mineralogical, palaeontological and tectonic processes.

The main outcome of the inventory is that the classified geosites are considered as "structural invariants", that is to say they are physical objects characterized by invariance. The invariants correspond to territorial components or landscape elements in cases where it is strategic to protect, conserve and enhance their distinctive features. The legal status of the term "structural invariants" is defined in the

Fig. 8 Stalactites and stalagmites in the Corchia cave (southern Apuan Alps Geopark; see location in Fig. 4) (photo by Giuseppe Nardini)

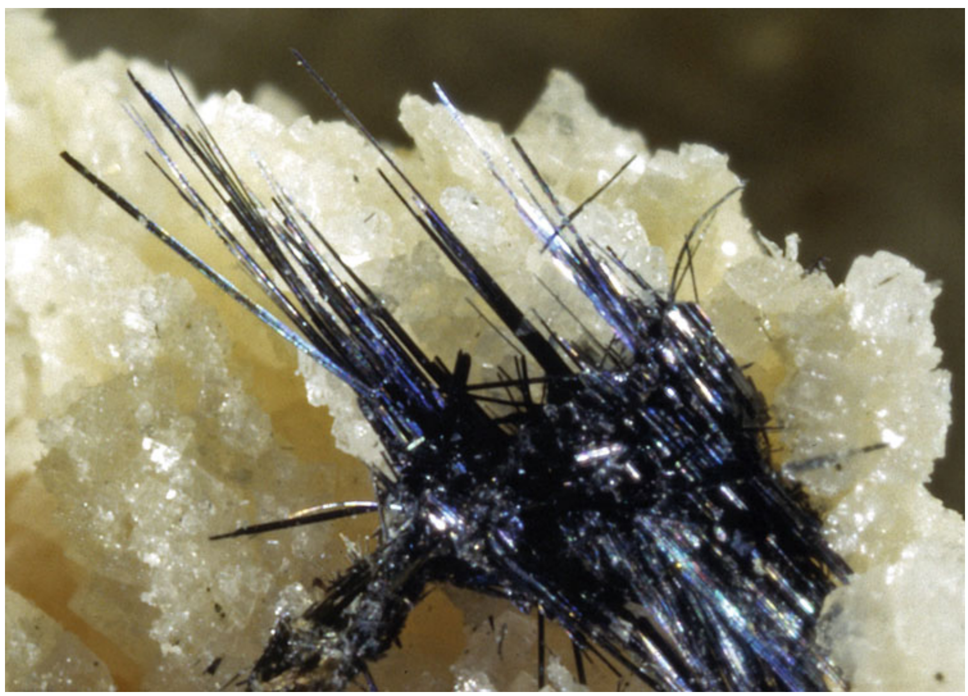

Fig. 9 Acicular crystals (max length 1 cm) of mineral scainiite, a lead-antimony sulfosalt first found at Buca della Vena mine (Orlandi et al. 1999) in the southern Apuan Alps Geopark (see location in Fig. 4) (macro-photo from Orlandi and Dini 2010)

Park Master Plan, the Provinces' territorial Coordination, and by Law no. 56/2000 of the Tuscany Region, all of which aim to conserve the Apuan geosites to avoid the risk of jeopardising their value. Examples of Apuan Alps geosites of international and national importance are briefly described below.

5.1.1 Geosites of International Importance

Among geosites of global scientific interest, the first to be mentioned should be the karst complex occurring inside the Mt. Corchia (Corchia Cave), located in the south-western part of the Apuan Alps near the village of Levigliani (Fig. 4). Until now the explored galleries and wells show a significant development of both depth (1,187 m) and length (about 53 km), reflecting the connection of different caves belonging to the same karst system (Fig. 8). The Corchia karst system is a geological and climatic archive that preserves a record of climate change in the Mediterranean area during the past 1.5 Ma or more (Woodhead et al. 2006; Piccini et al. 2008).

Fig. 10 Natural arch of Mt. Forato in the southern Apuan Alps Geopark (see location in Fig. 4) (photo by Paola Fazzi)

Another geosite of global interest is the Buca della Vena Mine (Stazzema) in the mining area of the central-southern Apuan Alps (Fig. 4), well known to the world community of mineralogists for its very rare mineral parageneses. During the last 20 years, more than 80 mineralogical species have been identified, ten of these for the first time, namely allanite-(La), apuanite, dessauite, marruciite, pellouxite, pillaite, rouxelite, scainiite (Fig. 9), stibivanite-2O, and versiliaite (Orlandi and Dini 2010). For the most part, these minerals have not been identified elsewhere in the world.

5.1.2 Geosites of National Importance

The records of Apuan geosites identified as being of national interest are considerably larger. This category includes hypogean karst systems whose dimensions are smaller than those of international status mentioned in the preceding section. However, the inventory includes sites with geomorphological features and others linked to glacial processes. Mt. Forato, a natural arch 26 m high and 32 m wide (Fig. 10) provides a good example of the former, and there are also elements in carbonate rocks, typical of the landscape in the Dolomites region of Italy, such as towers, aiguilles and pinnacles (Fig. 11). Sites linked to glacial processes are restricted to Würmian moraine deposits and pre-Würmian cemented deposits and are preserved only in a few sites (Equi Gorge, Vestito Pass, Terreno Valley) (Braschi et al. 1986). The Apuan Alps, however, retain widespread evidence of landforms indicative of glacial erosion and deposition (Braschi et al. 1986; Federici 2010) (Fig. 12).

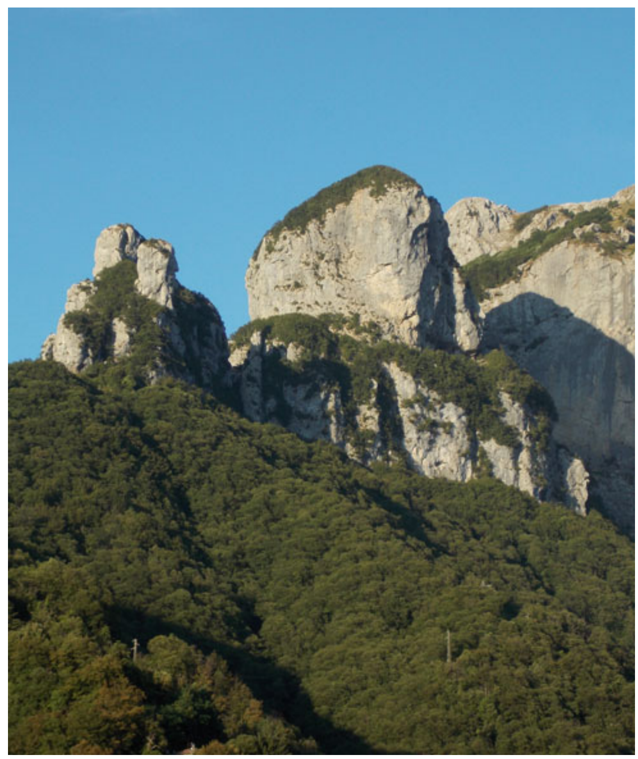

Fig. 11 Aiguilles and pinnacles of Mt. Procinto group in the southern Apuan Alps Geopark (see location in Fig. 4)

The potholes occurring along Fatonero and Anguillaja streams, on the southern flank of Mt. Sumbra, have been grouped in a geosite of national interest for their unique dimension (diameter more than 6 m), and regular circular form and concentration (Fig. 13). The formation of the potholes has been interpreted as a consequence of water forced through subglacial galleries developed under the glaciers of the last Glaciation (Amorfini and Isola 2010).

Fig. 12 Fociomboli overdeepened basin in the northern side of Mt. Corchia (southern Apuan Alps Geopark; see location in Fig. 4)

Fig. 13 Pothole along Fatonero stream in the southern side of Mt. Sumbra (central Apuan Alps Geopark; see location in Fig. 4) (photo by Giuseppe Nardini)

The Equi Terme karst complex in the northern sector of the Apuan Alps Geopark (Fivizzano Municipality) is of tourist and scientific interest. The karst cave opens into galleries and halls with stalactites and stalagmites which often resemble columns, limestone flows, curtains and lace-like forms and comprises the Tecchia prehistoric site, a neutral cavity where significant deposits of palaeontological, palaeoethnological and archaeological interest were found. 19th century excavations brought about the discovery of stone tools from the Mousterian to the Neolithic, together with Würmian and post-glacial faunas and, in particular, remains of *Ursus speleasus* (Rosenmüller and Heinroth), which probably inhabited the cavity that resembles a rock shelter (De Stefani 1916a, b; Palma di Cesnola 1970).

6 Enhancing the Geological Heritage

The awareness of managing and enhancing such a diverse area as the Apuan Alps has, from the outset, encouraged Park Authority to integrate its actions regarding research, conservation and the enhancement, in particular of the

Park's geological and biological diversity—both of which are key components of its heritage. The Authority also recognised the need to address the enhancement of geotourism to benefit the local communities in the Park area.

The following topics are discussed:

- Scientific interpretation of geological heritage and geosites;
- Cultural initiatives to popularize and disseminate the geological concepts to increase the awareness of local populations on the importance of preservation and protection of their geoheritage;
- Increase and improve geotourism for sustainable local economic development.

To achieve these objectives, agreements and memoranda of understanding have been signed with associations, federations and agencies for the protection, promotion and/or economic development of infrastructures linked to the Apuan geological heritage.

The updating of scientific interpretation of the geological processes observed in the Apuan Alps is ensured through cooperation with universities and other research institutions. In 2010, the Apuan Alps Park Authority signed a "Memorandum of Understanding on the development of geological knowledge and the protection and enhancement of the geodiversity of Apuan Alps" with the National Research Council of Italy, Institute for Geosciences and Earth Resources, the Centre for Geo-technologies of the Siena University and with the Earth Sciences Department of Pisa University. The Geopark cooperates with ISPRA to optimize the filing of geosites and standardize the geosite indexing of the Italian territory.

Among other partnership initiatives are agreements with the Tuscan Speleological Federation promoting protection and scientific and cultural management of the Apuan Alps karst environments, with the Environmental Protection Agency of the Tuscany Region (ARPAT) and with the Alpine Club of Italy.

Regarding actions with a potential economic impact, since 2009 the Apuan Alps Park Authority has been developing the *Being Green* project, aimed at promoting a unique geological resource, the "Cipollino" Marble. This is a green stone of great beauty with its own rich historical heritage.

The project aims to start the limited extraction of this decorative stone and to produce high quality pieces in a short-chain context in the Cardoso Valley (Stazzema Municipality). This activity should be part of the wider tourist experience, and be integrated with the natural and historical environment of the area.

6.1 Intangible Assets

The Park Authority has always been engaged in the promotion of tourism and in strengthening cultural and socio-economic relations in parallel with environmental education and within a framework that embraces all the natural elements of the area. The Geopark activities therefore include *intangible projects* where the geological heritage is the prevailing topic.

6.1.1 Environmental Education

Every year the Park Authority offers educational courses (named "Between Environment and Tradition: Knowledge, Skills and Actions") for primary and secondary schools. The programme includes excursions and educational trails assisted by the Geopark Guides, activities promoting the understanding and knowledge of landscapes and environments in the protected area, and initiatives on the tradition and culture of the Apuan territory.

6.1.2 Publications

The Park Authority is publishing its own scientific journal *Acta apuana* once a year. It contains articles reflecting the technical and scientific daily experience of the Park staff and the studies of scientists working in the Apuan Alps. The fields investigated are broad. However, given the prominence that geology plays in the Apuan Alps, the journal has always offered priority to Earth Sciences studies. *Acta apuana* also published two supplements based on the proceedings of the 2001 Workshop "Geosites, between nature enhancement and preservation" (Acta apuana 2005, 2010). Other monographs of the scientific journal have been dedicated to archaeological and archaeometric studies on the excavation and use of Apuan metalimestones during the pre-Roman, Roman and Medieval periods (Acta apuana 2004, 2007). Park Authority publications also include guides describing categories of biotic and abiotic phenomena of the Apuan Alps. At first, this series of publications was mainly devoted to botanical topics, with individual volumes covering the flowers, mushrooms, orchids and medicinal plants of the Apuan territory. In 2009, the first geological guide was issued, entitled "Marble minerals of the Apuan Alps" (Orlandi and Criscuolo 2009). The guide provides a comprehensive account of the mineralogical heritage preserved in metalimestones and metabreccias that are subject to traditional quarrying.

With the aim of explaining how popular tradition has tried to understand and hand down, through legends, the suggestive and evocative features of the Apuan mountains, an illustrated book, the "Legends of the Apuan Alps", has been published in three languages (Italian, English and German). It contains legends about six main peaks and important geosites of the Apuan range and represents a short treatise on the "ethnology of geosites" that enhances the culture and the traditions of local inhabitants and their ancestral relationships with the sacred nature of the most important peaks.

However, the most specific geological publication is the "Geological Map of the Apuan Alps Park, scale 1:50.000" (Carmignani et al. 2000). The work was funded by the Park Authority and the map is accompanied by geological cross-sections and tectonic and stratigraphic schemes.

In 2001, the Park Authority produced a CD entitled "The Park for the flood: documents and accounts on events and actions 5 years after the flood in Versilia and Garfagnana" (Parco Regionale delle Alpi Apuane 2001). It contains videos, photographs and thematic maps as well as text and oral accounts of the flood of 19th June 1996 in the central-southern part of the Apuan Alps. The flooding caused about 300 debris flows and overflows of watercourses destroying a large number of buildings and killing local residents. This is a multi-media essay containing scientific explanations in a more accessible language about the complex relationship between vegetation, soil and bedrock and, consequently, the different levels of hydrogeological instability of the valleys stricken by the natural disaster.

6.1.3 Apuan Alps Geopark Website

The Geopark website (http://www.apuanegeopark.it), dedicated to the geodiversity of the Apuan Alps, is accessible directly, and from the portal of the Nature Park of the Apuan Alps (http://www.parcapuane.it). It contains many links to geosites, geotourism (excursions and itineraries, guide availability, recommended accommodations, etc.), museum, conferences, education and geological documents (scientific articles, maps, old books) of the Apuan Alps Geopark. The content, in Italian and English, is regularly updated.

7 The Existing Tourist Facilities

To welcome tourists, the Apuan Alps Geopark manages, directly or in agreement with local authorities or tourist promotion agencies, five Visitors' Centers (Massa, Castelnuovo Garfagnana, Seravezza, Bosa di Careggine and Equi Terme).

The Geopark has organized its territory so that excursions can take place within a hunting-free area where animals are free to roam in an environment where human pressure is kept at a controlled level. Hiking trails in the protected areas are equipped with interpretative panels, in Italian and English, about geological and geomorphological topics. The Serenaia Valley Trail is equipped with facilities for disabled persons. The entire Apuan network of footpaths is served by 16 mountain huts, offering visitors the chance to spend the night, especially during summer months and on weekends during other seasons. These facilities, which are sometimes located quite far away from the main roads, ensure that people continue visiting the Geopark's geosites.

In 1964, the first attempt to make a geosite accessible to tourists was the Equi Terme Cave (Fivizzano Municipality), followed in 1967 by the Wind Cave, in the village of Vergemoli. The latter is a 4,570-m long karst system in which three equipped trails have been set up for a total of 1,250 m and it now represents a well-established tourist attraction managed by a private enterprise.

In order to enhance the appeal of the Park to tourists, the Park Authority has identified a number of geosites that, due to their geological significance and/or their extraordinary beauty, merited investment in the creation of appropriate infrastructure to support tourist activities. Three main cultural/tourism developments are described below.

7.1 Archaeomining Area of the "Bardiglio Cappella" Marble

In 2005, the Park Authority opened to the public an old quarrying area, probably in use since the Middle Ages, situated close to the Romanic St. Martin's Chapel, in the municipality of Seravezza (Fig. 4). A short guided walking route was set up, allowing visitors to observe traditional quarrying techniques in an area where a precious marble ("Bardiglio Cappella"), in demand for its unique intense blackberry grey colour, was excavated. The colour of the rock depends on the widespread presence of microcrystalline pyrite, which is also responsible for a typical sulphurous smell when the rock is crushed. The quarrying industry of this area became famous for the production of squared marble floor tiles, columns, door jambs and slabs. Two small quarries have been turned into museums reconstructing the main phases of excavation: the extraction of irregular blocks from the quarry face by blasting or the use of iron tools and the squaring of small and medium-sized marble blocks on the spot (Fig. 14). The tour also shows the "lizza's way", the technique historically used to move marble blocks to the valley. The area enjoys a wonderful view from the Versilia Valley to the main ridge of the Apuan mountain range. The visit does not require a ticket payment.

7.2 Karst-Palaeontological Park of Equi Terme Caves (Fivizzano Municipality)

The Park of Equi Termi Caves offers tourist facilities and trails including some designated geosites and archeosites in close proximity to each other. This park includes a cave produced by temporary karst resurgence (Fig. 15), caves of palaeontological and palaeoethnological interest, thermal springs (sulphur radioactive water) and routes along a deeply incised river valley (the Equi Gorge).

Fig. 14 Ancient quarry in the archaeomining area of the “Bardiglio Cappella” marble in which it is possible to reconstruct the main phases of excavation (southern Apuan Alps Geopark; see location in Fig. 4)

Fig. 15 Water outflows from the perpetual karst spring of Equi Terme during floods (northern Apuan Alps Geopark; see location in Fig. 4) (photo by Leonardo Piccini)

The Equi Terme Cave stretches over a total of 1,500, 320 m of which are open to the public, including the Tecchia prehistoric Cave. The tourist offer is enriched by the Museum of the Caves, an educational exhibition on the physical landscape of surrounding areas and the palaeo-environment in which Neanderthals coexisted with cave bears.

As previously mentioned, the tourist activity in the Equi Terme Cave started in 1964 but only since 2001, thanks to an agreement between the Fivizzano Municipality and the Apuan Alps Geopark, the goal of making all the Equi Terme geosites a tourist network has been achieved. In 2013, the Karst-palaeontological Park was further integrated with the

Fig. 16 Visitors along the underground trail in the Corchia cave (Corchia underground system; see location in Fig. 4)

ApuanGeoLab, an exhibition aimed at the dissemination of knowledge of the Earth Sciences located in the Equi Terme village. It was conceived as an interactive museum, where mechanical exhibits assist visitors to observe geological processes from the global to the local stage (Amorfini et al. 2013). Visitors of the Karst-palaeontological Park number approximately 7,000 each year, generating a total income of about 60,000 Euros.

7.3 Corchia Underground System

The most important Apuan geotourism project is the Corchia Underground System, a good example of management of geosites based on the direct involvement of the local community of Levigliani in the Stazzema Municipality.

The Apuan Alps Park Authority and the Stazzema Municipality set up a public limited company, named "Antro del Corchia", to enhance the use of the Corchia Cave for tourism and cultural purposes, through the creation of a fully equipped pathway available to the public in this cave, the largest Italian karst system. The underground trail develops along more than 1 km of natural galleries, fully equipped with 646 m of stainless steel bridges (Fig. 16).

The preservation of the integrity of the karst environments visited by people is guaranteed by a convention with ARPAT through a permanent monitoring system (three stations) detecting chemical and physical parameters, with particular attention to CO_2 concentration and wind speed, to avoid saturation conditions that might affect the calcareous deposits.

The Corchia Underground System integrates the Speleological Trail of the Corchia Cave with other tourist attractions linked to the Apuan geological heritage: the Quicksilver mines and the "Pietra piegata" Museum, both located in Levigliani. In 2008–2009 the local community and private companies working under the supervision of the Park Authority, for cultural enrichment, built two tourist trails inside two disused Quicksilver mines. The project was able to promote one of the oldest Apuan mining sites, which was already named in documents of the Middle Ages, and sporadically exploited in the following centuries, for the mining of mercury minerals. This location is one of the few places in the world where mercury is found in its native state in the form of metallic droplets in quartz veins (Hydrargirium or "Quicksilver").

Fig. 17 The "Pietra piegata" museum of Corchia underground system hosts Etruscan and Roman artefacts: an Etruscan funerary cippus with half-circle crowning (*left*) and a large fragment of trabeation of an imperial Villa Rustica (*right background*)

The "Pietra piegata" Museum, located in a late 18th century building in the village, was opened to the public in 2008 to display the best of the Apuan 'marble culture' that is preserved in the Park's territory (Fig. 17). It displays the most characteristic types of products made with Apuan marbles, beginning with those of serial character, to develop an archaeological knowledge and to preserve the historical memory of traditional craftsmanship which nowadays is, unfortunately, residual. The Museum is also a research centre where petrographic and microstructural analyses have been carried out on samples of Apuan marbles to identify their origins, especially when used in architectonic monuments or artwork.

The Corchia Underground System welcomes approximately 13,000 paying visitors every year, producing an income of about 500 thousand Euros, including money generated from merchandising and catering.

8 Conclusions

The Apuan Alps offer valuable insights into the geological evolution of the Mediterranean region. The Geopark's heritage is based largely on its geological setting and varied geology, the past exploitation of its valuable world-famous ornamental stones and minerals, and the associated, fascinating, archaeological and historical-cultural records that have been uncovered.

Geodiversity in Apuan Alps Geopark is expressed in various ways and on varying scales:

- the regional geological structures, especially the tectonic window that exposes Palaeozoic metamorphic rocks in its core;
- the wide range of mineralogical parageneses and mineral species, a significant number of which were first identified in the Apuan area;
- the karst features, especially, hypogean: the Corchia Cave and the Roversi Abyss are karst systems of global significance;
- the traces of the great climate change that led to glaciations, with related prehistoric settlements.

Two hundred and fifty three geosites that meet international standards have been defined to date within the Park boundary. The total attests to the significant geoscientific value of the Apuan Alps and the recognised sites are undoubtedly the principal assets of the Park.

Being fully aware of the geodiversity of the Apuan Alps, the Park Authority has made, and is continuing to make, considerable efforts to enhance its geological heritage and to promote a sustainable geotourism industry in its territory.

The Park Authority's experience clearly indicates that the best results have been obtained with the involvement of local communities, public authorities and organizations, and it has worked hard to stimulate all to participate proactively in operations, the provision of services, and in the decision-making process. The involvement of the private sector has been especially fruitful in implementing major projects such as the Corchia Underground System and the Karst-palaeontological Park of Equi Terme Caves. Within this framework, an assessment needs to be carried out of the territory's potential for the sustainable development of further, new, geotourism initiatives aimed at enhancing the geoheritage of Apuan Alps.

In Africa today, many countries face problems and situations similar to those faced by the Apuan Alps Geopark in its infancy, in particular outstanding features of the geological heritage but limited infrastructure and facilities and few "geotourists". The Apuan model integrates the preservation and scientific enhancement of its geological heritage and the conservation of the natural environment and its resources into a strategy for the economic development of local communities—a model that cannot be separated from their cultural development and awareness. This model could provide a useful guide to support the increasing number of Geopark initiatives in Africa and the African Geoparks Network.

Acknowledgments This article is dedicated to the memory of Giuseppe Nardini, President of the Apuan Alps Geopark whose work was important to securing the admission of the Geopark to the European and Global Geoparks Networks. We are grateful to Editors Ezzoura Errami, Margaret Brocx and Vic Semeniuk, for welcoming our paper in this special volume and to anonymous reviewers for their critical comments and suggestions. We thank Emanuele Guazzi and Silvia Ravani for their collaboration and all those who granted their pictures.

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Geoparks in China

Géoparcs en Chine

الجيومنتزهات بالصين

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Abstract

During the period 2000–2011 a total of 27 Global Geoparks and 140 National Geoparks have been established in China. 79 other parks have obtained the qualifications to become National Geoparks. The study of the geological background of the Chinese geoheritage resources in terms of their geomorphology, tectonic, and stratigraphy allows proposing a classification scheme for the geoparks in China. Chinese geoparks have been divided into 8 types, which covered the different geological settings and landscapes. Researchers in regard to these geoparks have made great achievements in several different areas including geoconservation, popularization, Earth Science education, socio-economic and cultural development. This paper discusses new measures of geopark construction and developments taken by China to meet these challenges.

Résumé

Au cours de la période 2000–2011, 27 géoparcs globaux et 140 géoparcs nationaux ont été mis en place en Chine. 79 autres parcs ont été qualifiés pour devenir des géoparcs nationaux. L'étude du background géologique des ressources géopatrimoniales de la Chine, de point de vue géomorphologique, tectonique et stratigraphique, a permis de proposer un schéma de classification des géoparcs en Chine. Ces derniers ont été subdivisés en huit types qui couvrent les différents contextes et paysages géologiques. Les chercheurs dans le domaine des géoparcs ont fait de grandes réalisations dans différents domaines, y compris la géoconservation, la vulgarisation, l'éducation des Sciences de la Terre et le développement socio-économique et culturel. Ce travail discute des nouvelles mesures prises par la Chine pour la création et le développement des géoparcs pour relever ces défis.

ملخص

خلال الفترة الممتدة مابين 2000 و2011، تم إحداث 27 جيومنتزها عالميا و140 جيومنتزها وطنيا بالصين. كما تم تأهيل 79 منتزها ليصبح جيومنتزهات وطنية. إن دراسة الأرضية الجيولوجية لموارد الجيومورث الصيني، من وجهة نظر جيومورفولوجية، تكتونية وطبقاتية مَكَّنَ من اقتراح خطة تصنيفية للجيومنتزهات بالصين. هذه الأخيرة تم تقسيمها إلى ثمانية أنواع، وهي تغطي مختلف السياقات الجيولوجية والمناظر الطبيعية. لقد حقق الباحثون في مجال الجيومنتزهات

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إنجازات كبيرة في مختلف المجالات، بما في ذلك الحفاظ على الجيومورث، التعميم، تعليم علوم الأرض، والتنمية الاجتماعية والاقتصادية والثقافية. يناقش هذا العمل تدابير جديدة اتخذتها الصين لإحداث وتطوير الجيومنتزهات لمواجهة هذه التحديات.

Keywords
China • Geoparks • Geological background • Distribution • Achievements

Mots-clés
Chine • Géoparcs • Background géologique • Distribution • Réalisations

الكلمات الرئيسية
الصين • جيومنتزهات • أرضية جيولوجية • توزيع • انجازات

1 Introduction

The topography and nearshore bathymetry of China includes the Tibetan plateau, the loess plateau, karst plateau, mountain valley areas, hills, plains, rivers, and the continental shelf, across different geomorphic units. With the diversification of the geological and geomorphic types, soil types and climatic conditions, there are various natural ecological systems such as snow-mountains, forests, grasslands, deserts, wetlands, plains, coastal islands and marine features. China, from the west to the Pacific, is located in the Asian monsoon zone with the largest environment change rate on the Earth, and the cycle among the sea-continent-atmosphere system has global significance.

Chinese natural conditions are unique, and provide geographical advantages in Earth Science research. The Pacific Rim belt, Central Asia belt and the Tethys orogenic belt occur in China (Wang 1985). These have contributed to the complexity of the lithosphere structure, and the dominant position in geological evolution in the world.

The geological record in China is rich and varied. From the viewpoint of geodynamic processes, the continental blocks in China have moved and interacted throughout geological time, and provide excellent opportunities for research into contemporary geodynamic processes, acting as important field research laboratories with global significance. The long evolutionary history and complex geodynamic processes have resulted in a great diversity of geologic and geomorphic units, as well as major global representatives.

2 Geological Background of the Geoheritage Resources in China

As a result of its long geological evolution, China is made up of several blocks, which are relatively stable in the long-term, and active belts between the blocks. The present geographic patterns of the Chinese subcontinent have been formed since the Cenozoic. Its main characteristic is the steppe topography which is high in the west, and low in the east, and the active fault belts that exhibit regular distribution (Ye et al. 1998). The Yanshan (Mesozoic) and neotectonic movements are the important internal geologic forces that created the landforms. The process of regional tectonic evolution and the comprehensive role of internal and external geologic forces formed the multi-level topography of the subcontinent. From west to east, there are three steppes and four topography terraces (Wu et al. 2001) as follows.

The first topographic terrace, the Tibetan plateau called “the roof of the world”, is the highest level topographic terrace, which is surrounded by the mountains of the Pamirs, Altun, Qilian, Hengduan and Himalayas. In the east, the Hengduan mountains were uplifted rapidly during the Cenozoic. The plateau altitude is 3,000–4,000 m, and 5,000 m in the northern part. The top of the plateau is relatively flat, and high in the west and low in the east. The plateau is the birthplace of the main Asian water system. Through the strong erosion of the Jinsha, Nujiang, and Lancang rivers, spectacular landscapes of high mountains and deep valleys were formed. At an elevation of 3,000 m, it forms the first steppe along the plateau verge.

To the east and north of the Tibetan plateau, the second level topography terrace is 1,000–2,000 m high. It consists of the Xinjiang, Alxa, and Inner Mongolia plateaux, the Loess plateau and Yun-gui plateau, and a few basins such as the Tarim basin, Sichuan basin and Hexi corridor. There also are neotectonic uplift mountains, such as the Tianshan, Qinling, and Yinshan mountains etc. The eastern boundary is along the Hinggan mountain, Taihang mountain and Xuefeng mountain. This is the second steppe.

The altitude of the third level topography terrace is less than 500–1,000 m. It consists of the eastern broad plains and low mountains. Three major plains: the Northeast, the North, and the Middle-lower Yangtze Plain are less than 200 m. In the east, there are fault-block uplifted low mountains and, intermittent volcanic rocks along the coastal zone (Zhao and Zhao 2009). These constitute the third steppe.

The fourth level topography is the continental shelf of the Yellow Sea, the East China Sea, and the South China Sea contiguous with the coastal plain of the mainland. The slope of the continental shelf is less than 1º. The coastal plain contains river deltas, criss-cross water channels, and lakes.

The overall appearance of the three steppes and the four topographic levels were developed by uniform tectonic dynamics which are the result of long-term interaction among the Eurasian Plate, the Pacific Plate, the Indian Plate, and the Philippines Plate The changes of the gravitational field and the magnetic field, especially the gravity anomaly mutation belt, and the depth of the Mohorovičić discontinuity, are associated closely with the geomorphic steppe components in the continent (Ma et al. 2009). It reflects the dynamic foundations of the surface topography changes.

China has undergone 3.6 billion years of geological evolution which developed systematic strata from the Archaean to the Cenozoic. There are 9 internationally-recognised, global stratotype sections and points (Chinese Strata Committee 2002), and some of them are included in national geoparks. In China, the outcrops of carbonate rocks cover 1,300,000 km^2, which occur mainly in the six provinces in southern China. The area of the most concentrated carbonate strata is about 730,000 km^2, which is one of the best developed karst landform regions in the world (Che and Yu 1985). Many kinds of magmatic rocks (granite, ophiolite, etc.) in different geological periods are distributed in China. The outcrop area of granites is 860,000 $km^{2;}$ among them; the largest area is Mesozoic granite, and the next is Palaeozoic granite (Natural Geography Group of China Science Academy 1980). As a result of the interaction of the tectonic plates, multi-period metamorphism shows the multi-cyclic evolution of the continental crust. Some special metamorphic rocks, such as eclogite, and glaucophane-schist Ye et al. (2004), have provided scientific evidence of the Earth in its early stages.

The rich and rare geological phenomena and their associated geological heritage, provide excellent conditions for the establishment of geoparks in China. Within this context, their significance is recognised by the Chinese government, and the active participation of stakeholders were important factors in promoting the development of geoparks in China (Jiang 2002). At the time of writing this paper, in China, there are 27 Global geoparks, 140 National geoparks, and 79 parks that qualify to become National Geoparks, and 259 provincial geoparks (Zhao et al. 2011). China now has a geopark system composed of Global geoparks, National geoparks, Provincial geoparks and developing County geoparks.

3 Characteristics and Types of Chinese Geoparks

On the basis of geological-geomorphological characteristics, the authors have analysed the factors of the geology that underpin Chinese geoparks; these are described below.

(1) The relatively concentrated zones of National geoparks are the three steppe zones where 70 National geoparks were established; these represent more than 50 % of the total National geoparks (Fig. 1). In the first steppe zone, there are 22 National geoparks (Fig. 1), such as Jianza geopark in Qinghai, Liujiaxia in Gansu, Longmenshan and Daduhe canyon and Xingwen in Sichuan, Lijiang

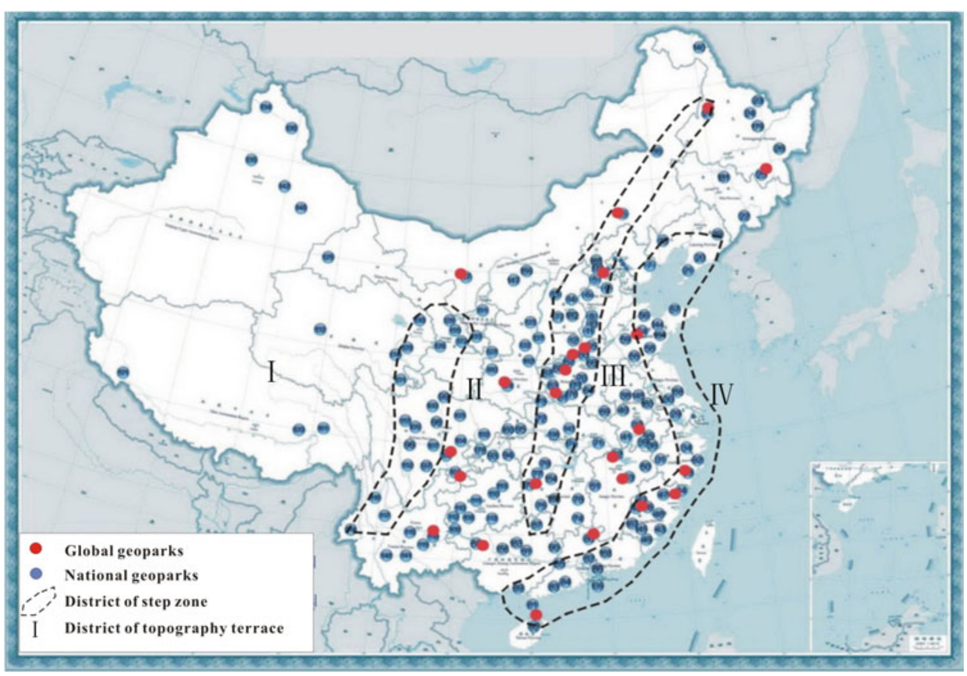

Fig. 1 Distribution map of Chinese geoparks

and Tengchong in Yunnan etc. (Figs. 2, 3 and 4). The second steppe zone is from Hinggan mountains to Xuefeng mountain. This steppe has 28 National geoparks (Fig. 1), such as Hexigten geopark in Inner Mongolia, Fangshan geopark in Beijing, Fuping and Zhangshiyan geopark in Hebei, Yuntaishan and Baotianman geopark in Henan, Hukou waterfall geopark, Zhangjiajie geopark in Hunan etc. (Figs. 5, 6, 7 and 8). There are 20 national geoparks in the third steppe zone (Fig. 1), such as Dalian geopark in Liaoning, Qinhuangdao geopark in Hebei, Chongmingdao geopark in Shanghai, Linhai geopark in Zhejiang, Tailaoshan geopark in Fujian, Huguangyan geopark in Guangdong etc. (Figs. 9, 10 and 11).

The three steppe zones are the more active tectonic regions, where the terrain change is very marked, and their geoheritage features are unique or rare. In the third steppe, the Pacific Rim volcanic belt is quite

Fig. 2 Colored hills in Jianzha geopark

Fig. 3 Strata in Liujiaxia geopark

Fig. 4 Nape structure in Longmenshan geopark

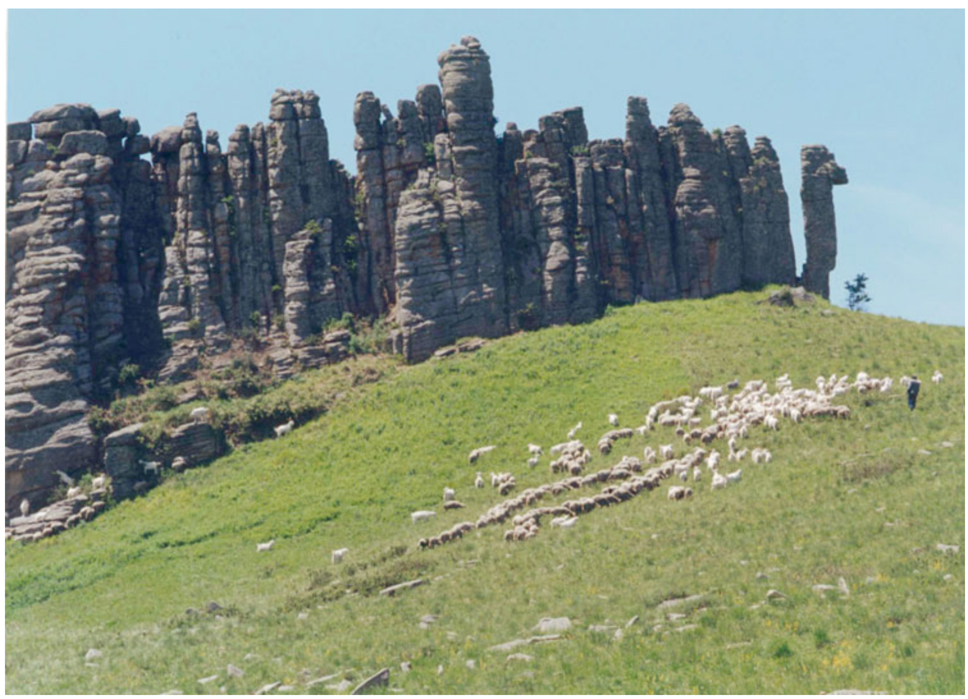

Fig. 5 Granite stone forest in Hexigten geopark

spectacular with different landform features in different sections. Some of them comprise hills, or occur along the coast. The majestic Taihang and Wuling mountains lie in the second steppe. The piedmont faults and differential uplift has created the red cliffs, long stone-wall landforms, and waterfalls (Zhao and Zhao 2009). The first steppe zone is the most active tectonic region where the differential uplift of the continent is most evident. The large nappe structure in the Longmen mountains, the Dadu river canyon, the glacial landforms in Hailuogou and Lijiang, and the volcanic relics and hot springs in Tenchong, are all due to the power of the Earth's evolution.

Along the region containing the steppe zones and its two sides, the difference in the crust movement reveals the workings of the crustal evolution (Zhao and Zhao 2009). The representative early evolutionary history of the crust can be seen in Fuping, Yuntaishan, and

Fig. 6 Karst cave in Fangshan geopark

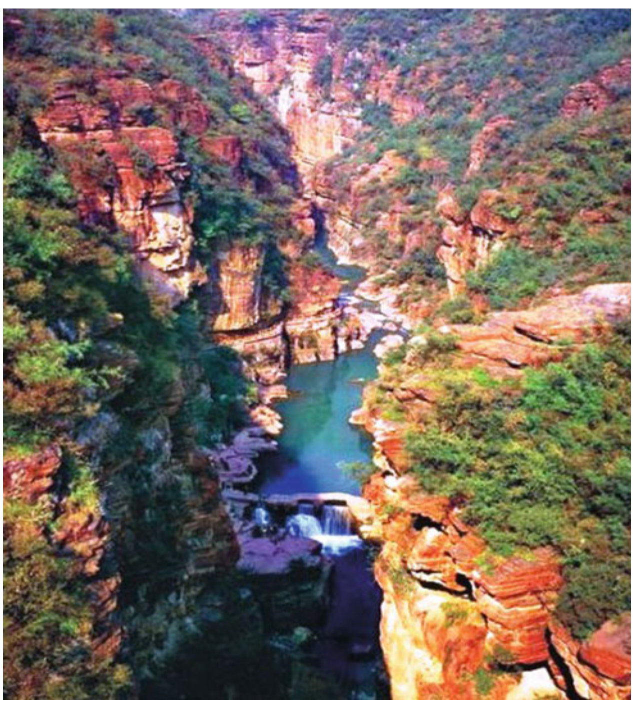

Fig. 7 Yuntai landform in Yuntaishan geopark

Baotianman geoparks, when the strata were exposed at the surface. The comprehensive geologic forces of the active geotectonic belt have gradually modelled changes in the geological landscapes in the Zhangjiajie and Hexigten geopark, into the beautiful sandstone peak-forests and granite stone-forests.

(2) In the topography terraces, there are about 60 National geoparks (Fig. 1). In parts of them, the dissection of faults and the differential uplift and erosion are the main formative factors of the landscapes, which has created spectacular peak stone "forests", towering stone-pillars, knife-edge crests, and deep ravines, etc. These occur in the karst stone-forest in Yunnan, the block mountain with glacial relics in Lushan, the granite peak forests in Huangshan and Tianzhushan, the steep quartzite peaks with geotectonic relics in Songshan, and the granite block mountain with Precambrian relics in Taishan (Figs. 12, 13, 14, 15, 16 and 17).

In the southern Yangtze platform, the Pacific plate activity since the Mesozoic era, formed a series of volcanic inland basins, where the thick red glutenite accumulated in dry climatic conditions. The Himalayan movement in the Cenozoic, and the subsequent dissection of by faults and erosion resulted in the special landscapes composed of the table mountains, peak forests, peak columns, long cliffs, narrow gorges, lane valleys, and rock galleries etc. These can be seen in the Taining geopark, Longhushan geopark, and Langshan geopark etc. (Figs. 18, 19 and 20). In the eastern platform part of the Pacific Rim during the Cenozoic, there were four volcanic activity events that formed the rift valley belt in East Asia (Liu 1999). Magma erupted along the faults in the rift valley, so the tectonic line and the volcanic belt are consistent with the continental margin. Wudalianchi geopark, Jingbohu geopark, Zhangzhou geopark, Hongkong geopark, and Haikou

Fig. 8 Sandstone peak forest in Zhangjiajie geopark

Fig. 9 Column of volcanic rock in Linhai geopark

geopark are the typical volcanic representatives in the different tectonic positions and periods (Figs. 21, 22, 23 and 24).

(3) In many geoparks, the geological heritage usually results from multi-episodic geologic processes. For example, there were four volcanic eruption events in Zhangzhou geopark that formed the overriding volcanic rocks with different structural characteristics. Columnar joints occur only in particular locations. Outcrops of the volcanic gas cones are exposed by the long-term marine erosion in the late-stage (Fig. 25). In Lushan geopark, since the Mesozoic, the rapid differential uplift of faults has led to the creation of block mountains, which supplied the important foundation for glacial development in the Quaternary. The hard metamorphic rock complex is the foundation of the cliffs and gorges. In the Shilin geopark, the prototype of the "stone forest" was formed before the Emeishan basalt eruption in the late Permian, as shown by the basalt in-filling of the karst caves. In the Cenozoic, the north-south Kangdian fault belt produced sa rift and differential uplift, which were the important factors resulting in the formation of the varied shapes in the "stone forests".

(4) The geological events often played a key role in the formation of some of the geological relics. Some are geologic hazard relics, such as the relics of landslides in the Cuihuashan geopark, the Qianjiang geopark, and the Yigong geopark etc. (Figs. 26 and 27). In the Zigong geopark and the Shanwang geopark, the palaeontological research shows cluster death and burial, which indicates a great geologic event and large palaeo-environment change in the period (Figs. 28 and 29).

Fig. 10 Granite landform in Taimushan geopark

Fig. 11 Maar lake in Huguangyan geopark

The type and distribution of the sites of geoheritage significance and of geoparks in China are related to the geologic background and morphological characteristics. To date, there have been few different geoheritage classification schemes developed (Chen et al. 1991; Ministry of Geology and Minerals 1995; Li et al. 2002; Zhao and Zhao 2009). The Guidelines of Global Geoparks Network (2010) gives a classification scheme, with emphasis on the geological relics involved with related geoscience disciplines such as: solid earth sciences, economic geology and mining relics, engineering geology, geomorphology, glacial geology, hydrogeology, mineralogy, palaeontology, petrography, sedimentology, soil science, stratigraphy,

Fig. 12 Stone forest in Shilin geopark

Fig. 13 Glacial relics in Lushan geopark

tectonic geology, volcanology, etc. Most scholars place emphasis on the principle disciplines and related main geologic factors in the geoheritage classification scheme. Through the comprehensive analysis of the types of National geoparks in China, and the revised Zhaoxun's scheme (Zhao and Zhao 2009; Zhao 2005), the authors have summarized the main geoheritage types (Table 1).

The geomorphology within the category of the 'Geological landforms' can be subdivided into: karst landform, granite landform, volcanic landform, glacial landform, Danxia landform, aeolian landform, sandstone landform, marine erosion landform and Yuntai landform. The geologic hazard relics (or 'Geohazard relic') can be divided into earthquake ruin relic, landslide relic, and debris flow relic.

Fig. 14 Granite peak cluster in Huangshan geopark

Fig. 15 Granite peak in Tianzhushan geopark

Fig. 16 Metamorphic rock hill in Songshan geopark

Fig. 17 Fault block mountain in Taishan geopark

4 Achievements of Chinese Geoparks

In the past decade, there has been rapid development of Chinese geoparks (Geological Environment Department of MLR 2002; Jiang et al. 2006). The primary objectives of the geoparks are as follows.

(1) *Promote the protection of sites of geoheritage significance*
The national geoparks are distributed in 31 provinces, with a total area of more than 70,000 km^2 (Geological Environment Department of MLR 2011). With the construction of geoparks, the public began to realize the importance of protecting both sites of geoheritage significance and the environment, resulting in many more people now taking part in the work. In addition people are made aware of the importance of geoheritage and the economic benefits it brings, thus improving awareness of environmental protection work and, as such, sites of geoheritage significance are being effectively protected.

(2) *Popularization and education of the Geosciences*
According to statistics from the 140 National geoparks, more than 20,000 explanation panels have been installed, and more than 5 million copies of scientific booklets, and pamphlets etc. have been produced (Geological Environment Department of MLR 2011). More than 16,000 scientific activities have been held, including more than 600 of these for children. Geoparks have become the base for geosciences popularization, and the scientific understanding of the development of a park allows people to obtain scientific knowledge combined with leisure. A geopark is not only a place for tourism, but also a garden for education and promotion of geoscience, which is becoming well received by the public.

(3) *Boost economic development*
Geoparks provide a national platform for local government, which promotes the development of tourism, the raising of income, the creation of more employment opportunities, and thus the changing of the local economic structure. Geoparks have become a new source of economic development. According to the statistics,

Fig. 18 Danxia landform in young stage in Taining geopark

Fig. 19 Danxia landform in old stage in Longhushan geopark

the income of all national geoparks is continuing to rise. Geotourism in geoparks also creates increased local employment opportunities.

(4) *Strengthen communication and cooperation*

National geoparks frequently form links ("twining") with each other, or with international geoparks which allow them to exchange ideas, and experience, on park development, management, and marketing, further allowing for park popularity and competitiveness (Luo et al. 2011). There are also many scientific activities and other communication activities now being held around geoparks, such as the 1st International Symposium on Development within Geoparks held at the Yuntaishan geopark in 2006, the 2nd International Symposium at the Lushan geopark in 2007, and the 3rd Symposium at the Taishan geopark in 2009. The development of Chinese geoparks accumulates experience for Global geoparks.

Fig. 20 Danxia landform in mid-age stage in Langshan geopark

5 Discussion and Conclusion

In the past decade there has been a significant increase in the development of Chinese National geoparks, but at the same time there have been many challenges, such as increasing numbers of geoparks, poor management and protection, or lack of funds, etc. (Yue et al. 2008; Zhang et al. 2011). For sustainable development in Chinese geoparks, some measures are being taken as follows:

(1) Revising and implementing the plans of all National geoparks—the geopark plans involve geoheritage protection, scientific popularization, geosciences research and interpretation, promotion, and geoheritage databases.

(2) Reforming the approval method of national geoparks—the National geoparks network receives applications every 2 years; every province can submit two applications for new Provincial geoparks; however, both the approval material and procedure need to be simplified. At present there are three steps in the process—(a) obtain qualification after the evaluation; (b) obtain construction approval; (c) if it meets national geopark standards, then it can formally become a member of the National geopark network.

(3) Establishing a supervision system and a database of National geoparks experts—National geoparks are currently supervised by 90 inspectors; the database of National geoparks experts is comprised of 23 professors with expertise in different subjects; in order to provide appropriate technical support in geoparks, the professors are encouraged to set up links with the geoparks.

(4) Promoting the management of geoparks—since 2009, 10 fields have been raised, which include: the geopark management organization, the geopark plan, geopark construction, geoheritage protection, scientific research, etc. There needs to be at least 50 information signs in a National geopark, and 80 signs in a Global Geopark; there are at least 3–5 geological engineers in a National park, and 5–8 in a Global Geopark; development of the geopark laws is important.

(5) Approval of the geopark investment mechanism—this is undertaken by a group composed of people from the central government, local government, and the geopark management; when approval is given, then promotion

Fig. 21 Lava pond in Wudalianchi geopark

Fig. 22 Volcanic-dammed lake in Jingbohu geopark

Fig. 23 Volcanic column in Hongkong geopark

Fig. 24 Volcanic cone in Haikou geopark

Fig. 25 Volcanic column in Zhangzhou geopark

Fig. 26 Landslide relics in Cihuashan geopark

and the construction of the geopark can proceed; currently the Chinese Central Government funds about 6 % of a geopark's costs, the local government about 19 %, and about 75 % is funded by geopark income.

The objectives of Chinese global geoparks are: conservation of geoheritage, popularization of geosciences, and development of geotourism. Before the establishment of the geoparks, tourists went to such scenic areas for leisure, without any knowledge of the interesting story of the geology of the area, often the only knowledge was based on unfounded local myths and legends. Through the interpretation and education system, and tour-guide information, the geoparks now play an important role in scientific literacy. As geoparks develop and provide more jobs through the

Fig. 27 Paleoearthquake relics in Qianjiang geopark

Fig. 28 Dinosaur fossils in Zigong geopark

Fig. 29 Neogene strata with fossils in Shanwang geopark

Table 1 Type and number of China geoparks. Statistics according to the main kinds of sites of geoheritage significance in 140 national geoparks

No	Type of geoparks	Number of geoparks	Cases
1	Stratigraphy relic	8	Changshan geopark, Jixian geopark
2	Structure geology relic	7	Songshan geopark, Longmenshan geopark
3	Palaeontology relic	18	Zigong geopark, Shanwang geopark
4	Rock and mineral relic	1	Qianan-Qianxi geopark
5	Geological landforms	92	
	Karst landform	27	Shilin geopark, Shidu geopark
	Granite landform	12	Huangshan geopark, Sanqingshan geopark
	Volcanic landform	15	Wudalianchi geopark, Hongkong geopark
	Glacial landform	8	Lushan geopark, Hailuogou geopark
	Danxia landform	14	Danxishan geopark,Taining geopark
	Yadan landform	4	Alax geopark, Dunhuang geopark
	Sandstone landform	3	Zhangjiajie geopark
	Marine erosion landform	4	Dalian coast geopark, Changshan archipelago geopark
	Yuntai landform	5	Yuntaishan geopark
6	Hydrogeology relic	10	Hukou falls geopark, Enping hotspring geopark
7	Engineering geology relic	1	Hongqi canal-Linlvshan geopark
8	Geohazard relic	3	Yigong geopark

promotion of tourism, they become closely linked with the local people and local communities. The public are now paying more attention to the geoparks in China.

For the purpose of the harmonious development of Chinese geoparks, there needs to be focus on the following aspects: institutional improvement, protection of geological vestiges, the functions of popularization, promotion and education, cooperation and communication, and research and management. Through the aims of geoconservation, the geoparks are being established in an orderly way. In this manner, the environment, the geopark, and the socio-economy are all harmoniously developed. As such, the sustainable development of the geoparks is playing an increasingly important role in China.

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The Karst Geomorphologic Regionalization in China

La régionalisation des karsts géomorphologiques en Chine

الجهوية الجيومورفولوجية الكارستية بالصين

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Abstract

Many geomorphologic types of karst are developed in China throughout an area of 910,000 km^2. Depending on the large differences in terrain types and climate throughout the country, and relying on genetic and morphological approaches, as well as assessing the maximum similarities and the minimum differences of karst landforms within each landform region, the karst features are classified into eight geomorphologic regions, i.e., humid tropical karst landform region (I), humid tropical-subtropical karst landform region (II), arid-humid subtropical-semihumid temperate karst landform region (III), humid-semihumid temperate karst landform region (IV), arid-semiarid temperate karst landform region (V), humid tropical-subtropical-humid-semihumid plateau temperate karst landform region (VI), humid subtropical-semiarid plateau temperate karst landform region (VII), and plateau-high mountain karst landform region (VIII). The karst landform in the region I is dominated by coral reefs (islands) and some scattered hilly karst where one national karst geopark has been established. Region II, typified by well-developed karst, is where 90 % of *fengcong* (cone karst) and all *fenglin* (tower karst) in China occur, with semi-karst formations of hilly karst, valleys and plains. Thirty-one national karst geoparks are established in the region. Region III is characterized by buried, covered karst, and some karst mountains and hills, especially the cap-shaped karst; two national geoparks are established in this region. Region IV is characterized by ridge hill valleys, cluster hill valleys and karst mountain valleys; one national karst geopark is established in this region. Region V consists of middle-high karst mountains and widespread semi-karst landforms of hilly mountains; only one national karst geopark is established in this region. Region VI is characterised by high-mountain karst such as *fengcong* deep canyons and gentle *fengcong* canyons, where five national geoparks of karst are established. Region VII is characterised by undeveloped karst being no different from the non-karst landscape. Region VIII is characterised by two basic types of karsts, the high karst mountains and the semi-karst mountains. No karst geopark has yet been established in regions VII and VIII.

Résumé

La Chine consiste en de nombreux types de karsts géomorphologiques développés sur une superficie de 910 000 km^2. Selon les types de terrain et le climat à travers le pays, en s'appuyant sur les approches génétiques et morphologiques, ainsi que sur l'évaluation des similitudes maximales et des différences minimales des reliefs dans chaque région karstique, les karsts sont classés en huit régions géomorphologiques: la région karstique tropicale humide (I), la région

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karstique tropicale-subtropicale humide (II), la région karstique subtropicale tempérée aride-humide semi-humide (III), la région des karsts humide semi-humide tempérée (IV), la région karstique tempérée aride semi-aride (V), la région des plateaux karstiques tempérée tropicale-subtropicale semi humide à humide (VI), la région des plateaux karstiques humides subtropicales semi-aride (VII), la région des plateaux karstiques tempérée subtropicale humide-semi-aride, et la région karstique des hauts plateaux et montagnes (VIII). Le paysage karstique de la région I est dominé par des récifs coralliens et des collines karstiques dispersées où un géoparc national a été établi. La région II, caractérisée par des karsts bien développés, englobe 90 % des *fengcong* (karsts à pitons) et tous les *fenglin* (karsts à tourelles) de Chine. Trente et un géoparcs nationaux karstiques ont été établis dans cette région. La Région III avec deux géoparcs nationaux se caractérise par des karsts couverts et enterrés, et quelques montagnes et collines karstiques, en particulier le karst en forme de chapeau. La région IV, avec un géoparc national karstique, se caractérise par des vallées et des crêtes de colline, des vallées d'amas colline et des vallées de montagne karstique. La région V, avec un seul géoparc national karstique, est formée de montagnes karstiques d'altitude moyenne et de vastes reliefs semi-karstiques de montagnes vallonnées. La région VI est caractérisée par des karsts de montagnes d'altitude moyenne à haute comme les profonds et les douces canyons des Fengcong, où cinq géoparcs karstiques nationaux ont été établis. La région VII est caractérisée par des karsts peu développés sans différences avec les paysages non karstiques. La région VIII est caractérisée par deux types de karsts, les montagnes karstiques élevées et les montagnes semi-karstiques. Cependant aucun géoparc karstique n'a encore été établi dans les régions VII et VIII.

ملخص

تتوفر الصين على العديد من الأنواع الجيومورفولوجية الكارستية الممتدة على مساحة 910000 كلم2. واعتمادا على الاختلافات الكبيرة في أنواع التضاريس والمناخ بجميع أنحاء البلاد، واستنادا على النهج التكوينية والمورفولوجية، وإضافة إلى تقييم أوجه التشابه القصوى والفُرُوقِ الدنيا للتضاريس بكل منطقة كارستية، تم تصنيف الأراضي الكارستية إلى ثمان مناطق جيومورفولوجية. وهي : منطقة كارستية استوائية رطبة (1(، منطقة كارستية استوائية إلى شبه استوائية رطبة (2)، منطقة كارستية شبه استوائية معتدلة جافة رطبة إلى شبه رطبة (3)، منطقة كارستية رطبة إلى شبه رطبة معتدلة (4)، منطقة كارستية معتدلة قاحلة إلى شبه قاحلة (5)، منطقة الهضاب الكارستية المعتدلة استوائية إلى شبه استوائية شبه رطبة إلى رطبة (6)، منطقة الهضاب الكارستية الرطبة شبه استوائية شبه قاحلة (7)، منطقة الهضاب الكارستية المعتدلة الاستوائية إلى شبه استوائية شبه قاحلة، والمنطقة الكارسيتة للهضاب العليا والجبال (8). المناظر الطبيعة الكارسيتة بالمنطقة الأولى تهيمن عليها الشعاب المرجانية والتلال الكارستية المتناثرة، حيث تم تأسيس جيومتنزه وطني واحد. المنطقة الثانية تتميز بأراضي كارستية مكتملة التكوين، تضم تسعين في المائة من الفنغكونغ (أراضي كارستية مخروطية) وجميع الفنغلين (أبراج كارستية) بالصين. تم إنشاء واحدا وثلاثون جيومتنزها كارستيا وطنيا بهذه المنطقة. المنطقة الثالثة، التي تضم جيومتنزهين وطنيين، تتميز بأراضي كارستية مغطاة ومدفونة، وبعض الجبال والتلال الكارستية، خصوصا الأرض الكارستية على شكل قبعة. المنطقة الرابعة، التي تحتوي على جيومتنزه كارستي وطني واحد، تتميز بوديانٍ وقممِ تلالٍ ووديان تلال متكتلة ووديان جبال كارستية. المنطقة الخامسة التي تضم جيومتنزها كارستيا وطنيا واحدا، مكونة من جبال كارستية ذات علو متوسط، ومن تضاريس واسعة شبه كارستية بالجبال المتموجة. المنطقة السادسة تتميز بجبال كارستية ذات علو متوسط إلى مرتفع، مثل الأخاديد العميقة والمتوسطة العمق بفنغكونغ، حيث تم إنشاء خمس جيومتنزهات كارستية وطنية. المنطقة السابعة تتميز بأراضي كارستية غير مكتملة التكوين، لا تختلف كثيرا عن المناظر الطبيعية غير الكارستية. المنطقة الثامنة تتميز بنوعين من الأراضي الكارستية، الجبال الكارستية الشاهقة والجبال الشبه الكارستية. مع ذلك لم يتم بعد تأسيس أي جيومتنزه كارستي بالمنطقتين السابعة والثامنة.

Keywords

Karst • Geomorphologic type • Geomorphologic regionalization • China

Mots-clés

Karst • Type géomorphologique • Régionalisation géomorphologique • Chine

الكلمات الرئيسية

أراضي كارستية • نوع جيومورفولوجي • الجهوية الجيومورفولوجية • الصين

1 Introduction

Geomorphologic regionalization has been carried out in China since 1959. Later, provincial regionalization was carried out in several provinces, however, their geomorphologic classification was too simple, but did include karst landforms. In terms of karst, the geomorphologic regionalization mostly recognized four main karst zones by climatic geographical boundary (DKGI 1979; Lu 1986; Yuan et al. 1991; Zhu 2005), i.e., humid tropical-subtropical karst region (I), humid-semihumid subtropical-temperate karst region (II), arid-semiarid karst region (III) and plateau-high mountain karst region (IV). The regionalization is of karst instead of geomorphologic karst, and they contain several karst landform elements, but more importantly, their regionalization depends on the difference of karst hydrogeology instead of climatically-determined geomorphology.

Carbonate rocks are widespread in China, with an outcrop area of 910,000 km^2 (Li et al. 1983; Fig. 1). Because of differences in geology, terrain and climate throughout the country, the karst landforms are more complicated than karst hydrogeology, and they have so many differences and similarities that different karst terminologies have been used in different provinces and autonomous regions. A geomorphologic regionalization of karst is necessary to promote our understanding of karst in China and to plan national economic development.

According to the karstological regionalization, to set up a geopark related to karst and caves is more reliable and comparative.

2 Regionalization Approach

Genetic and morphological approaches may be used to classify the typological category of karst geomorphology in China.

The genetic approach stresses the origin and development of the karst features, and the processes and conditions essential to their formation. The lithology may be first used to classify the formations underlying the karst geomorphology. At the first level of classification, they are subdivided into three karst types, namely, the whole karst, the semikarst and the biokarst landforms depending on the

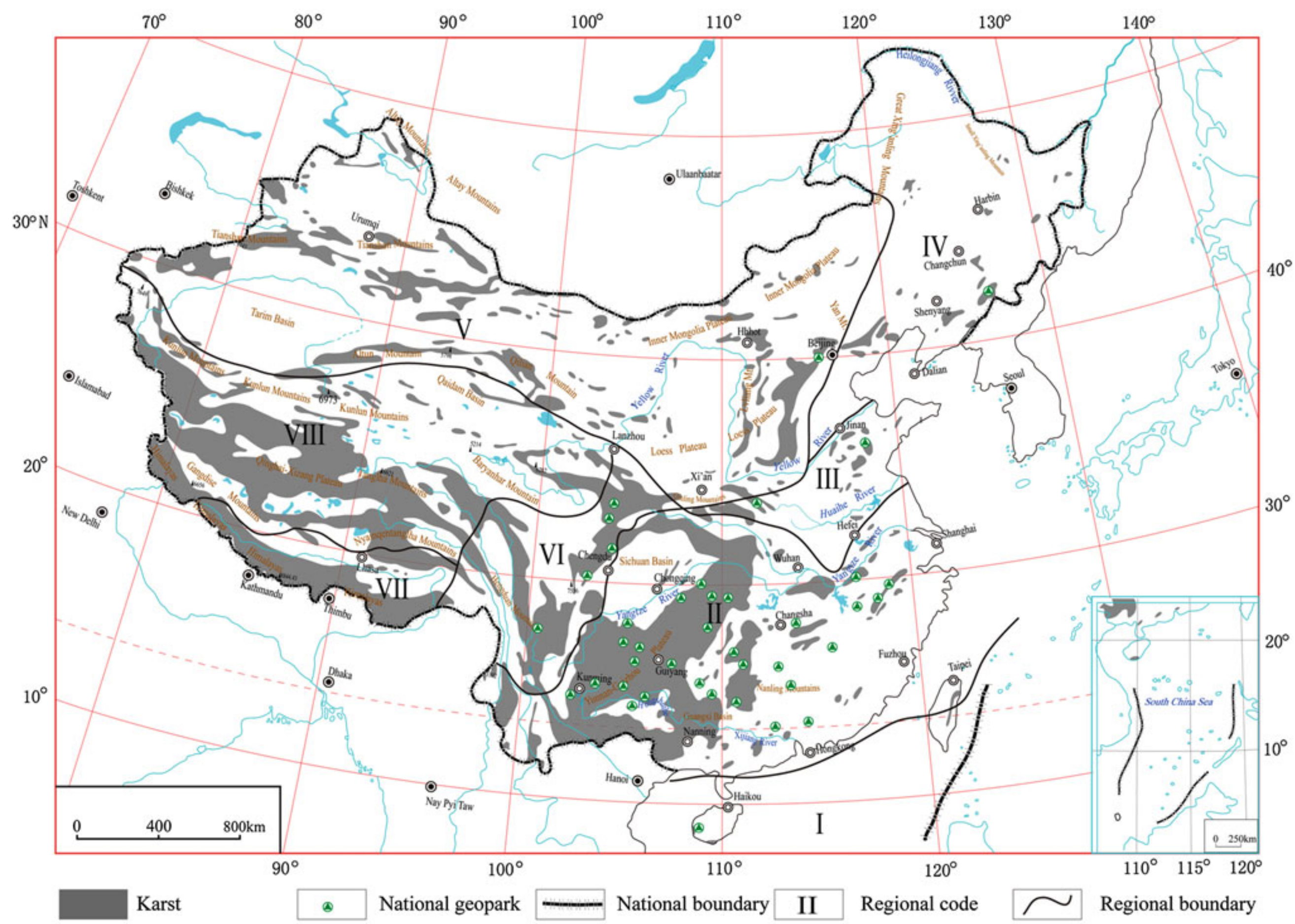

Fig. 1 The geomorphologic regionalization of karsts in China

purity of carbonate rocks. Beyond lithology, a second class of karst geomorphology is recognized, dependent on the zonal factors and external factors to classify six climatic-geomorphologic types and seven karst landforms, respectively.

Whole karst landforms and semi-karst landforms can be separated from non-karst areas by how much non-karst rocks occur in the region. For example, a terrain is classified into whole karst area if the non-carbonate clastic rocks are less than 20 %, otherwise it is classified into semi-karst landform. The geomorphological approach uses characteristics of shape and dimensions, and lithologic characters and formation process of rocks as principal criteria for delineating karst types. Twenty-three morphological types are thus classified (Table 1). The development of the karst landform is complex, influenced by many factors, and has a variety of combinations. The geomorphologic types can be vague, unclear and overlap near the regional boundaries when making geomorphologic regionalizations. Consequently, the following methods are used.

(1) The maximum similarity and the minimum differences of karst landforms are required within each landform region; however, in different landform regions, the minimum similarity and the maximum differences of karst landforms are required.
(2) The combination of karst features and typical formations should be used to determine a regional boundary. For example, if the combinations of karst landforms in humid tropical regions are *fengcong* (cone karst) but the typical ones are *fenglin* (tower karst), then the regional boundary is designated by the distribution of *fenglin*.
(3) Since karsts are widespread throughout China, and karst landforms are mainly controlled by climatic factors (Qin et al. 1984), regional boundaries are determined, firstly, by different climatic zones, such as tropical, subtropical, temperate and plateau high-mountain (alpine) zones, as well as humid, semihumid, semiarid and arid zones, depending on the main climatic index, as well as temperature, precipitation, evaporation and dryness. For example, the coral reef lithology that hosts karsts is distributed in tropical regions; the tower karst is in the humid tropical-subtropical zone. However, the karst landforms are also influenced by non-climatic factors, such as geological structure, lithology and topography. So, a comprehensive analysis should be considered to set up the sub-region boundary.
(4) Karst landforms may be grouped into the same geomorphologic regions if they manifest two important characteristics, firstly, that the positive and negative landforms have formed together and comprise a complete topographical structure (Zhu et al. 1988); and, alternatively and secondly, that the high-mountain (alpine) karst landform system with several thousand meters height difference located within (altitudinally) different climatic zones, is actually in the same complete karst system geomorphologically, and therefore within the same geomorphologic region.

According to the methods and criteria mentioned above, karst landforms in China are divided into eight karst geomorphologic regions, i.e., humid tropical karst landform region (I), humid tropical-subtropical karst landform region (II), arid-humid subtropical-semihumid temperate karst landform region (III), humid-semihumid temperate karst landform region (IV), arid-semiarid temperate karst landform region (V), humid tropical-subtropical-humid-semihumid plateau temperate karst landform region (VI), humid subtropical-semiarid plateau temperate karst landform region (VII) and plateau-high mountain karst landform region (VIII) (Fig. 1).

3 The Main Features of Karst Landform Regions

3.1 Humid Tropical Karst Landform Region (I)

This region is situated in the south of the line of Leizhou Peninsula–Penghu Islands–southern Taiwan–Diaoyu and Chiwei Islands. Its average annual temperature is >22 °C and its annual precipitation is >1,500 mm (EBPGC 1984).

It belongs to the Caledonian fold zone of circum-Pacific tectonic domains in the north and South Sea platform in the south (CAGS 1975; Zhang 1983). Few carbonate rocks were discovered in southern counties of Hainan Province. They are Middle-Upper Carboniferous limestone, and Cambrian, Ordovician carbonate clastic rocks, about 560–930 m thick (Chen et al. 1988). They form a small area of *fengcong*, and some karst hills.

The karst landform in this region is mainly distributed in the South China sea area and is characterised by coral reefs (Huang 1980). Many coral islands occur within this region and are widely distributed around the South China Sea islands and near Taiwan. It is the only region in China which contains biological (coral reef) karst topography; there is one national karst geopark in this region.

3.2 Humid Tropical Subtropical Karst Landform Region (II)

The boundary of the humid tropical-subtropical karst landform region is the Qinling Mountains to the north, extending from Qinling to Dabie mountain, the watershed of Yangtze River and Huaihe River, and East China Sea to the east,

Table 1 The karst geomorphologic types in China

Geomorphologic type				Formation conditions	
Genetic type		Morphologic type		Lithology	Climate
Whole karst landform	Dissolution landform	Mountain	*Fengcong* doline	Pure carbonate rocks covered by loose soils on surface in doline or valley	Humid tropical-subtropical
			Gentle *Fengcong* doline		Mainly humid, alternative tropical and subtropical
		Hill	*Fengqiu* doline		
	Erosion-dissolution landform	Mountain	*Fengcong* Canyon		Humid subtropical
			Quasi-*fengcong* doline		
			Gentle *fengcong* valley		Mainly humid, alternative tropical and subtropical
			Mountain valley		Alternative subtropical and temperate
			Mountain dry valley		Semiarid-semihumid temperate
		Hill	*Fengqiu* valley		Mainly humid, alternative tropical and subtropical
			Hill valley		Alternative humid and arid subtropical-temperate
			Hill dry valley		Semiarid-semihumid temperate
	Erosion-dissolution-accumulation landform	Plain	*Fenglin* plain		Humid-rainy subtropical
			Fengqiu plain		
			Quasi-*fenglin* Plian		Humid subtropical
	Erosion-denudation landform	Mountain	Mountain		Arid-semiarid temperate-high cold
Semi-karst landform	Dissolution-erosion landform	Hill	Peaks hill valley	Impure carbonate rocks or carbonate rocks inter-layered with non-soluble rocks	Humid-semihumid tropical-subtropical-temperate
			Cluster hill valley		
		Table land	Gentle hill valley		
	Erosion-dissolution-accumulation landform	Plain	Gentle hill plain		
	Dissolution-erosion landform	Mountain	Mountain		Arid-semiarid-temperate-high cold
		Hill	Hill		
Bio-karst landform	Dissolution-erosion-denudation-accumulation landform	Plain	Plain		
	Bioaccumulation-dissolution-sea eroding landform	Coral reefs	Coral reefs	Reef limestone, beach rock	Tropical marine climate

extending from Qinling to the Eastern Anemaqen Mountain, turning to the south to Yulong Mountain, then to the Eastern Himalayas to the west. There are very different geomorphologic types in this region, consisting of the Sichuan Basin and the Yunnan-Guizhou Plateau as well as middle-high mountains around to the west, with elevations of 1,500–2,000 m or more (excluding the Sichuan Basin), while in the east they are less than 1,000 m ASL. This karst region occurs essentially in a humid subtropical climate except in the border area to the south. Its average annual temperature is 15–19 °C and its annual precipitation is 1,000–1,400 mm.

This karst region is mainly situated in the Yangtze Platform to the east and Himalayan block to the west, and is underlain by carbonates >10,000 m in total thickness with ages from the Cambrian to the Triassic. There is an almost continuous carbonate outcrop of 500,000 km^2 (Li et al. 1983) where karst landforms are well-developed (Gao et al. 1986; Zhu et al. 1988) (Figs. 2, 3 and 4). Thirty-one national karst geoparks are established in this region. More than 90 % of *fengcong* (cone karst) and all *fenglin* (tower karst) are distributed in this region, except to the north of Region I and to the southeast of Region VI in southwestern Sichuan and in northwestern Yunnan, with areas of 134,500 and 101,000 km^2 respectively (Li et al. 1983). In addition, the semi-karst is well distributed and is characterised by different formations of hilly karst, valleys and plains, with a total area of 56,800 km^2.

3.3 Arid-Humid Subtropical-Semihumid Temperate Karst Landform Region (III)

The northern boundary of the arid-humid subtropical-semihumid temperate karst landform region is from Shandong Peninsula along the Yellow River to Qinling Mountains. It borders Region II in the south. This region consists of the Huaihe River drainage area and a small part of the Yellow River Basin, and features higher topography in the west, and hilly area to the east, slightly tilting to Huanghuai plain in the southeast. The region is located in humid northern subtropical-southern temperate climate, with average annual temperature of 12–15 °C and annual precipitation of 700–900 mm. The arid-humid subtropical-semihumid temperate karst landform region is located among the North China platform and the Yangtze platform, and the eastern extension of the Kunlun-Qinling-fault and fold belt. The carbonate rocks that underlie it are mainly late mid-Proterozoic to Early Paleozoic in age, some 927 m thick at most. Two national karst geoparks are established in this region.

After the Cenozoic period, continental sediments of >6,000 m thickness were deposited as a result of the decrease in tectonism, and most of the karst features were buried by the sediments of the plain. As such, the karst in this region is well buried. At the same time, the areas in central-southern Shandong and western part were uplifted by fault movement, and about 1,000 km^2 area of karst was exposed to form karst mountains and hills (especially the

Fig. 2 Region II karst landform (*fengcong* karst in Guangxi by Li Jin)

Fig. 3 Region II karst landform (*fenglin* karst in Guangxi by Zhu Xuewen)

Fig. 4 Region II karst landform (Gorge karst in Chongqing by Chen Weihai)

cap-shaped karst landform with relief less than 800 m ASL) (Yuan 1993) (Fig. 5).

3.4 Humid-Semi-Humid Temperate Karst Landform Region (IV)

The humid-semihumid temperate karst landform region is located to the north of Region III and borders the Great Xing'anling Mt., to Yan Mt., Daqin Mt.-Lvliang Mt. and Qinling Mt. to the west. It is located in a humid-semi-humid temperate climatic zone with average annual temperature of 2–12 °C and annual precipitation of 500–700 mm. This region is located in the Songliao block and the North China platform with Caledonian and Yanshan fold belts. Various types of carbonate rocks underlie the region and they range in age from Archaean to Cenozoic, though mainly Cambrian to Ordovician and part of the Proterozoic Sinian period. Their thickness is some 2,031 m at most, but with scattered distribution. This region has the most complete and well-

Fig. 5 Region III karst landform (cap-shaped karst in Shandong by Chen Weihai)

developed temperate karst types regionally (Yuan 1993), including bare karst, covered and buried karst, with an area of 100,651 km^2 in total. It is characterised morphologically by ridge hill valleys, cluster hill valleys and karst mountain valleys (dry valley, Fig. 6) (Chen 1988). Only one national karst geopark is established in this region.

3.5 Arid-Semiarid Temperate Karst Landform Region (V)

The arid-semiarid temperate karst landform region borders Region IV to the east, and its southern boundary is from the Qinling Mountains to Qilian Mountain, Altun Mountain and

Fig. 6 Region IV karst landform (karst dry valley in Hebei by Zhang Yuanhai)

Western Kunlun mountains. It consists of the Inner Mongolia Plateau, Ordos Plateau, Loess Plateau, Hexi Corridor, Junggar Basin, Turpan Basin, Tarim Basin, and several large mountain ranges such as eastern Yin, Helan Mountains, central Kitayama, western Tianshan, Altai Mountains. The region belongs to the middle temperate climatic zone except southern Xinjiang and some parts of Shaanxi, Shanxi and Gansu in the southern temperate zone. Its annual precipitation is 100–300 mm (<50 mm in Turpan Basin-Alxa plateau region and 300–500 mm near Region IV to the east); its average annual temperature is 2–10 °C except in the western area with 4–10 °C.

The region belongs to the Tarim platform structural domain in China, Tianshan Hercynian fold region, Lanzhou-Xining block, and the Junggar block of Siberia-Mongolia continental tectonic domain, as well as Altai Caledonian fold belt. The carbonate rocks underlying the region are old, with total thickness of 16,000 m, and range in age from Archaean to Palaeozoic, though pure carbonate rocks in the region are about 5,000 m thick. The karstification in this region is very weak because of the dry, cold, windy and low rainfall environment. This has resulted in middle-high karst mountains with an elevation of 1,150–3,400 m (XCI 1978); the whole karst covers an area of nearly 6,000 km^2. The semikarst landforms are more widespread, being characterised by karst mountains and hilly mountains with an altitude of 1,500–2,500 m (Fig. 7). One national karst geopark has been established in the region.

3.6 Humid Tropical-Subtropical-Humid-Semihumid Plateau Temperate Karst Landform Region (VI)

This region is located in the west of Sichuan and to the east of Qinghai-Xizang Plateau, and it borders Region II to the east and to the south; its western boundary extends from the northeastern Himalayas to the eastern Tanglha Mountains, then to the southern Baryanhar Mountain. The region consists of a series of parallel and alternating mountains and canyons, i.e., Hengduan Mountains. The average elevation of the mountains is 4,000–5,000 m; the highest one being 6,884 m ASL. The canyons are generally 1,500–2,000 m deep, the lowest one being 1,500 m ASL. The region is in the plateau temperate humid climatic zone, however there are semihumid features in the central and northwestern area. Its annual precipitation is 500–700 mm but the adjacent area of Sichuan, Yunnan and Tibet near Jinshajiang River has an annual precipitation about 400 mm. Its average annual temperature is 2–8 °C.

Most of the region is located in the Bayanhar and Nagqu fold belts, being across two ancient blocks, the Southern Gondwana and the Southern China. Carbonate rock deposits are >24,000 m thick and range in age from Sinian to Triassic, with the main strata from Silurian to Permian in age. The majority of rocks are interlayered, impure and metamorphosed carbonate rocks. The region mainly features high-mountain karst, such as *fengcong* deep canyons and

Fig. 7 Region V karst landform (Helan Mt karst in Inner Mongonia by Liang Yongping)

Fig. 8 Region VI karst landform (alpine karst in Western Sichuan by Zhang Yuanhai)

gentle *fengcong* canyons, with an elevation of 4,600–5,500 m and a relative height of 2,400–3,500 m (Wang 1990) (Fig. 8). This region contains five national karst geoparks.

3.7 Humid Subtropical-Semiarid Plateau Temperate Karts Landform Region (VII)

Region VII is situated to the south of Nyainqentanglha-Kailash and to the north of the Himalayas. It is characterised by high mountains with low-middle mountains (of elevations from 5,000–6,000 m, the highest being Mt Everest with an altitude of 8,848 m), hills and small plains in valleys, as well as canyons of 1,000–4,000 m in depth. This region is located in a semiarid plateau temperate climatic zone, with a large difference in precipitation from west (100 mm) to the east (500 mm); its annual average temperature is 0–8 °C, decreasing from the east to the west, and it is less than 0 °C above 5,000 m ASL. The snow line increases from 4,500–5,000 m ASL in the east to 6,000 m ASL in the west. This region is located in the tectonic unit of Himalayan blocks, Brahmaputra folds, Nagqu folds and Gangdise blocks. It is underlain by carbonate rocks some 3,580 m thick in the central region, being characterised by limestone interlayered with shale, sandstone and volcanics deposited in the Middle and Lower Triassic, Middle and Lower Jurassic, Upper Cretaceous and Palaeogene periods. There are also carbonate rock deposited before the late Permian period, i.e., from late Sinian to early Permian periods with the exception of the Cambrian, late Silurian and early Carboniferous periods); for example, there is a 1,000 m thick Lower Ordovician limestone with shale, sandstone and their metamorphosed equivalents and 240 m thick Lower Permian limestone with clastic rocks near Mt Everest.

Because of the climatic conditions in this region, the karst landforms are undeveloped. Erosional phenomena and negative karst landforms are very few, and erosion and weathering in particular are influenced by severe frosts on the surface, and the karst formations have no difference from non-karst landscapes. There are no karst geoparks in this region.

3.8 Plateau-High Mountain (Alpine) Karst Landform Region (VIII)

This region consists of high mountain areas among Qilian, Altun, Kunlun, Gangdise, Nyainqentanglha and Tianshan mountains, and is characterised by an average high elevations of >3,000 m. It is located in a cold-arid climate. The annual average temperature <0 °C (<−8 °C in the plateau hinterland); the annual precipitation is <100 mm (<50 mm in Qaidam Basin and Ali area). This region belongs to the continental tectonic domains of the North (Siberia-Mongolia), the Northern China, the Southern China and the South Gondwana. Carbonate rocks are commonly scattered in this region except for the area of Qaidam Basin, Tanglha-Kailash

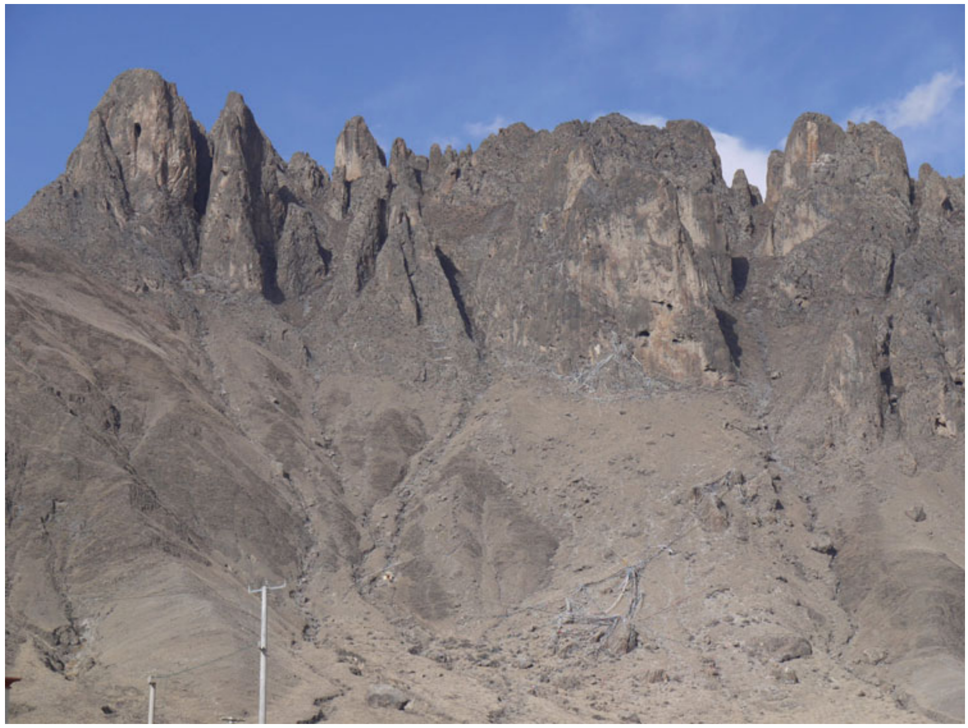

Fig. 9 Region VIII karst landform (Tibet karst by Tony Waltham)

-Central Tianshan Mountains, and where there are metamorphic rocks and interlayered carbonates from Proterozoic to Early Tertiary period (Wang 1990; Gao et al. 2001). The rock sequence is generally more than 1,400 m thick in the Kunlun mountains area reaching 4,000 m in thickness to 7,000 m thick in the eastern Kunlun Mountains. It also comprises limestone with clastic rocks over 4,000 m in thickness in the Baryanhar Mountains, while in the Tianshan area it consists of clastic sedimentary rocks with carbonates nearly 10,000 m thick. In the southern region (to the south of Kunlun mountains), there are several thousand meters thick Carboniferous-Permian limestone with clastic rocks, and Upper Triassic- Cretaceous clastic rocks with limestone. In addition, there is 2,900 m thickness of limestone with oolitic limestone and dolomite in the western Qilian mountain area.

In this region, there are two basic types of karst landforms: one is the karst high mountains composed of Middle-Upper Devonian limestone, biogenic limestone and dolomite in the southern Tianshan, and Middle Sinian limestone in Western Qilian Mountains, with a total area of 3,353 km^2 and average altitudes of 4,000–4,500 m and relative height of 1,500–2,500 m; the other is semi-karst mountains composed of Proterozoic to Palaeogene carbonate rocks interlayered with clastic rocks or impure and metamorphosed carbonate rocks. These carbonate rocks are scattered throughout the region except in the area of Qaidam Basin and Tanglha mountains as well as Kailash Mountains, with an total area of 677,626 km^2 and average elevation of 4,500 m (Tianshan area) to 4,900 m (Qinghai-Xizang Plateau area), and relative height from 400–1,000 m in low mountains to 1,500–2,000 m in high mountains (QTPCSI 1983; Gao et al. 2001) (Fig. 9). No karst geoparks have yet been established in region VIII.

4 Discussion and Conclusions

The geomorphologic regionalization of karst in China, presented in this paper, provides a systematic and comprehensive classification of karst landform development and distribution in China, based on geographical and geological data, and their analysis.

The subdivision of karst in China into eight karst geomorphologic regions is based mainly on the differences of geomorphology and climate. Some sub-regions are recognized based on the difference of regional landform, geological structure and other indicator criteria. The main eightfold subdivision presents karst landform regional distribution features. However, because the karst research is very unbalanced in the western and the eastern China, obviously there has been more complete research on karst in the eastern China. For example, the 1:1,500,000 karst geological survey is used as the base map in western China, however, sufficient data are available in eastern China, and, as such, for the latter, sub-regions of karst landform can be recognized (not discussed here).

Due to limited data, the comparison and analysis of karst landform and karst cave evolution were not discussed in this paper. The result would be sketchy only according to the macro-regional geological history, palaeogeography and palaeoclimatic changes. The evolutionary history and developed ages of different karst landforms and caves in China should be studied in detail in the future.

This subdivision of karst into eight regions provides a template to rationally recognizing and allocating national geoparks.

The karst landforms are both a natural element and a natural resource. The geomorphologic regionalization of the karst landforms provides a way to an in-depth understanding of the landforms structure and evolution, and the necessary regional information for agricultural production, resource utilization and environmental protection, and national economy development. It is important not only for China but also as a model of methods and approaches for African countries and elsewhere globally.

Acknowledgments Many thanks to all our colleagues who work and have worked in the department of karst geomorphology and speleology, Institute of Karst Geology, for their hard work in the past of more than ten years for the project of 1:4,000,000 China karst geomorphological map compilation.

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Using the Geoheritage Tool-Kit to Identify Inter-related Geological Features at Various Scales for Designating Geoparks: Case Studies from Western Australia

Utilisation du toolkit pour identifier les caractéristiques géologiques et désigner de potentiels géoparcs - cas de l'Australie occidentale

استخدام مجموعة من الأدوات لتحديد الخصائص الجيولوجية ومؤهلات الجيومنتز هات -غرب أستراليا نموذجا

M. Brocx and V. Semeniuk

Abstract

To further the disciplines of geoheritage and geoconservation, a Geoheritage Tool-kit has been developed in Western Australia to systematically compile an inventory of the full diversity at various scales of geological and geomorphological features in a given area, assess their levels of significance, and address whether geoheritage features are treated in isolation or as inter-related suites that should be conserved as an ensemble. The objective of the Geoheritage Tool-kit is to provide a systematic approach to develop a database or inventory of sites of geoheritage significance. Use of the Geoheritage Tool-kit begins with identifying geological regions, then listing their geological essentials to develop a database for sites of geoheritage significance. The next stage is to locate good examples, of these features, or of inter-related ensembles of features, regardless of scale, and assess them according to significance criteria. After an assessment of the range, categories, inter-relationships, and level(s) of significance of the geological features, the final step is to determine what type and what level of geoconservation the area requires. Three areas: King Sound and the tide-dominated delta of the Fitzroy River; Leschenault Peninsula, a retrograding Holocene dune barrier in south-western Australia, and its leeward estuarine lagoon; and the Walpole-Nornalup Inlet estuary, provide case studies of the application of this Tool-kit. Each of these coastal areas comprises a wide variety of geological and geomorphological features, from large to fine scale, and varying in significance from International to National to Regional. Some key features of global significance include: the tide-dominated delta at King Sound, the calcrete, beach rock, and calcitised sea rush roots at Leschenault Peninsula, and the intra-estuarine deltas in the Walpole-Nornalup Inlet estuary. In terms of geoconservation, addressing the various features of geoheritage value in this area is best achieved by viewing the systems as an integrated geopark of interactive processes, geology, and geomorphology.

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Résumé

Pour promouvoir les disciplines du géopatrimoine et de géoconservation, un toolkit a été développé en Australie occidentale pour compiler un inventaire systématique des caractéristiques géologiques et géomorphologiques à différentes échelles d'une zone donnée, évaluer leurs niveaux de signification, et définir si ces caractéristiques géopatrimiales sont traités isolément ou comme suites inter-liés. Ceci dans le but de développer une base de données des sites d'importance géopatrimoniale et de déterminer leur niveau de géoconservation. Trois zones, King Sound et le delta la rivière Fitzroy, la péninsule de Leschenault, et l'estuaire de Walpole-Nornalup Inlet ont été choisies pour l'application de ce toolkit. Chacune de ces zones côtières comprend une grande variété de caractéristiques géologiques et géomorphologiques d'échelles et d'importances variables. La géoconservation, des différentes caractéristiques de valeur géopatrimoine de cette zone, est mieux réalisée dans le cadre d'un géoparc.

ملخص

لتعزيز تخصصات الجيوتراث والجيومحافظة، تم تطوير مجموعة من الأدوات بغرب أستراليا لجمع قائمة جرد منهجي للخصائص الجيولوجية والجيومورفولوجية على مستويات مختلفة لمنطقة معينة، وتقييم أهميتها، وتحديد ما إذا كانت هذه الخصائص الجيوتراثية قد تمت معالجتها على انفراد أم أنها مرتبطة الواحدة بالأخرى. وهذا من أجل تطوير قاعدة بيانات للمواقع الجيوتراثية الهامة، وتحديد مستوى الجيو محافظة عليها. وقد تم اختيار ثلاثة مناطق هي: كينك سوند" و" دلتا نهر فتزوري" و "شبه جزيرة لتشنولت" ومصب "والبول-نورنلوب إنلت" لتطبيق هذه الأدوات. كل منطقة من هذه المناطق الساحلية تتضمن مجموعة متنوعة من الخصائص الجيولوجية والجيومورفولوجية ذات سلم وأهمية متنوعين. إن الجيومحافظة، على مختلف الخصائص ذات القيمة الجيوتراثية لهذه المنطقة، تنفذ أفضل في إطار جيومنتزه.

Keywords

Geoheritage • Geoconservation • Geoheritage Tool-kit • Western Australia • King sound • Leschenault peninsula • Walpole-Nornalup inlet

Mots-clés

Géopatrimoine • Géoconservation • Tool kit • Western australia • King sound • Péninsule leschenault • Walpole—nornalup inlet

الكلمات الرئيسية

جيوتراث • جيومحافظة • مجموعة أدوات • أستراليا الغربية • كينك سوند • دلتا نهر فتزوري • شبه جزيرة لتشنولت • والبول-نورنلوب إنلت

1 Introduction

To further the disciplines of geoheritage and geoconservation, we provide a description of the "state of the art" of geoheritage and geoconservation in Western Australia using a Geoheritage Tool-kit which provides techniques for identification of features, and assigns to them a level of significance. In a given area, geoheritage features can range from large scale to fine scale, from international to local in significance, can encompass a wide range of geological/geomorphological features, and can occur in isolation, or as an inter-related suite that should be conserved as an ensemble. This Geoheritage Tool-kit has been designed to build an inventory of geological/geomorphological features, to recognise the scales at which they are expressed, and to assess their significance. Where the geology forms an integrated system ranging from small- to large-scale features, an area lends itself to being conserved as an ensemble and considered as a geopark.

This paper provides case studies of the use of the Tool-kit in three areas, viz., King Sound and the tide-dominated delta of the Fitzroy River, the Leschenault Peninsula and its leeward estuarine lagoon, and the Walpole-Nornalup Inlet estuary. This tool-kit aims to address the classification and assessment challenges for land managers and geoheritage practitioners.

In the context of the First International Conference on African and Arabian Geoparks held in November 2011 in El Jadida, Morocco, we suggest that the Geoheritage Tool-kit developed in Western Australia and applied to a wide variety of geological settings can be applied to northern Africa. In this context, it has already been applied to the Anti-Atlas of Morocco to identify sites of geoheritage significance as a basis to assigning them to geosites, Sites of Special Scientific Interest, and geoparks (Errami et al. 2011).

2 Categories of Geoheritage Features, Scale, and Level of Significance

Prior to describing the Geoheritage Tool-kit, some background information is provided in terms of the scope and categories of geoheritage, and the scale and levels of significance applied to sites of geoheritage. The term *geoheritage* is used as follows (Brocx and Semeniuk 2007): globally, nationally, state-wide, to local features of geology, such as its igneous, metamorphic, sedimentary, stratigraphic, structural, geochemical, mineralogic, palaeontologic, geomorphic, pedologic, and hydrologic attributes, at all scales, that are intrinsically important sites, or culturally important sites, that offer information or insights into the formation or evolution of the Earth, or into the history of science, or that can be used for research, teaching, or reference. This perspective places many aspects of geology under the umbrella of geoheritage.

While geoheritage relates to features of a geological nature, geoconservation is the action that works towards the preservation of sites of geoheritage significance once their level of significance has been determined.

Sites of geoheritage significance can be assigned to one of four conceptual categories, viz., reference sites, culturally significant sites, geohistorical sites, and modern, active sites (Fig. 1).

Scale is important to consider in geoheritage and geoconservation since sites of geoheritage significance can range from landscapes and geological phenomena at montane-scale, to those of outcrops, beddings planes, or a crystal (Brocx an Semeniuk, 2007). The scales of reference and their terms to address this range are: regional scale (or megascale) = 100 km × 100 km or larger; large scale (or

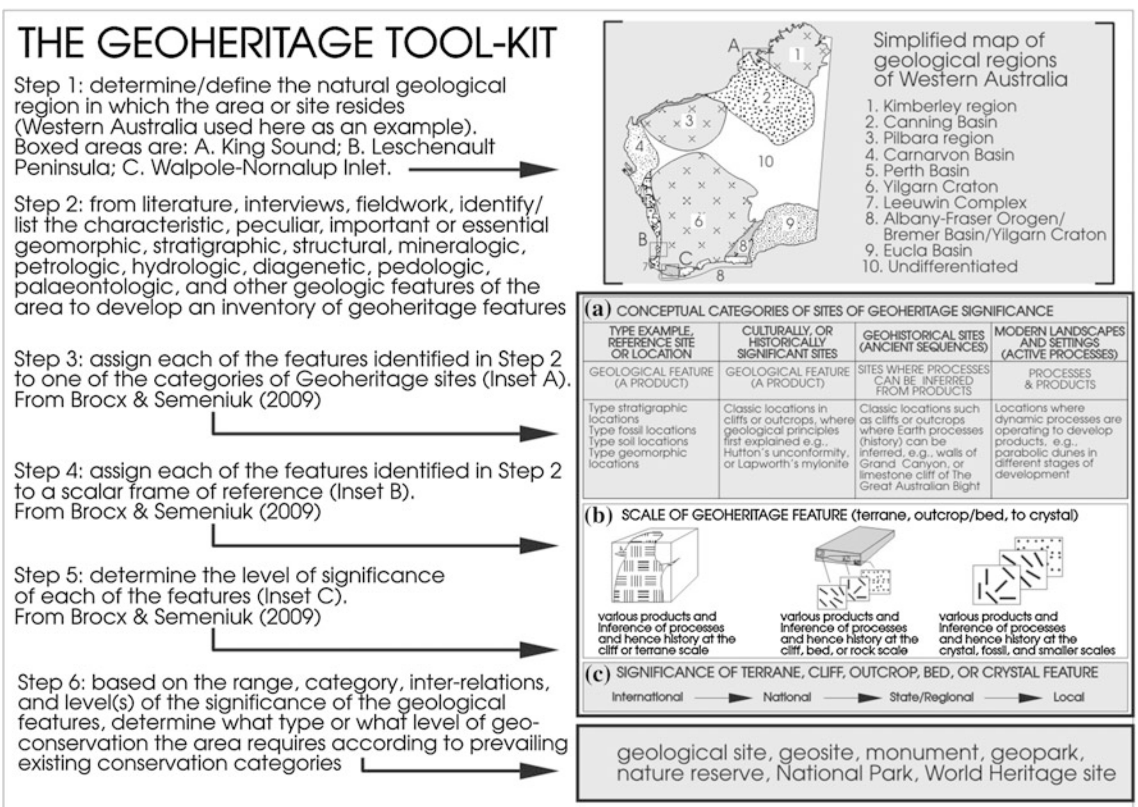

Fig. 1 The Geoheritage Tool-kit showing the five steps in its application leading to assessment of types of geoconservation. The map of Western Australia in Step 1 also shows the location of the three Study Areas. The simplified geological regions of Western Australia is from Brocx and Semeniuk (2010) modified from the Geological Survey of Western Australia (1990). The boxed text/illustrations labelled A, B, C, from Brocx (2008), summarise the scope of geoheritage in terms of its conceptual categories, its scales of application, and potential levels of significance that can be assigned to sites

macroscale) = 10 km × 10 km; medium scale (or mesoscale) = 1 km × 1 km or larger; small scale (or microscale) = 10–100 m × 10–100 m; fine scale (or leptoscale): = 1 m × 1 m; very fine scale = 1 mm × 1 mm or smaller.

Levels of significance assigned to geoheritage sites have been defined for Western Australia (Brocx and Semeniuk 2007), but the principles are applicable worldwide. While various levels of significance have been used globally, nationally in Australia, and within Western Australia (viz., International, National, State-wide/Regional, and Local), there generally have not been definitions of these terms until recently (Brocx 2008). The criteria adopted here for levels of significance are those of Brocx and Semeniuk (2007); they are: 1. International: one of, or a few, or the best of a given feature globally; 2. National: though globally relatively common, one of, or a few, or the best of a given feature nationally; 3. State-wide/Regional: though globally relatively common, and occurring throughout a nation, one of, or a few, or the best of a given feature state-wide or regionally; 4. Local: occurring commonly through the world, as well as nationally to regionally, but especially important to local communities.

3 The Geoheritage Tool-Kit

There are a number of ways that sites of geoheritage significance have been identified. British and European literatures provide a history of how this has been achieved, with the final outcome being an inventory-based approach (Doyle et al. 1994; Wimbledon et al. 1995, 1996; Brocx 2008). For instance, since 1949, the assessment and subsequent selection of sites in the United Kingdom has been undertaken on the basis of a series of blocks which may be based on geological time, subject, or regional divisions, or combinations thereof. In 2001–2002, ProGEO contributed to a number of important geoconservation initiatives that included the incorporation of a policy statement relating to the importance of geology and physical landscapes in the Pan-European Biological and Landscape Diversity Strategy (ProGEO 2002).

The British and European approaches to develop an inventory of geological features of significance have been successful towards the goal of geoconservation in that numerous and varied aspects of geology have been identified and secured, but the approach has been thematic. This is because the geology of British and European terrains is reasonably well known and the countries are relatively small. In contrast, Western Australia presents a vast array of quite varied geological features, from Archaean metamorphic and igneous terranes and geological systems, to Proterozoic rock systems, and to Phanerozoic stratigraphy, lithology, palaeontology, mineralisation, etc., representing a wide diversity of processes and products. Thus the themes of British and European geoheritage cannot be applied elsewhere, therefore, we have developed another system to systematically identify and assess sites of geoheritage significance, and have termed it the "Geoheritage Tool-kit" (Brocx an Semeniuk 2009). It is called a "tool-kit" because it provides a series of different steps or procedures (or conceptual tools) that enable the geoheritage practitioner to systematically progress through the geology of a region, and identify, describe, categorise, and assess sites of geoheritage significance (Fig. 1). In terms of information and data collected, some parts of the "tool-kit" identify categories (nominal data as categorical data), e.g., identification of regions, or the allocation of sites to category of geoheritage, while some are ranked semi-quantitative, e.g., assessment of significance, and allocation to scale of reference.

The *Geoheritage Tool-kit* is defined as follows: a procedure, or series of five steps, that enables a geoheritage practitioner to identify areas, geosites and/or features of igneous, metamorphic, sedimentary, stratigraphic, structural, geochemical, mineralogic, palaeontologic, geomorphic, pedologic, hydrologic, and other aspects of geoheritage significance within a given natural region or terrane, allocate them to a conceptual category of geoheritage and to a scale of reference, and assess their level of significance.

The next, and sixth step in the geoheritage/geoconservation procedure which is outside the scope of this paper, is to determine what type and what level of geoconservation or management the area, geosite, or geological feature requires.

As not all aspects of the geology of the Earth would be present in one region, and not all aspects of the geology of a region may be of geoheritage significance, so the steps in the Geoheritage Tool-kit, after identifying geological regions, seek to compile an inventory of the geological essentials comprising that region, and assess their significance.

Step 1 of the Geoheritage Tool-kit identifies geological regions, providing a natural boundary to the area being investigated in terms of geological and geoheritage features, and an indication of the types of materials and styles of geological features that may be expected. It also ensures that comparisons in assessing levels of significance are undertaken wholly within similar geological regions. Identifying the geological essentials of a region requires recognising those geological features that characterise, or are peculiar to, or are restricted to a given geological region. Listing the geological essentials of a region does not necessarily translate to just listing isolated sites of geoheritage significance, but may also lead to the identification of and linkages to interrelated ensembles of features.

The Chalk of southern England and the Shark Bay area of Western Australia illustrate the concept of a region and that of geological essentials within a region. The Chalk, well exposed along the southern coast of England, is an essential feature of the geology of the region of the south-eastern and southern coast of England, and has geological characteristics of chalk cliffs, chert nodules, chalk litho types, chalk diagenesis, Cretaceous shelly fossils, fossil taphonomy, Cretaceous ichnofauna, Quaternary landforms, hanging valleys, and shoreline ribbons of flint-pebble conglomerate (Gallois 1965; Melville and Freshney 1982; Brocx and Semeniuk 2010). In Australia, Shark Bay, a World Heritage site not replicated elsewhere globally, is a distinct geological region. Some of its essential features include its large-scale stratigraphy, the deep-embayed limestone coastal morphology, seagrass banks, the coquina deposits, stromatolites, high-tidal crusts, high-tidal gypsum crystals, gypsum-filled birradas, modern ooid sand banks, Pleistocene oolite, and high cliffs cut into Pleistocene limestone (Logan 1970, 1974; Brocx and Semeniuk 2010). For the two examples cited above, the geological essentials tend to be unique and internationally significant and of geoheritage significance.

An inventory of the geological essentials of a given region can be compiled using a staged three-pronged approach to develop a database on the geology, and at the same time, potentially identifying sites of geoheritage significance. The three-pronged approach involves drawing on the experience of geologists as published in the literature, and/or seeking the views of geologists still practising in the field through questionnaires/interviews (providing information and personal insights about the geoheritage potential of an area), and after identifying gaps in information, seeking to systematically obtain by fieldwork further information based on regional geology (for instance, an undeformed fossil-rich or sedimentologically diverse region requires a different style of fieldwork to a metamorphosed structurally-complex terrane). For all three approaches, there will be some degree of overlap in information and outcomes. The staged three-pronged approach to obtain the essential geological information was the approach adopted in Western Australia as part of the Regional Forests Agreement where sites of geoheritage significance were determined within a framework in which the *geological essentials* of the region first were identified (Semeniuk 1998). The Regional Forests Agreement was an Australian National exercise to determine the significance of natural terrains in forested areas, and assessment of geoheritage values, was part of the evaluation process (Australian Government 2004).

The inventory of the geological essentials of a region forms the basis to identifying the sites of geoheritage significance. The next stage would be to locate good examples, regardless of scale, of these features, or of inter-related ensembles of features, and assess them according to the significance criteria outlined above.

After an assessment of the range, categories, inter-relationships, and level(s) of significance of the geological features, the final step is to determine what type and what level of geoconservation or management the area requires.

4 Case Studies of the Application of the Geoheritage Tool-Kit in Western Australia

Three case studies in Western Australia illustrate the use of the Geoheritage Tool-kit, wherein inter-related geological features at various scales are identified and assessed as a basis for designating geoparks; from north to south, they are: 1. King Sound and the tide-dominated delta of the Fitzroy River (Semeniuk and Brocx 2011); 2. the Leschenault Peninsula and its leeward estuarine lagoon (Brocx and Semeniuk 2011a); and 3. the Walpole-Nornalup Inlet estuary (Semeniuk et al. 2011). While each is a coastal area, the Geoheritage Tool-kit, however, can be applied to any geological site, or region, to determine its values for geoconservation and management.

Figures 2, 3 and 4 summarise the geoheritage features of each of the areas, showing the categories of geoheritage sites, a representative range of geological features at decreasing scale, and the assessment of significance of each of the geological essentials.

King Sound and the tide-dominated delta of the Fitzroy River present geological and geomorphic features of International to National geoheritage significance. Set in a tropical semiarid climate, the delta of the Fitzroy River has the largest tidal range of any tide-dominated delta globally. Within King Sound there are 12 geological features of geoheritage significance. Some of the key features include: 1) the Quaternary stratigraphy, with early-Holocene gulf-filling mud formed under mangrove cover, followed by middle- to late-Holocene deltaic sedimentation; and 2) the relationship between Pleistocene linear desert dunes and Holocene sediment that are globally unique and provide important stratigraphic and climate history models. King Sound illustrating the principles underpinning the erosion styles and mechanisms of various types of erosion (sheet, cliff and tidal creek erosion) combining to develop tidal landscapes and influence (mangrove) ecological responses (illustrating tidal landscape evolution determining mangrove response, i.e., an example of geodiversity determining biodiversity response), provides a unique global classroom for such principles and processes. The high-tidal muddy salt flats have hypersaline groundwater; responding to this, carbonate nodules of various mineralogy are precipitated. Locally, linear sand dunes discharge freshwater into the hypersaline flats. With erosion, there is widespread exposure of Holocene and Pleistocene stratigraphy,

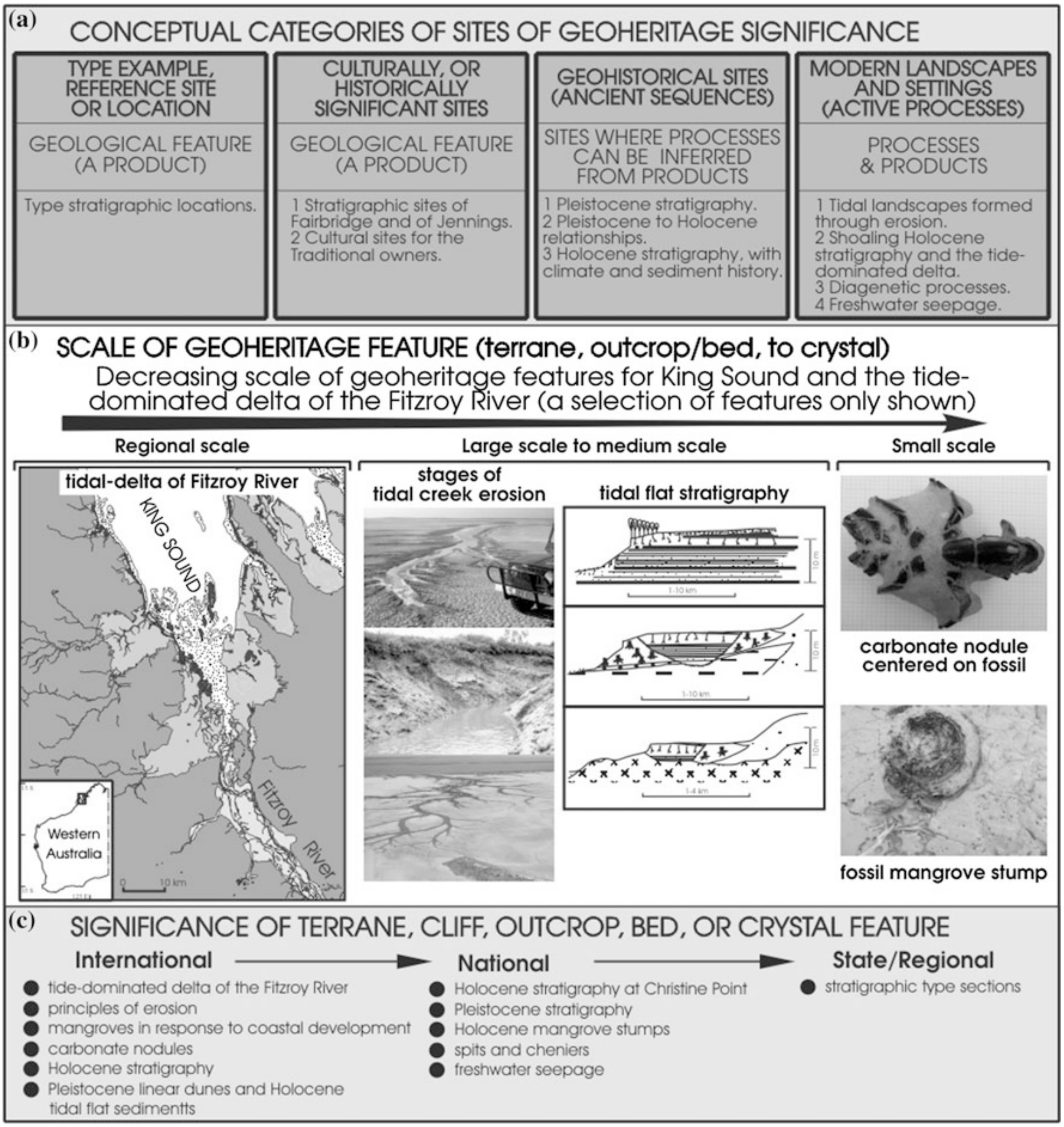

Fig. 2 Application of the Geoheritage tool-kit to king sound and the tide-dominated delta therein. The boxed areas in *Inset A* shows that all categories of geoheritage are applicable in this area (Semeniuk and Brocx 2011). The majority of features in the area are Internationally significant

and development of spits and cheniers in specific portions of the coast. The features comprising the "geoheritage essentials" of this area are shown in Table 1. Application of the Geoheritage Tool-kit to King Sound and the tide-dominated delta of the Fitzroy River is shown in Fig. 2.

The Leschenault Peninsula, a retrograding dune barrier in south-western Australia, and its leeward estuarine lagoon, with a variety of geological and geomorphological features from large to small scale, and varying in significance from International to State-wide, provides another example of the application of the Geoheritage Tool-kit. There are 24 geological features of geoheritage significance in this area. Some of the key features include: an active parabolic dune landscape, retreating on its seaward edge and encroaching into the estuary; an interface between dunes and estuary that is the most complex sedimentologically, hydrologically, and ecologically in Western Australia; a stratigraphy that records a complex Holocene sea-level history; barrier retreat that is recorded by parallel strips of submerged beach rock; a thin sheet of calcrete forming above the water table; and the distinctive and complex estuarine shore stratigraphy including calcitisation of sea rush roots under the high tidal flat. Categorisation of the 24 geological features and evaluation of their significance are shown in Table 2.

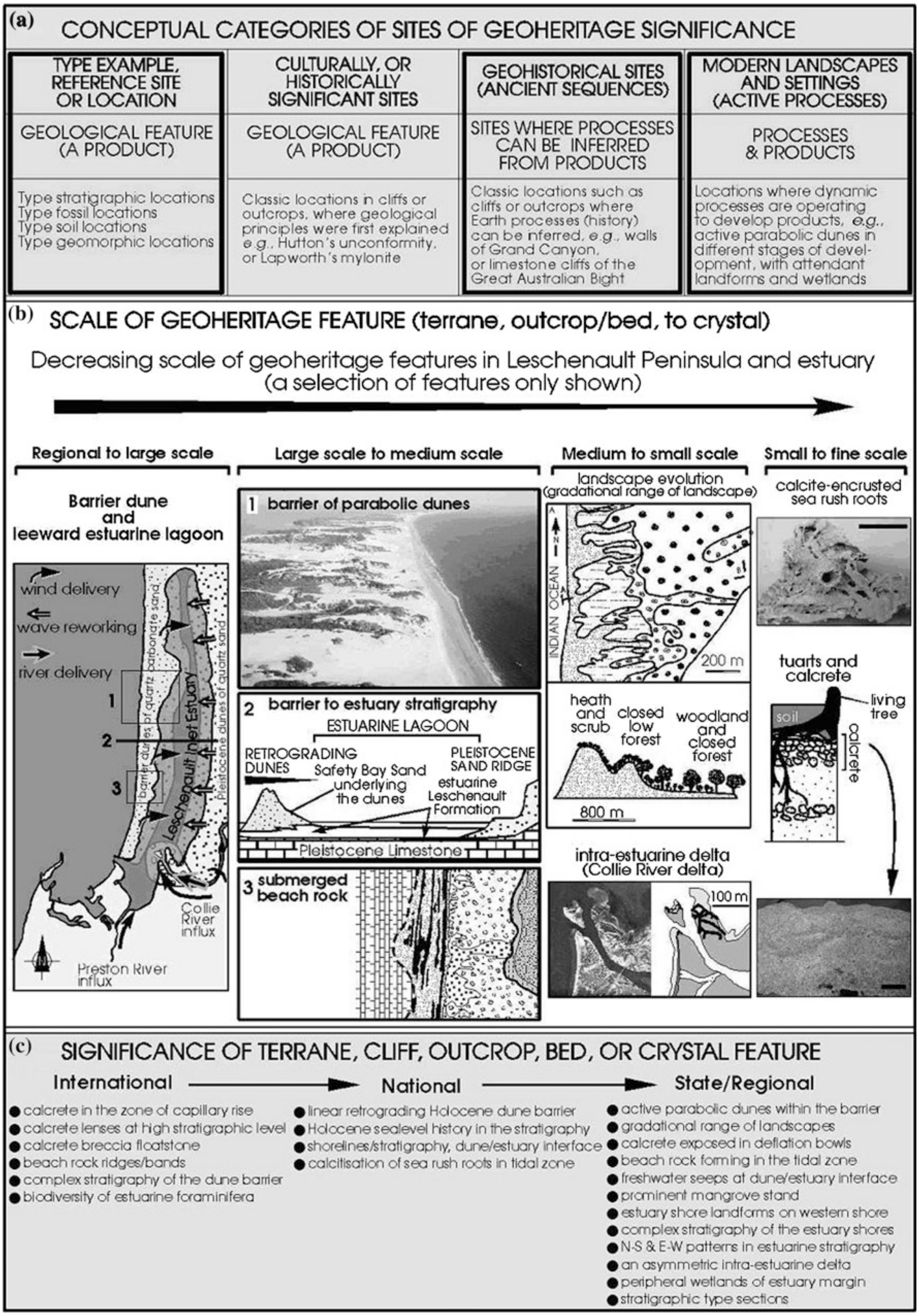

Fig. 3 Application of the geoheritage tool-kit to the Leschenault Peninsula and its leeward lagoon. The boxed areas in *Inset A* shows that three categories of geoheritage are applicable in this area (Brocx and Semeniuk 2011). The majority of features in the area are of State/Regional significance and many are of International and National significance

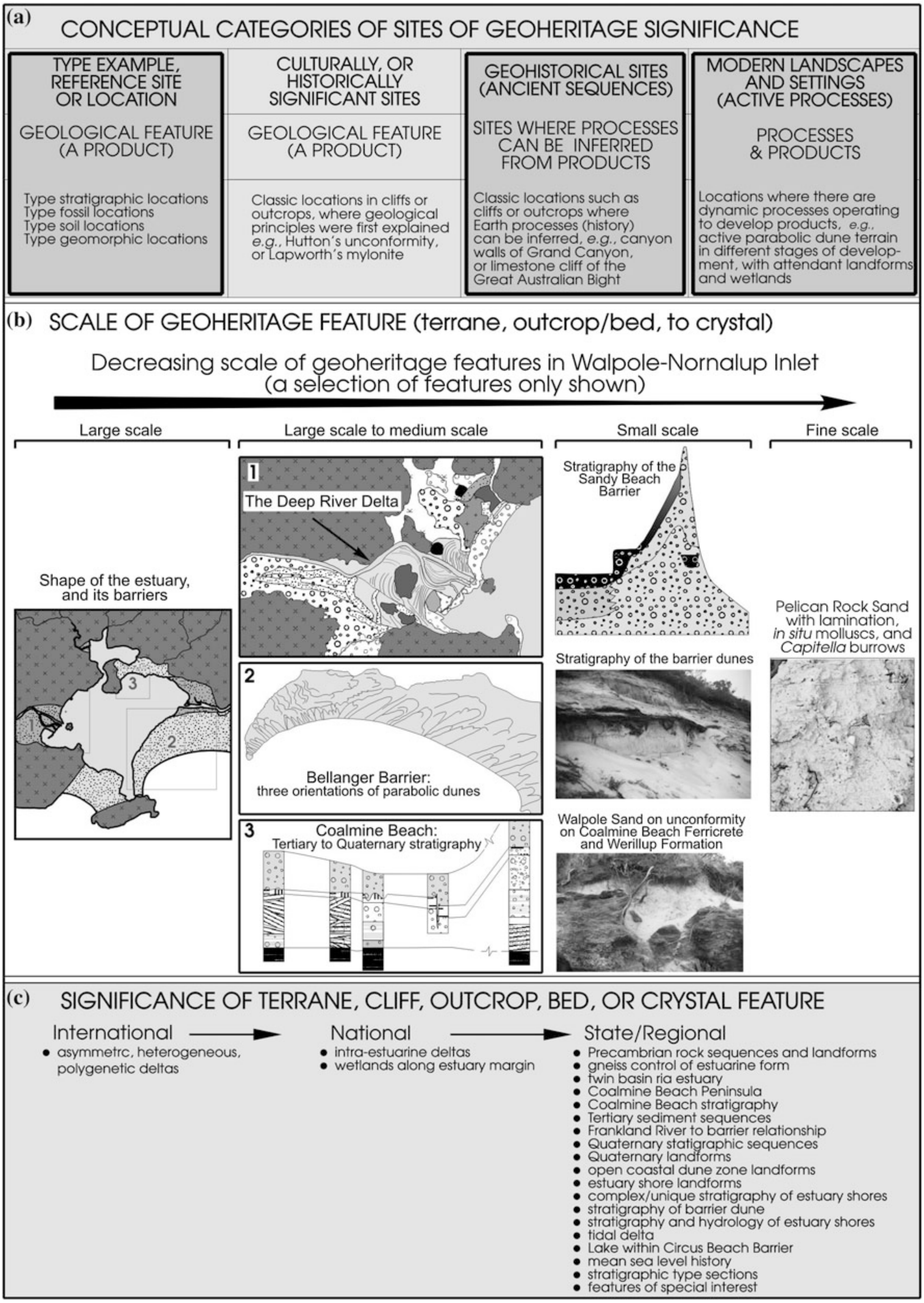

Fig. 4 Application of the geoheritage tool-kit to the Walpole-Nornalup Inlet estuary. The boxed areas in *Inset A* shows that three categories of geoheritage are applicable in this area. The majority of features in the area are of State/Regional significance, two are of National significance, and one is of International significance

Table 1 Features of geoheritage significance in King Sound and the tide-dominated delta of the Fitzroy River, and the rationale for the assessment

Geological feature	Type of site, and its scale (category of site from Fig. 1)	Significance	Rationale for assigning the level of significance
Tide-dominated delta of the Fitzroy River	Modern landscapes and setting (active processes); regional scale	International	Geomorphic, sedimentologic and stratigraphic description of a tide-dominated delta in a tropical semiarid climate; this is a tide-dominated delta globally with the largest tide
Principles and processes of tidal erosion	Modern landscapes and setting (active processes); fine scale to large scale	International	Tidal creek erosion and formation of tidal landscapes provides an international model of coastal development in a tropical, macrotidal environment, particularly in the transition of the small scale to the large scale which provides a powerful natural laboratory
Mangroves in response to coastal development	Modern landscapes and setting (active processes); medium scale to large scale	International	An example of geodiversity where landscape evolution determines mangrove response
Carbonate nodules	Modern landscapes and setting (active processes); small scale	International	First description of the variety of Holocene carbonate nodules under tropical tidal flats; sets a standard as a type location for Holocene carbonate nodules under tidal flats
Holocene stratigraphy	Geohistorical site; medium scale to large scale	International	One of the most stratigraphically complex tidal flat systems in the world and also unique because of its tropical and macrotidal setting; well exposed along Airport Creek
Pleistocene linear dunes and Holocene tidal flat sediment	Geohistorical site; medium scale	International	Important site for stratigraphic relationship of Quaternary tidal sediments and linear desert dunes, for models of coastal geomorphic adjustments with sea level rise, and climatic history
Holocene stratigraphy at Christine Point	Geohistorical site; medium scale to large scale	National	The most southern occurrence of the deposits of the "Big Swamp" phase of the early Holocene of sedimentation in northern Australia and an important indication of climate history and fossil mangrove biogeography
Pleistocene stratigraphy	Geohistorical site; medium scale to large scale	National	First and only description to date nationally of Pleistocene tidal flat stratigraphy; an important record of Pleistocene climate history, sedimentation, and diagenesis
Holocene mangrove stumps	Geohistorical site; small scale to medium scale	National	Outcrop of fossil mangrove stumps embedded in situ in grey clay, extending to below MSL
Spits and cheniers	Geohistorical site and modern landscapes and setting (active processes); medium scale to large scale	National	Response of linear dunes to coastal erosion and the effect of coastal process on the exposed northern tip of the Point Torment Peninsula; in Australia. this is the only sand-based north-facing peninsula in a large gulf, where wave cation, storms, and cyclones have consistently reworked the sand peninsula foundation to form a set of prograded parallel cheniers
Freshwater seepage	Modern landscapes and setting (active processes); medium scale	National	Example of coastal freshwater seepage from dune sand aquifer that has been onlapped by tidal flat sediments; this is the only one of two places in Australia where tidal flat sediments onlap linear dunes, the latter discharging freshwater into the saline subsurface Mathews et al. (2011), Semeniuk (1980, 1983, 2008)
Stratigraphic type sections	Reference sites; medium scale	State-wide/ regional	The area contains a number of stratigraphic type sections (stratigraphic type sections are significant because they are the reference section in the State or Nation for a stratigraphic unit)

Table 2 Features of geoheritage significance in Leschenault Peninsula and its leeward lagoon, and the rationale for the assessment

Geological feature	Type of site, and its scale (category of site from Fig. 1)	Significance	Rationale for assigning the level of significance
Calcrete in zone of capillary rise	Modern landscapes and setting (active processes); small to fine scale feature	International	First and only description to date globally of Holocene calcrete forming in the zone of capillary rise in relationship to plants
Calcrete at high/low stratigraphic levels	Geohistorical site; small to fine scale feature	International	First use of Holocene calcrete to reconstruct Holocene climate history
Calcrete breccia floatstone	Modern landscapes and setting (active processes); small to fine scale feature	International	First description of lenses of Holocene calcrete breccia floatstone in soils, developed as a consequence of tree heave by storms
Complex stratigraphy of barrier	Geohistorical site; medium scale feature	International	One of the most complex dune barriers stratigraphically in the world because of the local sea level history superimposed on dune barrier development
Stranded submerged beach rock forming bands/ridges	Modern landscapes and setting (active processes), and geohistorical site; medium to small scale feature	International	First and only description to date globally of stranded beach rock forming submerged shore-parallel bands/ridges with barrier retreat
Biodiversity of foraminifera forming rich (neo) palaeontological assemblage	Modern landscapes and setting; very fine scale feature	International	Richest biodiversity of Holocene estuarine foraminifera (neo)palaeontologically in the world
Linear retrograding barrier	Modern landscapes and setting (active processes); large to medium scale feature	National	The only linear retrograding Holocene dune barrier barring a barrier-parallel linear lagoon in Western Australia, and only one of a few nationally; in terms of sediments, ecology, and hydrology of Leschenault Inlet and the dune barrier are incomparable to any other system in Australia
Holocene sea level history recorded in the stratigraphy	Geohistorical site; small scale feature	National	Unique Holocene sea level history recorded in the stratigraphy and reflecting local tectonism
Complex shorelines/stratigraphy along the dune/estuary interface	Modern landscapes and setting (active processes); large to medium scale feature	National	Since the dune barrier is only one of a few occurring Nationally, the complex of shorelines and stratigraphy at the dune/estuary interface in this climate setting are Nationally uncommon
Calcite encrustation of sea rush roots	Modern landscapes and setting (active processes); fine to very fine scale feature	National	Encrustation (and permineralisation) by calcite. Mg-calcite, and dolomite of sea rush roots in the tidal zone at the dune/estuary interface in this climate setting is Nationally uncommon
Well-documented Holocene palynological record as a model for estuaries	Modern landscapes and setting (active processes); very fine scale feature	National	The documented patterns of pollen distribution in the Holocene estuarine sequence provides model to interpret estuarine palynology
Active parabolic dunes in barrier	Modern landscapes and setting (active processes); medium scale feature	State-wide/ Regional	The geometry and style of active parabolic dune development within the barrier is unique in the State; compared with other parabolic dunes that change shape and orientation with respect to progressively changing wind directions and wind speed latitudinally (see Semeniuk et al. 1989)
Gradational range of landscapes: mobile dune to undulating plain	Modern landscapes and setting (active processes); large to medium scale feature	State-wide/ Regional	In this climate, with the vegetation contributing organic matter to soils, and the natural geomorphic gradation from mobile dunes to fixed dunes to plains, this transition is unique in Western Australia
Calcrete exposed in deflation bowls of parabolic dunes	Modern landscapes and setting (active processes); small scale feature	State-wide/ Regional	Normally, dune bowl excavation proceeds to the water table and forms dune slacks, but calcrete arrests this excavation; calcrete exposed in bowls is a unique landscape feature in this calcrete-and-parabolic dune setting in Western Australia

(continued)

Table 2 (continued)

Geological feature	Type of site, and its scale (category of site from Fig. 1)	Significance	Rationale for assigning the level of significance
Beach rock in the tidal zone	Modern landscapes and setting (active processes); medium scale to small scale feature	State-wide/ Regional	This type of beach rock is restricted to this part of Western Australia, and reflects the hydrochemical interchange between the freshwater reservoir in the barrier and the marine shore
Freshwater seepage at dune/ estuary interface	Modern landscapes and setting (active processes); small scale feature	State-wide/ Regional	Freshwater seepage along the dune/estuary interface produces complex ecological responses, and results in the second most complex estuarine shore in Western Australia
Mangrove stand and its lithotope at dune/estuary interface	Modern landscapes and setting (active processes); small scale feature	State-wide/ Regional	A prominent mangrove stand is formed at the dune/estuary interface where there is freshwater seepage from the tip of a parabolic dune encroaching into estuary; geologically it represents the effects of hydrological processes and also the formation of a mangrove sedimentary lithotope
Estuary western shore landforms graded south to north	Modern landscapes and setting; large scale feature	State-wide/ Regional	The south to north transition of shore landforms along the western estuary shore reflects the unique nature of the northerly oriented linear lagoon, and its relation to wind and wave dynamics, and is a feature of State significance
North-south and east-west patterns in sediments and stratigraphy of estuary	Modern landscapes and setting; large to medium scale feature	State-wide/ Regional	The linear lagoon bordered by distinct landforms and provenances has resulted north-south and east-west patterns in sediments and stratigraphy of the estuary that are unique in Western Australia
An intra-estuarine delta	Modern landscapes and setting (active processes); medium scale feature	State-wide/ Regional	At the southern end of a north-south oriented estuarine lagoon, the Collie Delta is asymmetric reflecting fluvial construction and a storm influenced northern part that faces the long fetch of the lagoon—a feature unique in Western Australia
Peripheral wetlands along western and eastern shore of estuary;	Modern landscapes and setting (active processes); large scale feature	State-wide/ Regional	The stratigraphy, landforms, and freshwater seepage along the estuarine shores from the dune barrier and the Eaton Ridge has resulted in distinct peripheral wetlands along western and eastern shores of the estuary that are found nowhere else in Western Australia
Stratigraphic type sections;	Reference sites; small scale feature	State-wide/ Regional	The area contains a number of stratigraphic type sections

The Walpole-Nornalup Inlet estuary in southern Western Australia provides a third example of the application of the Geoheritage Tool-kit. There are 22 features that characterise its "geoheritage essentials". The key features include the Tertiary stratigraphy, Tertiary sediment sequences, the river to barrier landform relationship, the Quaternary stratigraphic sequences, the complex and unique stratigraphy and hydrology of the estuary shores and the complex stratigraphy of the barrier dunes, the intra-estuarine deltas, and the wetlands along the estuary margin. There also are features of special interest such as in situ polychaete tubes in stranded shallow marine sand, and peat capping deltaic and shoreline stratigraphic sequences (see Table 3) that are unique to the region (Semeniuk et al. 2011). Categorisation of the 22 geological features and evaluation of their significance are shown in Table 3.

5 Discussion and Conclusions

This paper provides a description of the "state of the art" of geoheritage and geoconservation in Western Australia, and a case study of the application of the techniques of identification of features and assessment of features, i.e., the Geoheritage Tool-kit. The main objectives of earlier works (Brocx and Semeniuk 2007; Brocx 2008) were to define geoheritage within a broader context of geology, conceptualise the various categories of what constitutes geoheritage, deal with the issue of scale, and more rigorously define levels of significance. These outcomes are essential foundations to design classification and assessment systems to identify sites of geoheritage significance in Western Australia and elsewhere.

In all the case-study areas outlined above, the individual geoheritage components should be viewed *not* in isolation, as type locations, or "best example of a given feature", but as the integrated system of geological products and processes-and-products. Hence, together they form a "geopark". And given the important and unique nature of the areas, they qualify to be a national or state geopark (with features of international significance), thus integrating the various scales of geology and geomorphology into a single geoconservation unit, i.e., a geopark since they contain numerous "geological heritage sites of special scientific importance".

In the case studies along the coast of Western Australia, the Geoheritage Tool-kit has been applied to identify sites of geoheritage significance, deriving from an inventory-based approach that rigorously assigns a level of significance to geological features, regardless of their scale and within a framework of the broadest possible definition of geoscience. While three areas were used as case studies because they contain a wide variety of geological and geomorphological features, ranging from large scale to fine and very fine scale, and varying in significance from International to State-wide, in fact the Geoheritage Tool-kit can be applied to any geological site, or region, of any age to determine geoheritage values for conservation and management.

The Geoheritage Tool-kit provides a method to give context to a range of inter-related smaller features such as those found, for instance, in King Sound (the crustacean fossils, or the mangrove stumps), and in the Leschenault Peninsula and leeward estuarine lagoon (the permineralised sea rush, or the calcrete) because there is a need not only for geoconservation of large-scale features but also of significant smaller-scale features in these systems. Geoconservation involves conservation of individual smaller-scale features as well as integrated geoconservation that preserves the geological setting and the surrounding geological suite as an inter-related ensemble. Thus, in terms of geoconservation, addressing the various features of geoheritage value in King Sound and in the Leschenault Peninsula area and its associated estuarine lagoon, that individually rank from Regionally significant to Nationally to Internationally significant, is best achieved by viewing the system holistically as an integrated (geo)park of interactive processes, geology, and geomorphology. Therefore, given this background and the important and unique nature of these areas, it should be viewed as a national or state geopark within which there are also features of International significance, thus integrating the many smaller-scale features of geology and geomorphology into a single geoconservation unit. King Sound and its tide-dominated delta and the Leschenault Peninsula and its associated estuarine lagoon qualify in containing numerous "geological heritage sites of special scientific importance". The various components of the geoheritage of these areas should be viewed *not* in isolation, as type locations, or "best example of a given feature", but as the integrated system of geological products and as integrated systems of processes-and-products. Landscape evolution is an example of these principles. For the three different areas, calcrete, intra-estuarine deltas and their asymmetric nature, the peripheral wetlands, the dunes of the barrier system, and the distinctive and complex estuarine shore stratigraphy, amongst the many geological features inherent to a given specific area, also provide examples. The fine- and very fine-scale features, such as calcitisation of sea rush roots by encrustation and permineralisation under the high tidal flat along the shores of Leschenault Peninsula, that is dependent on the groundwater seepage from the adjoining dunes, provide specific example of these principles in that without the calcite-bearing dune sand, the parabolic dune encroaching into the estuary, and the nature of the dune sand to estuary hydrology, there would not be the calcitisation of the roots of the sea rush. The International significance of the calcitised roots of the sea rush needs to be addressed by not only preserving the calcitised sea rush roots but also the dune

Table 3 Features of geoheritage significance in Walpole-Nornalup Inlet estuary, and the rationale for the assessment (Semeniuk et al. 2011)

Geological feature	Type of site, and its scale (category of site from Fig. 1)	Significance	Rationale for assigning the level of significance
Precambrian rock sequences and landforms	Geohistorical, and modern landscapes and setting (active processes); large scale feature	Regional	Variety of metamorphic and igneous rock types distinct to this part of the Albany-Fraser Orogen of southern Western Australia Wilde and Walker (1984), Semeniuk et al. (2011)
Gneissic control of estuarine form (morphology of the estuary)	Modern landscapes and setting (active processes); large scale feature	State-wide	The geological strike of the mega lithologic units control the shape of the estuary, the only such example in coastal Western Australia
Coalmine Beach stratigraphy	Geohistorical site; medium scale feature	Regional	The Coalmine Beach Peninsula exposes excellent exposes of Tertiary stratigraphic sequences, which are unusual in southern Western Australia see Wilde and Walker (1984), Geological Survey of WA (1990), Semeniuk et al. (2011) the exposure is well preserved because the rocks are protected from Southern Ocean swell by the estuarine setting
Tertiary sediment sequences	Geohistorical site; small scale feature	Regional to State-wide	The stratigraphy along the Coalmine Beach Peninsula is well exposed, and provides good examples of the Tertiary sequences, unlike in other coastal locations that are more exposed to Southern Ocean swell
Frankland River to barrier landform relationships	Modern landscapes and setting (active processes); large scale feature	State-wide	The Bellanger Barrier has in a major way deflected the major river of the Frankland, producing river to barrier landform relationships that is unique in Western Australia
Quaternary stratigraphic sequences	Geohistorical site; medium scale to small scale feature	Regional to State-wide	The barrier, estuary and hinterland has produced a complex array of stratigraphic sequences that are well developed and unique to estuary/barrier situations in Western Australia
Quaternary landforms	Modern landscapes and setting (active processes); medium scale feature	Regional	The barrier, estuary and hinterland in this Southern Ocean setting have produced a complex array of Quaternary landforms that are well developed and unique to estuary/barrier situations in Western Australia
Open coastal dune zone landforms	Modern landscapes and setting (active processes); large scale feature	State-wide	The barrier, barring the estuary, and facing the Southern Ocean setting has produced open coastal dune landforms that are well developed and unique to estuary/barrier situations in Western Australia
Estuary shore landforms	Modern landscapes and setting (active processes); large scale feature	State-wide	The estuary, because of its shape and its relationship to the barrier has produced estuary shore landforms that are well developed and unique to estuaries in Western Australia
Complex and unique stratigraphy of the estuary shores	Geohistorical sites; reference sites; medium scale to small scale feature	State-wide	Because of its geological setting and Quaternary history, the area contains a distinctive stratigraphy along the estuarine shores unique to estuaries in Western Australia
Complex stratigraphy of the barrier dunes	Geohistorical sites; reference sites; large scale feature	Regional	Because of its coastal and oceanographic setting, the barrier is complex in its history, and contains a number of distinctive stratigraphic type sections unique to estuaries in Western Australia
Stratigraphy and hydrology of the estuary shores	Geohistorical sites and modern landscapes and setting (active processes); reference sites; large to small scale feature	State-wide	The stratigraphy and hydrology of the estuarine shore are closely inter-related, and the varied and complex stratigraphy of the estuarine shores has resulted in a varied and complex coastal hydrology unique to estuarine Western Australia

(continued)

Table 3 (continued)

Geological feature	Type of site, and its scale (category of site from Fig. 1)	Significance	Rationale for assigning the level of significance
Intra-estuarine deltas	Geohistorical sites and modern landscapes and setting (active processes); reference sites; large scale feature	National	Three rivers drain into the estuary creating intra-estuarine deltas that are distinct to Western Australia; the deltas in different hydrodynamic settings; the deltas are variably exposed to wave actions, or tides or are dominated by fluvial processes and this has resulted in variable delta forms that are dependent on the estuarine setting of a given delta
Asymmetric, heterogeneous, and polygenetic nature of the intra-estuarine deltas	Geohistorical sites and modern landscapes and setting (active processes); reference sites; large scale feature	International	Each of the three deltas in their different hydrodynamic settings have produced distinctively different forms in terms of their asymmetry, heterogeneity, and polygenetic nature; the deltas reflect their asymmetric formation depending on whether their components are wave-dominated, tide-dominated, or fluvially dominated
The tidal delta	Modern landscapes and setting (active processes); reference sites; medium scale feature	State-wide	The entrance inlet of the estuary has produced a large and distinctive flood-tidal delta unique in form and size in Western Australia
Wetlands along the estuary margin	Modern landscapes and setting (active processes); reference sites; Medium scale feature	National	In this most humid part of Western Australia, this estuarine system is bordered by wetlands (mainly paluslopes) that are variable in form and dynamics dependent on estuarine setting; in the humid climate, the wetlands are underlain by peat; the ensemble of wetlands bordering this estuary and their peat deposits are unique to this part of Western Australia
Lake within the Circus Beach Barrier	Modern landscapes and setting (active processes); reference sites; medium scale feature	State-wide	The dune lake in the Circus Beach Barrier, formed by wind deflation and water table rise, is a unique landform to coastal Western Australia
Mean sea level history	Geohistorical site; small scale feature	State-wide	There is a unique local Holocene sea level history recorded in the shallow marine deposits in this area that is different to the rest of coastal Western Australia
stratigraphic type sections	geohistorical site; small scale feature	State-wide	The area contains a number of stratigraphic type sections
Features of special interest	Geohistorical site; small scale feature	Regional, to State-wide significance	There are number of significant geological features of special interest in this estuarine area; these are: peat capping the deltaic sequences in all three deltas; peat formed in response to subartesian upwelling the occurrence of in situ polychaete and mollusc assemblages stranded 1 m above their current environment; saprolitic gneiss in the cliffs; and local palaeosols (see Semeniuk et al. (2011) for more details)

terrain, dune stratigraphy, and dune-to-estuary hydrology, all of which sustain the calcitisation process.

Successful application of the Geoheritage Tool-kit at these three locations along coastal Western Australia, as well as inland Western Australia in the Precambrian terranes of the Pilbara region suggest that it could have world-wide applicability. As noted earlier, it has already been applied to the Anti-Atlas of Morocco (Errami et al. 2011) to identify sites of geoheritage significance as a basis to assigning such sites to geosites, Sites of Special Scientific Interest, and geoparks.

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Microscale Geology and Micropalaeontology of the Becher Point Cuspate Foreland, Australia: Significant Geoheritage Values at the Smallest Scale—A Model for Identifying Similar Features in Geosites and Geoparks

La microgéologie et la micropaléontologie du promontoire du Point Becher Cuspate en Australie : un géopatrimoine significatif à petite échelle

الجيولوجيا وعلم المتحجرات الدقيقين لنتوء خليجي لنقطة رأس "بشير كسبات" بأستراليا :جيوتراث هام على نطاق صغيرر

V. Semeniuk, C.A. Semeniuk, F. Trend, and M. Brocx

Abstract

Geological features of heritage significance can range from the largest scale (montane and drainage basin) to microscale. The smallest scale of geoheritage include globally significant features such as the Archaean zircon crystals from Jack Hills, Australia (the oldest crystals on Earth), snowball garnets from Sweden (illustrating kinematic rotation under metamorphism and shear), and microbiota in Precambrian rocks. It also can include regionally significant microscale features that provide insights into the more local history of the Earth, hydrology, hydrochemistry, climate, and vegetation. The Becher Point Cuspate Foreland, a Holocene accretionary sandy deposit in south-western Australia, is recognised as an internationally significant area for its geomorphology, stratigraphy, wetlands, and record of climate history. Of specific importance are the wetlands that occur in the inter-ridge swales of the beach ridges. The wetlands record in their sediments a history of climate, vegetation, hydrology, and hydrochemistry, staged over a 4,500 year interval in the oldest wetlands, and over an interval of <1,000 years in the youngest wetlands. Whilst Becher Point has been recognised as Internationally significant as a Ramsar site for its macroscopic features, its importance as a site of geoheritage significance continues to the smallest scale in that its microscale geology (calcrete, carbonate grain dissolution) and micropalaeontology (pollen, calcified charophyte fructifications, and other microbiota) provide important (metaphoric) "letters of the alphabet" that can be used to read the history of the sedimentary and climate record of the region.

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This area provides an excellent example of how the pollen and charophyte fructifications and other microscale geological features function as important markers and signatures within the Holocene history of the beach ridge plain and wetlands and, as such, represent significant geoheritage values at the smallest scale.

Résumé

Les caractéristiques géopatrimoniales peuvent varier de grande échelle à petite échelle (les cristaux des zircons archéens de Jack Hills et les microorganismes des formations précambriennes), donnant un aperçu sur l'histoire géologique locale de la Terre. Le promontoire du Point Becher Cuspate, un dépôt de sable d'accrétion Holocène dans le sud-ouest de l'Australie, est reconnu comme une zone d'importance internationale par sa géomorphologie, sa stratigraphie et ses zones humides. Ces dernières enregistrent dans leurs sédiments l'histoire du climat, de la végétation, de l'hydrologie et de l'hydrochimie sur un intervalle de 4500 ans dans les zones humides les plus anciennes, et sur un intervalle <1000 ans dans les zones humides les plus jeunes. Alors que le Point Becher est reconnu comme site Ramsar pour ses caractéristiques macroscopiques, son importance géopatrimoniale s'étend à petite échelle, (calcrête, dissolution des carbonates pollen, charophyte calcifiée et autres microorganismes) et peut être utilisée pour reconstituer l'histoire sédimentaire et le climat de la région. Cette région est un bon exemple qui montre l'utilisation des pollens, des charophytes et d'autres caractéristiques géologiques à petite échelle comme marqueurs importants dans la reconstitution de l'histoire des crêtes de plage et des zones humides et représentent ainsi une valeur géopatrimoniale significative.

مجردة

يمكن لخصائص الجيوتراث أن تتدرج من مقياس كبير إلى صغير (بلورات الزركون الأركي "لجاك هيلز" والكائنات الدقيقة لتشكيلات ما قبل العصر الكمبري)، مانحة بذلك لمحة عامة عن التاريخ الجيولوجي المحلي للأرض. تعتبر نتوءات خليج نقطة رأس "بشير كسبات"، وهي مجموعة من الرمال المتراكمة من رواسب عصر الهولوسين جنوب غرب أستراليا، منطقة ذات أهمية عالمية بجيومورفولجياتها، وطبقاتها وأراضيها الرطبة. هذه الأخيرة تسجل برواسبها تاريخ المناخ، والغطاء النباتي، والهيدرولوجيا وكميائيتها التي تكونت على فترة زمنية تقدر ب 4500 مليون سنة (م س) بالأراضي الرطبة القديمة، وأقل من 1000 م س بالمناطق الرطبة الحديثة. في حين تم الاعتراف بنقطة رأس "بشير كسبات" كموقع رامسار نظرا لخصائصه العيانية، وأهميته كموقع للجيوتراث يمتد على نطاق صغير (كلس الكالكريت، تحلل حبوب الكربونات، حبوب اللقاح، نبات الكاروفيت المكلس وكائنات دقيقة أخرى) ويمكن استخدامها لإعادة بناء تاريخ الترسب والمناخ بالمنطقة. تعتبر هذه المنطقة مثالا جيدا يُظْهِرُ كيفية استخدام حبوب اللقاح، ونبات الكاروفيت وغيرها من الخصائص الجيولوجية الدقيقة كعلامات مهمة في إعادة بناء تاريخ كثبان الشواطئ والأراضي الرطبة وهي بذلك تمثل قيمة جيوتراثية كبيرة.

Keywords

Geoheritage • Microscale • Becher wetlands • Australia • Palynology • Charophytes • Sponges • Calcrete

Mots-clés

Géopatrimoine • Petite échelle • Zones humides de becher • Australie • Pollen • Charophytes • Calcrète

الكلمات الرئيسية

جيوتراث • نطاق صغير • أراضي رطبة "بشير" • استراليا • حبوب اللقاح • نبات الكاروفيت • كلس الكالكريت

1 Introduction

Geoheritage is wide-ranging in scope, encompassing globally, nationally, state-wide to locally significant geological sites that offer information on or insights into the formation and evolution of the Earth, into the history of Science, or sites which can be used for research, teaching, or reference. Geoheritage also is wide-ranging in scale, transcending terranes and major drainage basins to cliffs and bedding to finer scale features such as crystals and microfossils (Brocx 2008; Brocx and Semeniuk 2007). While many geological reconstructions of Earth history commonly involve information at large frames as in structural geology and metamorphic petrology, such research often begins at the finer scale. As such, finer scale features become important components of the alphabet in reading the history of the Earth yet, generally, the smallest scale of geological features in a given area are not afforded the same status of significance as the larger scale features. However, we contend that, from the point of view of geoconservation, if principles of superposition, unconformities, or the history embodied in lithology, structures, lithological relationships, xenoliths, dropped pebbles, folding, faults, relative ages, amongst many other geological features are of geoheritage importance, then microscopic versions of such patterns, for instance, encased within crystals, or reflected in the microfossils, are also important (e.g., constructing evolutionary history, reconstructing magmatic history, or progressive and retrograde metamorphism). That is, various finer scale geological features such as Precambrian microfossils, or Phanerozoic microfossils that provide information about environments, climates, or evolution, and crystals (in their composition, arrangement, origin, marginal resorptions, zoning, inclusions) tell a story of the Earth, and qualify to be assessed as geologically significant (Brocx and Semeniuk 2010).

Thus, while the history of the Earth can be read at the larger scale in the "language" of geology and in rock fabric and texture, there is also a story that can be read in the smaller scale features. Where significant, these finer scale features need to be specifically addressed in geoconservation, or presented as part of the suite of features in any proposed, or designated, Geopark. We argue that geoconservation should also focus on microscale features useful in deciphering the history of the Earth, or that are associated with the history of Earth Science. That is, what has been assessed at the macroscale as geologically significant features in unravelling the history of the Earth (viz., stratigraphy, unconformities, structures, and igneous, metamorphic and sedimentary lithology), and afforded geoheritage significance, should also be directed to the microscale if similar principles and patterns are present therein. It is also often at this scale that the story of the Earth unfolds. The Precambrian microfossils of the Bitter Springs Formation (Australia), the snowball garnets of Moine (Scotland), Västerbotten (Sweden), and Tasmania (Australia), or zircons from Jack Hills (Australia) all tell important stories about the Earth manifest at the finer geological scales. In other words, the metaphoric "alphabet" of the story of the Earth should be afforded geoheritage significance, as well as the "paragraphs" and "pages" of Earth history constructed from that alphabet. To continue with the alphabet metaphor, the different stories of the Earth with different alphabet and language in different locations globally should be afforded equal geological significance and geoconservation.

Within south-western Australia, an accretionary cuspate foreland, designated as a system of International importance, contains a suite of wetlands, the Becher Point Wetlands that record the history of the middle to late Holocene in their stratigraphy and biota (Semeniuk 2007). The wetlands manifest various types of biota in their fossil record, including pollen, algal spores, diatoms, charophytes, sponges, ostracods, gastropods, bivalves, and insect exoskeletons. This paper explores the microscale geology and micropalaeontology of the Becher Point Cuspate Foreland and its wetlands, concentrating on the small scale geology and the fossil record of pollen and calcified charophyte fructifications (gyrogonites), to emphasise their significant geoheritage values.

In the context of the First International Conference on African and Arabian Geoparks held in November 2011 in El Jadida, Morocco, we provide geoheritage practitioners with a model of how the microscale geological aspects of an established Ramsar site can be emphasised and amplified to bring geoheritage and geoconservation into the consciousness of land managers and decision makers. We focus on the microscale geology and micropalaeontology of the Becher Point area and their regional, National and International geoheritage importance. This approach and outcome have applicability to the northern African situations since therein there are many Nature Reserves, National Parks, Ramsar sites, and World Heritage sites (Baldwin et al. 1988; Magin 2001; Taleb and Fennane 2011; Ramsar Database 2012) that, although they have been inscribed on biological and other bases, have potential to be described from a microscale geological point of view such that their geodiversity and geoheritage values are given more emphasis. Moreover, these Nature Reserves, National Parks, Ramsar sites, and World Heritage sites in northern Africa, though Research, Science and Education, have potential to be used to emphasise that geodiversity underpins biodiversity in already existing Reserves.

This paper presents information on the microscale geological features of the Becher Point area in terms of its calcrete and carbonate grain dissolution, and the micropalaeontological features of a wetland basin (designated as wetland 161 by Semeniuk (2007)) in terms of its pollen and charophyte record, and its sponge spicule record and taphonomy.

2 The Becher Point Cuspate Foreland and Its Wetlands—Background Information

The Becher Point Cuspate Foreland in coastal south-western Australia is a Holocene triangular accretionary sandy deposit formed leeward of nearshore limestone reefs (Fig. 1). It is underlain by a shoaling sequence comprising carbonate and quartz sand formed in seagrass bank to beach to beachridge environments (Semeniuk et al. 1988). Its history began circa 6,000 years ago. With accretion of prograded shore-parallel beach ridges it formed a coastal plain up to 10 km wide. The beach ridges alternating with inter-ridge swales record cycles of ocean storminess and climate changes reflected in their type, height, and spacing (Semeniuk 1995, 2007). The beachridge plain is underlain by a shallow, unconfined freshwater body and, with progradation, the water table inland of the strandline has progressively naturally risen such that, in time, inter-ridge swales have become waterlogged then inundated and, set in a carbonate sand stratigraphy, the wetlands are filling with carbonate mud. The wetlands have been designated as Wetlands of International Importance, and listed for protection under the Ramsar Convention for their outstanding scientific values as unusual coastal wetlands (Semeniuk 2007). In contrast to other wetlands globally, which usually are large and filled with water or habitat for rare flora and internationally migratory birds or rare fauna, the Becher Point wetlands are small basins, colonised by coastal herbs, sedges and shrubs, and support a local population of marsupials and reptiles but with no rare taxa.

The progradation of the beach ridges means that landward (eastward) parts of the plain are circa 6,000 years old, and seaward (westward) parts are <1,000 years old, or modern. In its progradational history, the plain has experienced progressive climate change from mid- to-late-Holocene, forced by Earth-axis Precession, with relative aridity changing to humidity, and has recorded cyclic changes in ocean climate on 250-year cycles and 45-year cycles (Semeniuk 1995). The former had effects on sand composition, calcrete development, diagenesis, and soil development, graded across the plain, while both are reflected in large beach ridges *versus* small beach ridges (Semeniuk 1995). With a rising water

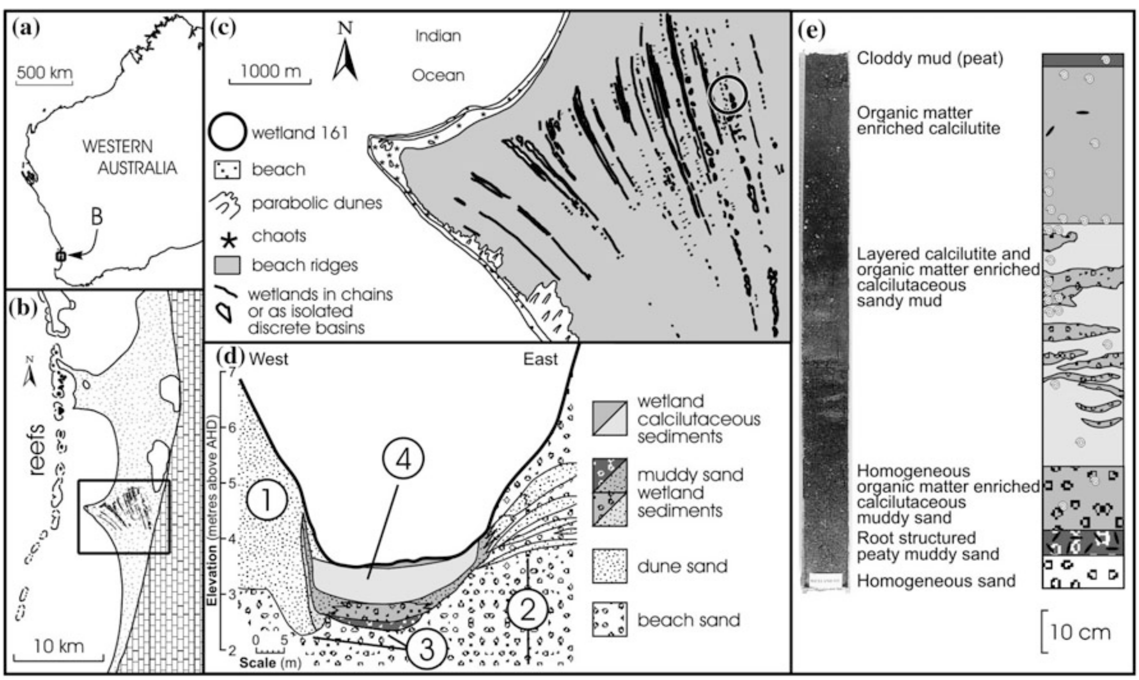

Fig. 1 The Becher Point Cuspate Foreland South-Western Australia and details of its wetlands (modified from Semeniuk 2007). **a** Location in South-Western Australia. **b** Location of the wetlands (*black*) in parallel array across the beach-ridge plain (*stippled*) and the location of *inset* C in the southern part of the twin cuspate foreland. **c** Location of the wetlands (*black*) in parallel array across the beach-ridge plain, and location of wetland 161 towards the eastern (*oldest*) part of the plain. **d** Stratigraphy of basin 161 showing (*1*) dune sand overlying (*2*) beach sand, (*3*) evidence of dissolution and subsidence, and (*4*) sequence of sedimentary fill of muddy sand, calcilutite, and organic matter enriched calcilutite; the elevation of the contact between beach sand and dune sand has subsided under the wetland, and the more pronounced dissolution on the basal western side of the wetland where groundwater plumes have further dissolved the carbonate of the underlying sediments. **e** Core from basin 161 showing more detailed three-layered stratigraphy with a *lowermost* muddy sand, a middle section of interlayered calcilutite and organic matter enriched calcilutite, and an *uppermost* section of organic matter enriched calcilutite

table, wetlands have been inserted onto the prograded plain, commencing some 4,500 years ago and continuing to the present. As such, the wetlands are of different ages, and record wetland sedimentary filling of different durations, set in the mid- to late-Holocene climate change, and the shorter term 250-year climate cycles, and interacting with an evolving hydrology and hydrochemistry, all features reflective of geological processes. The wetlands have been recognised as of International importance with respect to their inter-beach ridge setting, their carbonate-rich basal sand (which influences hydrochemical patterns), the archival information in the Holocene sediments, carbonate muds as basin fills, the hydrological responses to a varied stratigraphy, and the resulting diversity of vegetation. Overall, the Becher Point Cuspate Foreland and its wetlands represent a well-documented global example of coastal plain with a range of multi-disciplinary and inter-related geological aspects from Holocene beachridge plain development under progressively changing climate and cyclically changing climate, with attendant effects on geomorphology, coastal processes, hydrology, and sand composition, to wetland sediments and their evolution, to soil development, intra-wetland hydrochemistry, hydrological dynamics, diagenesis, and biodiversity. A selection of geological features of the Becher Point Cuspate Foreland and its wetlands, graded in scale, is shown in Fig. 2.

3 The Becher Point Cuspate Foreland and Its Wetlands—Microscale Features

Whilst the area of Becher Point has been recognised as of International significance and afforded protection as a Ramsar site (mostly for its macroscopic features such as beach rides, wetland basins, and vegetation), its importance as a site of geoheritage significance continues to the smallest scale. Its microscale geology (calcrete, and carbonate grain dissolution) and micropaleontology (pollen, calcified charophyte fructifications, and other microbiota) provide important (metaphoric) “letters of the alphabet” that can be used to read the history of the Becher Point wetland sedimentary and climate record. In a globally significant area such as Becher Point, the pollen and charophyte fructifications function as important geological markers within the Holocene history of the wetlands of the Cuspate Foreland.

Approximately 200 wetlands occur as basins in the interdune depressions of the Holocene beach ridge plain in the Rockingham area. Eighteen of these were studied in detail in terms of their landscape setting, stratigraphy, hydrology, hydrochemistry, and vegetation, (Semeniuk 2007). Sixteen of this group of eighteen were studied further by Semeniuk et al. (2006a) for their pollen record in the surface sediment, and five of this group were studied further by Semeniuk et al. (2006b) for their pollen record in the stratigraphic profile.

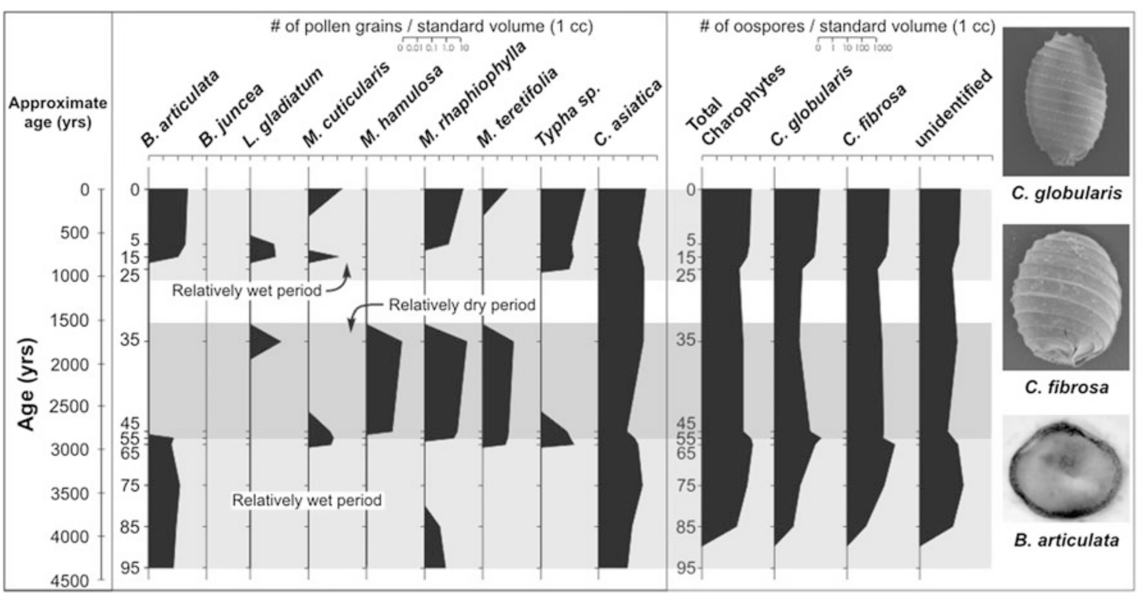

Fig. 2 Biostratigraphy of pollen and charophytes in wetland 161, and environmental interpretation. The time intervals along the *vertical* axis have been arithmetically spaced; as such, the sampling locations at 10 cm intervals between 0 and 95 cm have been adjusted to correspond to this regular temporal spacing (after Semeniuk 2007). *Insets* of *Chara globularis*, *Chara fibrosa*, and *Baumea articulata* shown

Radiometric dating of the sediment cores was used to provide an age structure for five wetland basins (Semeniuk 2007). Pollen from the main species in the wetlands was studied biostratigraphically. The species studied were: the herb *Centella asiatica* (L.) Urb., the sedges *Baumea articulata* (R. Br.) S. T. Blake, *Typha* (L.) sp., the paperbarks *Melaleuca teretifolia* Endl., *M. rhaphiophylla* Schauer, *M. viminea* Lindley assemblage, *M. cuticularis* Labill., the wetland peripheral grasstree *Xanthorrhoea preissii* Endl., the wetland peripheral sedge *Isolepis nodosa* (Rottb.) R. Br. and the sea couch *Sporobolus virginicus* (L.) Kunth.

Comparison of pollen diversity and abundance against wetland age structure indicated that, except for the grasstree *Xanthorrhoea preissii* and local sedge *Isolepis nodosa*, most wetland species were present over the interval of 4,500 years BP to the present in the middle-to late-Holocene. However, there were a number of other important patterns in the down profile abundance of wetland pollen taxa and their inter-basin variation at isochronous levels such as: a lack of continuity down profile for some species; fluctuations in numbers of pollen taxa that were continuous; lack of correlation in timing of the peak pollen numbers between separate basins; variable total composition at the same isochron level from wetland to wetland; variable total composition of wetland pollen at different ages within the same wetland; the association of pollen species with sediment types; increases and decreases of wetland margin pollen taxa in the down profile composition; and the recent appearance of *I. nodosa* and *X. preissii* within the last circa 1,500 years (Semeniuk 2007). The patterns of pollen derived from wetland vegetation in individual wetlands suggest that the ancestral distribution and abundance of plant assemblages in the Becher wetlands was a function of intra-basin environmental changes caused by wetland evolution. In contrast, pollen derived from upland vegetation exhibited continuity down profile, suggesting that delivery of upland pollen has been largely consistent, though variable in abundance and composition from basin to basin, and being exogenic, it has not reflected (hydrochemical, edaphic or hydroperiod) environmental conditions within the wetlands.

3.1 Wetland Basin 161 Stratigraphy

Wetlands on the Becher Point Cuspate Foreland generally are small geomorphic and hydrologic features, generally <100 m in size. As noted above, the wetlands of the beach ridge plain are graded in age from oldest to the east and youngest to the west. The oldest wetland is basin 161 (Fig. 1c, d) that provides a wealth of geological features and information at the small scale and microscale. It records the thickest accumulation of sediments, the diagenetic effects of past and ongoing dissolution along its basal interface with underlying and adjoining dune and beach sands, basin subsidence linked to dissolution, and a complex history of expansion and contraction of the basin (Semeniuk 2007) (Fig. 1).

3.2 Pollen and Charophyte Record

Wetland basin 161, in its 4,500-year old stratigraphy, records a variable pollen and charophyte biostratigraphy (Semeniuk et al. 2006a, b).

In the pollen record, thirteen key and recurring species of wetland plants were selected for the study (Semeniuk 2007), viz., *Baumea articulata*, *Baumea juncea*, *Typha orientalis*, *Typha domingensis*, *Isolepis nodosa*, *Juncus kraussii*, *Lepidospermum gladiatum*, *Centella asiatica*, *Sporobolus virginicus*, *Melaleuca rhaphiophylla*, *M. teretifolia*, *M. viminea*, *M. cuticularis*, and *Xanthorrhoea preissii* (a wetland margin inhabitant). There is fluctuation in numbers of pollen of these species down the stratigraphic column (Fig. 2), which Semeniuk (2007) interpreted as recording climate change due to Earth-axis Precession (resulting in a general increase in regional humidity) and recording the intra-basinal hydrochemical adjustments as one vegetation assemblage succeeded another (essentially, freshwater assemblages alternated with brackish water assemblages reflecting both ecologically driven changes and cyclic climate changes).

Biostratigraphically, charophyte gyrogonites in wetland 161 largely mirror the palynological record. The gyrogonites of the two charophyte species are present down the stratigraphic column, viz. *Chara globularis* and *Chara fibrosa*. These species inhabit freshwater to brackish water (1–9 % TDS) so that, in this context, they are not sensitive indicators of wetland salinity in the Becher Point system. Their contribution to environmental reconstructions is that they represent periods of marked carbonate production, which can be related to climate, such as early summer drying of wetlands (and hence a trend towards aridity), and increased water temperature, when end-of-winter surface waters are warmed by insolation.

The pollen and charophyte record has important use geologically in the reconstruction of climate history, hydrology, and hydrochemistry for individual wetlands and for the region. The combined pollen and charophyte record suggest the following patterns (Semeniuk 2007):

1. the pollen record shows fluctuating numbers of the various species in response to intra-basin hydrological and hydrochemical patterns;
2. the pollen record shows that the grasstree *X. preissii* and the sedge *I. nodosa*, appear in the past 1,500 years, related to the general increase in climate humidity;
3. the species indicators of wet conditions *Typha* and *Baumea* broadly show relatively wet conditions in lower

and upper parts of the stratigraphic record, and relatively drier conditions in the central part of the stratigraphic record, corresponding to intervals of 4,500–3,000 years BP, 3,000–1,500 years BP, and 1,500 years BP to present, respectively;
4. the record for the two species of *Chara* show that charophytes have been in the wetlands from their inception;
5. the record for the two species of *Chara* is broadly similar to each other, with peaks in numbers near the base and near the top of the stratigraphic record, with relatively lower numbers in the central part of the stratigraphic record;
6. *Chara* is most abundant at the times that *Baumea* is most abundant, and near the top of the stratigraphic column, when *Typha* is most abundant, signalling that they reflect wet times in the basin.

These patterns partly reflect regional climate changes, and also intra-basin hydrologic and hydrochemical evolution (Semeniuk 2007).

3.3 Sponge Record and Taphonomy

Spicules of the sponge *Heterorotula muliformis* (Weltner) occur in the stratigraphic profile of wetland basin 161. In contact with carbonate mud and pellicular water that is alkaline (Semeniuk 2007), the biogenic silica of the sponge spicules is in various stages of dissolution. Over a length of ~100 cm of core extracted from wetland basin 161, which represents the thickness of carbonate mud filling the wetland basin and representing ~4,500 years of stratigraphic record, sponges spicules occur in the upper third of the stratigraphic profile, they are corroded (etched) over the central parts of the profile, and absent in the lower part of the profile. Dissolution clearly has taken place, and the older parts of the profile, with etched and corroded spicules show that the longer the spicules have been in contact with alkaline groundwaters the more they are corroded, until eventually they have been dissolved away.

The history of the sponge spicules shows that while sponge remains were originally present in the wetland, with burial and diagenesis they have become etched and selectively dissolved away, essentially removing a biotic component from the biostratigraphic record.

3.4 Carbonate Grain Dissolution

The base and margins of wetland basins in the Point Becher area may be weakly acidic. There are hydrochemical plumes discharging from the floors (Semeniuk 2007). These hydrochemical plumes coming into contact with the underlying beach sand (composed of carbonate grains of aragonite, Mg-calcite, and calcite) are agents for selective dissolution of carbonate grains. With dissolution, there can be loss of carbonate content from 40 % carbonate to 25 % carbonate, or even 40 % carbonate to 5 % carbonate and, as such, with loss of carbonate volume, the floor of the wetland subsides into the dissolving underlying sheet of beach sand (Semeniuk 2007). Asymmetry in the hydrochemical plumes, due to groundwater flow from east to west results in asymmetric dissolution and asymmetrical wetland basin subsidence (Semeniuk 2007).

The principle that is evident here is that the microscale geological processes have a major effect on determining the evolution (deepening) of the wetlands basins.

3.5 Calcrete and Reconstruction of Climate History

Calcrete and tuart trees are closely linked. Tuarts are a phreatophytic eucalypt tree (*Eucalyptus gomphocephala* DC) that, with extraction of water at the water table, causes precipitation of fine-grained calcite around their root mats. This fine grained calcite is termed 'calcrete' (Semeniuk and Meagher 1981). Depending on climate setting and proximity of the water table, tuarts develop different types of calcrete, viz., in wetter climates where there are abundant tuarts, the calcrete is a sheet parallel to the water table; in drier climates with less abundant tuarts forming isolated copses, the calcrete is a series of lenses parallel to the water table; in terrains located high above a water table, calcrete is in the form of rhizocretions (Semeniuk 1986). The use of calcrete as a climate indicator allows reconstruction of climate history and shows the climate in southwestern Australia became humid only some 2,000 years ago (Semeniuk 1986).

In the Becher Point area, calcrete occurs in isolated lenses along the water table. Its occurrence as a small-scale geological feature is an indicator of the former occurrence of tuarts, and the fact that the calcrete is thin scattered in occurrence and lensoid is an indicator of past climate.

4 The Becher Point Area as a Geosite and a Geopark—and Its Microscale Features

Often geoparks are selected for their splendour or scenic grandeur, which attracts tourism, with macroscale geological features that can be described as to their age or physical characteristics. In this context, the Becher Point area provides a plethora of inter-related geological features that can be used in a geopark. These features include the landscape evolved from coastal processes, the development of the wetlands in response to progradation and water table rise, the evolution of wetlands geomorphologically and stratigraphically, the imprint of climate, hydrochemistry and hydrology on the wetland sediments stratigraphically and biostratigraphically, the diagenesis of the wetland and the diagenetic relation between the wetland and adjoining parent sediments. Many of these features are globally unique, and hence globally significant. At the macro-scale, as an ensemble, these features form an integrated system of geological process-and-products that also can function as individual components of interest in a geopark. The geological features can also be used as an outdoor classroom for Science and Education endeavours for students and scientists, as well as for geotours.

However, we have ventured further with the geological importance of the Becher Point Cuspate Forelands and its wetlands using only macroscale features. In this paper, we have endeavoured to show that the importance and diversity of the Earth heritage elements of Becher Point extends to the microscale, with small scale stratigraphy, sponges, and pollen, charophyte gyrogonites as indicators of environmental and climate change, past hydrological processes, and the evolution of vegetation complexes, in an evolving landscape. Thus we highlight the importance of that which lies hidden from the naked eye as an important component for both Science and Education in Earth heritage.

We proffer that the same approach can be applied elsewhere, i.e., areas that are inscribed for biological reasons, such as Ramsar sites or National Parks, in Northern Africa and elsewhere, can be documented in terms of both their macroscale as well as microscale geological features to add to the inventory of why an area is significant in terms of its geoheritage.

In this paper, we have endeavoured to provide a model for Science and Education using an existing Ramsar site and proposed Geopark. We contend that, in addition to the features of large geological scale, land managers and conservation park managers by documenting the microscale can significantly add to the importance of an area. This will particularly be the case if the objects at the microscale are Nationally or Internationally significant. However, even if the microscale geological features are only of local or Regional significance, they can add to the Educational information provided in the interpretative panels, information centres, geotrails, and scientific information in brochures as they provide the scientist, interested naturalists, and the public with knowledge integrated from the large scale to the small scale, the latter not evident to the unaided eye, to highlight the range of scales at which geology operates, that the scales at which it operates is integrated (inter-related), and that features of large scale and small scale both are complementary and useful in the reconstruction of Earth processes and history. Of course, different areas around the World will have different components of important small scale features. For instance, a geopark at Jack Hills in Australia clearly would emphasise the Archaean sand-sized zircons and their regional geology and context, a Geopark sited on the Bitter Springs Formation in Australia would emphasise the Precambrian microfossils also in their larger scale geological context, and a Geopark site at Moine in Scotland would emphasise the significance of the snowball garnets (Brocx and Semeniuk 2007).

We recommend that Educational information provided in interpretative panels, information centres, geotrails, and scientific information in brochures in Geoparks and Geotrails add the small scale geological features for that site as it complements the larger-scale features of a Geopark and raise the consciousness of scientist, interested naturalists, and the public to features to the importance of the world evident at the microscale.

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