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ORIGINAL ARTICLE

Geosites inventory of the northwestern Tabular Middle Atlas of Morocco

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Abstract Across the northwestern Tabular Middle Atlas of Morocco there are many examples of landscapes, rocks and fossils that provide key evidence of a particular moment or period in Earth history. Such Earth heritage sites are important for educating the general public in environmental matters. They also serve as tools for demonstrating sustainable development and for illustrating methods of site conservation as well as remembering that rocks, minerals, fossils, soils, landforms form an integral part of the natural world. The significance of certain sites for aesthetic or tourism reasons is obvious. There are numerous geosites, which could contribute to effective exploitation of geotourism, often in conjunction with ecotourism. The strategy employed to such sites involves close consultation with all communities in the vicinity of the respective geosite and is not only aimed at tourism and education, but also at sustainable improvement of the infrastructure of the people of this area. Geological heritage sites, properly managed, can generate employment and new economic activities, especially in regions in need of new or additional sources of income.

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Introduction

Our geological heritage is the "Memory of the Earth, record inscribed both in its depths and on the surface, in the rocks and in the landscapes…" (Declaration of the Rights of the Memory of the Earth, Digne, France, 1993). That heritage is the Earth's archives, as it were, in their countless forms. Geosites are a means of protecting these archives.

A geosite is a site or an "area", a few square meters to several square kilometers in size, with geological and scientific significance, whose geological characteristics (mineral, structural, geomorphological, physiographic) meet one or several criteria for classifying it as outstanding (valuable, rare, vulnerable, endangered).

When a special zone includes more than one particularly rare or beautiful and geologically significant feature, it is referred to as a "geopark" (UNESCO 2000). The features must be representative of the region's geological history as well as of the events and processes that shaped it (Prichonnet 2001).

There are many criteria for classifying sites as outstanding. Only a single criterion may be required for a geological site to be declared worthy of being considered part of our heritage.

A combination of criteria is usually considered (Aguirre 2000).

Here is list of selection criteria for geosites (Aguirre 2000):

- scientific value,
- geotourism appeal,

- educational value,
- historic value,
- cultural, spiritual, and social value,
- international significance,
- link to biodiversity,
- sanctuary for rare or endangered species,
- aesthetic value,
- accessibility.

The goals of the geosite strategy must always be kept in mind (MENV 2002).

- Improving knowledge about the evolution of environments, life, and therefore our own evolution;
- being accessible to everyone, so that no one can take possession of geosites for their own use;
- contributing to local, national, or all of humanity's economic development;
- having aesthetic value.

The goal of the geological heritage protection strategy now being prepared is to protect and conserve geological diversity or "geodiversity" (MENV 2002). However, this geological diversity is endangered by natural catastrophes and by man's interventions in his environment.

Protecting geodiversity is important because it makes it possible to improve our understanding of all the features of the geological cycle. These features are the subject of many scientific studies, which lead to perfecting knowledge about them. It also amounts to a legacy for future generations so that they, too, can benefit from the geological as well as the biological components of ecosystems (MENV 2002).

Geotourism is rapidly being recognized as an exciting new direction for tourism surrounding geological attractions and destinations. Geotourism is concerned with sustaining or enhancing a destination's geographic character.

Across the northwestern Tabular Middle Atlas of Morocco there are many examples of landscapes, rocks and fossils that provide key evidence of a particular moment or period in Earth history.

Geology of the middle atlas

The Middle Atlas is a intracontinental mountain range belonging atlasic system (Choubert and Marcais 1952). It is constituted by faults zone bends whose principal ones are directed NE–SW. This mountain range is divided into two units (Fig. 1): the northwestern Tabular Middle Atlas (=Causse Moyen Atlasique) and the southeastern Folded Middle Atlas (=Moyen Atlas Plissé) separated by the Northern Middle Atlas fault (Termier 1936; Colo 1961). Structural shapes indicate two main structures: a large syncline depocenters and straight anticline ridges with local gabbroic intrusions (Fedan 1988).

The Moroccan Atlas system consists of intracontinental mountain ranges. Its evolution was controlled by the opening of the Atlantic and by the Alpine orogeny. Fault systems along strike of these mountain ranges played a major role in this process. The Northern Middle Atlas Fault (=Accident Nord Moyen Atlasique): ANMA—sinistral strike-slip fault—divides the Middle Atlas into two units: the northwestern Tabular Middle Atlas (=Causse Moyen Atlasique) and the southeastern Folded Middle Atlas (=Moyen Atlas Plissi). The mainly NE/SW trending fault zone bends into N/S direction along its central third. Related to the NE/SW main trend are transversal NW/SE-fault trends. The NE/SW strike-slip faults as well as their NW/SE trending transversal counterparts both represent hercynian age basement faults affecting sedimentary cover by multiple reactivation since the Triassic. During the

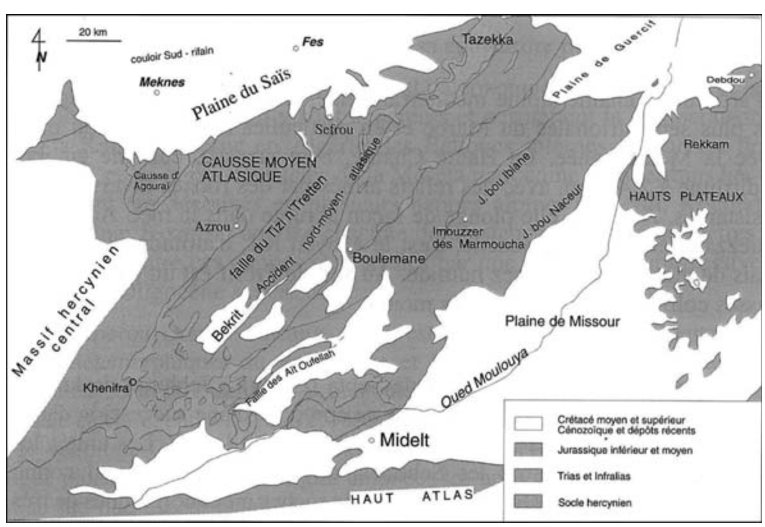

Fig. 1 Shematic Geological map of the middle Atlas

Mesozoic and Tertiary the following important events can be distinguished (Rhrib 1997):

- Synsedimentary active normal faults have been proofed along the ANMA, especially for block rotations along normal faults during the Upper Triassic, for intraformational unconformities during the Carixian and Domerian, and for the generation of a Toarcian halfgraben) (Rhrib 1997).
- Slump structures closely related to NE/SW striking faults provide evidence for block tilting during the Dogger. The compressive Cretaceous–Eocene period started in pre-Barremian times and reached one maximum during the Senonian. The development of facies and thickness distribution resembles intense synsedimentary tectonic activities. Basal angular unconformities and conglomerates of variable thickness indicate continuing tectonic activities) (Rhrib 1997).
- Tertiary thrusts develop during renewed compression, which are contemporaneous with decollement of the sedimentary cover of the Qued Zra-Block) (Rhrib 1997).
- The paroxysmal character of the compressional tectonics during Upper Miocene and Quaternary can be confirmed through the development of mega tension fractures in the Middle Atlas by blocking the NE–SW sinistral strike–slip movements. These fractures reach the deeper lithosphere and cause rising of magma) (Rhrib 1997).

The evolution of longitudinal NW/SE trending Miocene basins was related to extensional fault systems, that controlled the development of halfgrabens, thus locking strike–slip motions along the ANMA) (Rhrib 1997). Such motions are also indicated by the occurrence of asymmetric *Z*-folds with vertical axes in Upper Eocene rocks from the Ain Nokra syncline as well as amygdal-structures from Jbel Hayane. Furthermore, the amount of lateral transport (7 km) along the ANMA can be estimated due to the discovery of a tectonic friction-breccia 20 km south of Taza consisting of Toarcian carbonate and basalt components supported by a matrix of red Triassic pelites. Besides, the *Z*-folds permit the calculation of the main deviatoric paleostress τ_1 directly at the ANMA) (Rhrib 1997).

Lakes

In the Middle Atlas Mountains, one can count more than 40 dayats (lakes) corresponding to tectono-karstic collapses with fluvio-lacustrine deposits. The existence of these plio-quaternary basins in the tabular, allows us to analyze the tectonic episodes responsible of their genesis and their evolution. This study focuses on the structural evolution to contribute to the comprehension of their genesis and their evolution, and to establish a chronology of the tectonic phases dating from the study of syrisedimentary structures and kinematics analysis of microtectonic sites (Angelier and Goguel 1979; Carey 1979).

Synthetic lithostratigraphic columns of the plio-quaternary fluvio-lacustrine beds were established dating from the detailed logs that we realized in the deposits of the lakes Aoua and Afourgagh; who shows the best outcrops of the lacustrine basins of the Middle Atlas. Two different groups of deposits are recognized: the marginal facies and the central facies.

A morphostructure of lakes Aoua, Afourgagh, Ifrah, and Aguelmam Sidi Ali shows us that the morphology of these basins is related to fault intersections, whose major directions are N 135′, N 080′, N 030′ and N 170′. The creation and the multiple reactivations of these faults are attribute to Upper Miocene-Quaternary. The effects of these faults are amplified by the karstification of liasic carbonates.

The analysis of the brittle deformation in these basins deposits and in the Jurassic substratum allows us to characterize four principal tectonic episodes responsible for the genesis and evolution of these fluvio-lacustrine basins. The first episode is an Upper Miocene NE–SW extension. The second is a Mid-Upper Pliocene NNW–SSE extension. The two last Quaternary episodes correspond to stress fields with $\sigma 3$ directed N 120′ in the Lower-Mid Quaternary, and with $\sigma 3$ directed N 080′ in the Mid-Upper Quaternary.

Aguelmam Afourgagh (Dayet Afougha/Afourgah)

The lake (latitude: 33°37′N; Longitude 04°53′W; Area 5 ha; Cond 97 1.6 mS), mainly made of Triasic silts and Liasic dolomites (about 63% of the surface), is located in a karstic environment (Fig. 2). Karst and the local tectonics induced the formation of closed depressions where groundwater crops out (Chillasse et al. 1999).

Fig. 2 Photo of Aguelmam Afourgagh

The lake Afourgagh (6 ha), located in the Middle-Atlas Mountains (Morocco), showed a strong decrease of its water level during the last 20 years (6 m between 1987 and 1996) (Flower et al. 1989), inducing consequences on the local population life. This recent decrease of the water level allows to observe and study the most recent (Holocene) lake deposits.

The lacustrine records consists of interbedded pluri-decimetric white layers of charophytes tufas containing, sometimes, a lot of well preserved encrustated stems and gyrogonites that show the strong authigenic production), pluri-centimetric dark layers (with samples containing a lot of organic components) and silty–clayey detrital layers. The tufas are mainly made of calcite, high magnesium calcite and aragonite that can account for up to 81% of the bulk. Aragonite shows that the water was probably rich in sulfate and magnesium.

The sediments present variable amounts of gyrogonites and oogonium of characeae, ostracods and molluscs. The study of these organisms gives us a lot of clues about the recent evolution of the lake: water level fluctuations, water chemistry, hydrology, climate.

The study of the geometry of the deposits coupled to the study of the different facies make possible to reconstruct the lake evolution during the Holocene and to discern the natural and anthropic factors responsible of the recent hydrological variations.

During the 1970s and early 1980s, this was the most important of the Middle Atlas lakes for breeding and wintering waterbirds (Thévenot 2000), and was still a clear-water lake in good condition (with a conductivity of 0.75 mS) in 1984 (Flower et al. 1989), yet by 1987 all the reedbeds had been removed by cutting and grazing, many waterbird species had disappeared and numbers of wintering waterbirds had crashed (Franchimont et al. 1994). It is now greatly reduced in area, highly turbid, totally devoid of submerged vegetation and with very few waterbirds (only 31 cattle egrets and 4 other birds on 9.10.97). Half of the shoreline is now surrounded by arable land. In 1997 this lake had an exceedingly low water level, and only c.30% of the basin was flooded. Exotic fish include *Esox lucius* and black bass *Micropterus salmoides* (Chergui et al. 1999). Marbled teal were formerly present at this site (with 150 in September 1969, Thévenot 2000) but have not been recorded since 1981 (Green 1993). Crested coot used to breed there, and up to 300 ruddy shelduck (in November 1978) was recorded in winter (Thévenot 2000).

Dayet Aoua

The Dayet 'Awa' (latitude 33°39′20″N; Longitude 05°02′ W; Area 50 ha; Cond 99 0.42 mS) is located in a karstic environment (Malaki 2006) (Fig. 4). Karst and the local tectonics induced the formation of closed depressions where groundwater crops out (Chillasse et al. 1999). The Dayet 'Awa (140 ha), located in the Middle-Atlas mountains (Fig. 3) (Morocco), This remains a relatively well-conserved and diverse lake of great conservation importance. The vegetation community remains rich, although there is no fringe of *Phragmites* and *Scirpus lacustris* along the southwest shore as described by Morgan, probably due to overgrazing and reed cutting (Franchimont et al. 1994). However, these and other emergent plants are found at the eastern end. Pumping of subterranean water from the underlying aquifer leads to low water levels in years of dry rainfall (Dakki and El Hamzaoui 1997). "Pedalo" boats are no longer in use, although local tourism (picnickers from Fes and Meknes) has intensified (Franchimont et al. 1994). The development of intensive chicken farms in the catchment may lead to significant pollution. This lake is enormously important for crested coot, and 1,200 marbled teal were recorded in April 1999. Morgan underestimated the area of this lake, which is 140 ha (El Agbani 1997). Exotic fish include *Esox lucius* and *Tinca tinca* (Chergui et al. 1999; Fig 4).

The latest news from September 2001 is that this lake was completely dry. It is unclear whether or not this is a "natural" event due to reduced precipitation, or to what extent increased water extraction for agriculture may be responsible. It is also unclear whether the lake will reflood again in the near future or not.

Dayet Ifrah

This lake (Fig. 5) (latitude 33°33′45″N; Longitude 04°55′ W; Area 100 ha; Cond 99 0.96 mS) has been highly degraded since Morgan's time. Rapid sedimentation from the surrounding steep slopes now denuded of trees is the probable cause of a reduction in the lake area and high turbidity. As a result, submerged vegetation has been

Fig. 3 Photo of Dayet Aaoua

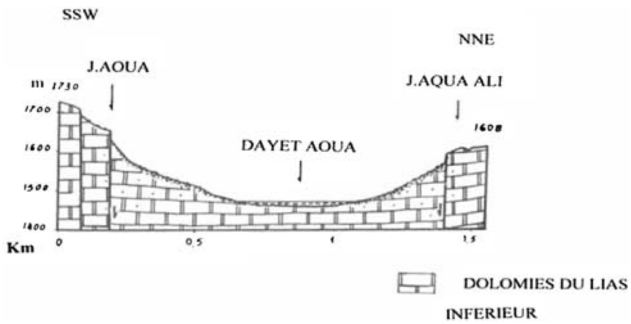

Fig. 4 A Synthetic geological cut of the graben of "Dayet Aoua"

eliminated except for tiny patches of *Ranunculus.* Numbers of wintering waterbirds have decreased steadily since 1983 (Franchimont et al. 1994). This site has lost its former importance for marbled teal, of which 300 were counted in 1973 (Green 1993). Exotic fish include *Esox lucius*, *Rutilus rutilus*, *Phoxinus phoxinus* and *Perca fluviatilis* (Chergui et al. 1999).

Aguelmame Sidi Ali

This lake (latitude 33°04′34″N; Longitude 05°00′13″W; Area 150 ha; Cond 99 1.1–1.6 mS) was considered by Morgan (1982) as "fresh", we recorded conductivities of 1.1–1.6 mS, equivalent to oligosaline. Water levels are now reduced (Fig. 6) and the marsh to the south–west of the lake described by Dorst (1951) no longer exists. Numbers of wintering waterbirds have decreased markedly since 1983, and poaching of the protected *Tadorna ferruginea* and other waterfowl is a major problem (Pouteau 1993; Franchimont et al. 1994).

Grazing pressure in spring and summer by flocks of sheep and goats brought by nomads is intense, and emergent vegetation is almost eliminated. The nesting of *Podiceps cristatus* as described in 1965 occurred up to at least 1985 (Thévenot 2000) but is now impossible owing to lack of vegetation. The native grayling-trout *Salmo pallaryi* became extinct after the introduction of the carp *Cyprinus carpio* in 1934 (Chergui et al. 1999). Other exotic fish include *Esox lucius*, and *Stizostedion lucioperca* (Chergui et al. 1999).

Volcanoes

The basaltic plateau of Azrou is characterised by its unique volcanic landscape (Malaki 2006), as well as botanical and faunal diversity. This Quaternary-Age basaltic volcanic complex is also one of the most diverse in North Africa, including Aa and, Cinder Cones, composite or stratovolcano, caldera, crater lake and plateau basalt.

Bou Tegrrouine

Bou Teguerrouine (Fig. 7) Forms as a result of alternating eruptions of pyroclastic material and lava flows (Fig. 8). Results in alternating layers of lava and volcanic ash. The lava flows protect underlying ash deposits from erosion. Due to their relatively high viscosity, the flows cannot flow

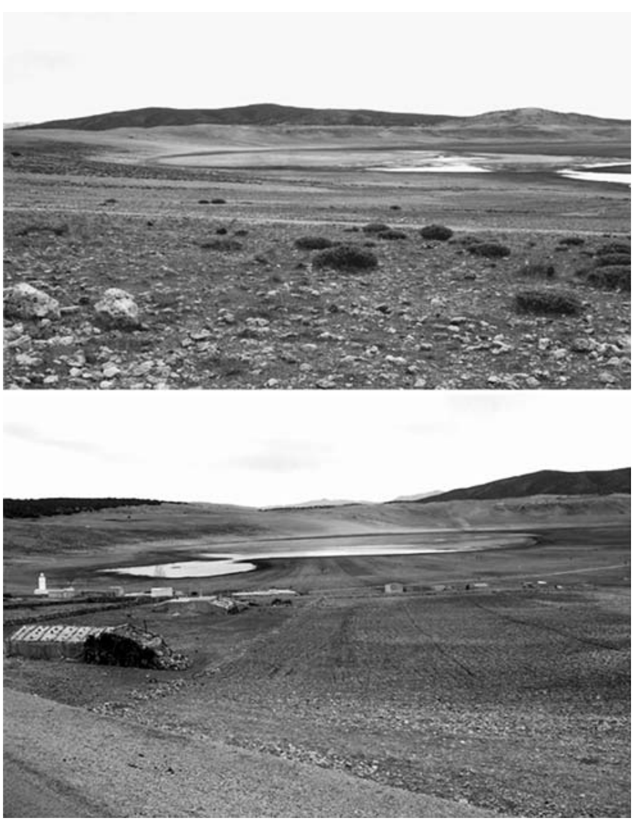

Fig. 5 Photos of Dayet Ifrah

Fig. 6 Photo of Aguelmame Sidi Ali

Fig. 7 Photo of Bou Teguerrouine

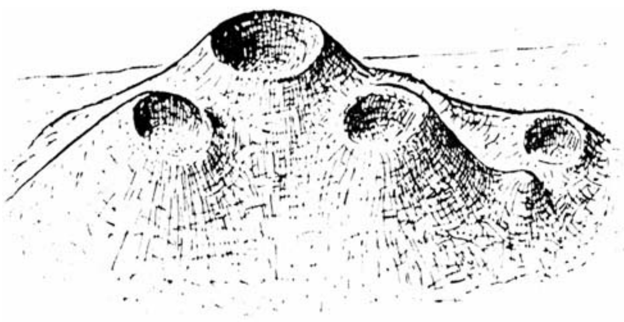

Fig. 8 Schematic representation of Bou Teguerrouine

great distances from their source. Consequently, composite volcanoes are typically high and have very steep slopes.

Due to high magma viscosity, composite volcanoes are characterized by highly explosive eruptions, producing a greater volume of pyroclastic material than lava flows.

This composite volcano has a crater at the summit, which contains a clustered group of vents. Lavas either flow through breaks in the crater wall or issue from fissures on the flanks of the cone. Lava, solidified within the fissures, forms dikes that act as ribs which greatly strengthen the cone (Decker and Decker 1989).

The caldera of the Michliffen

The caldera of the Michliffen is a circular depression (Figs. 9, 10) at the summit of a volcano. It was formed when magma is withdrawn or erupted from a shallow underground magma reservoir. The removal of large volumes of magma may result in loss of structural support for the overlying rock, thereby leading to collapse of the ground and formation of a large depression.

The largest and most explosive volcanic eruptions eject tens to hundreds of cubic kilometers of magma onto the Earth's surface. When such a large volume of magma is removed from beneath a volcano, the ground subsides or collapses into the emptied space, to form a huge depression called a caldera.

Ruiniform landscape

Tidirine is a wide and astounding area of ruiniform rocks (Malaki 2006) (Fig. 11), born out of the limestone plateau dating back to 200–140 millions years. Its landscape's feature is a series of ruiniform rocks. Winds and rains had made their work on those rocks, by eroding them, so as to provide them with strange shapes.

Conclusion

Geology is, indeed, part of the fabric of our social and historical culture. Geological features are a vital part of the world's nature heritage and geoheritage conservation is a means of ensuring that we can pass them on to future generations.

For too long now the heritage value of geological resources has been neglected. While some progress has been made in some countries. The situation is serious as more and more of them succumb to the pressure of development and the impact of ignorance.

The most effective mechanism for overcoming the conundrum is to build public awareness. Such awareness

Fig. 9 Photos of the Michliffen

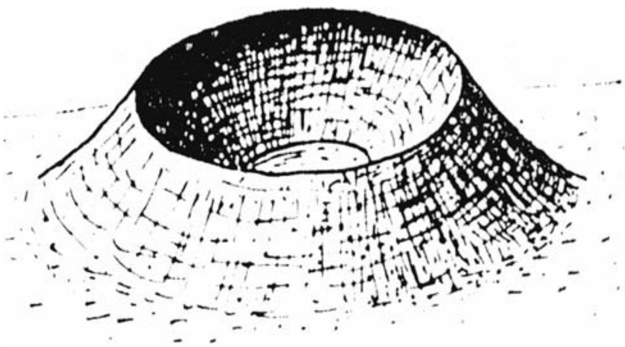

Fig. 10 Schematic representation of Michliffen

Fig. 11 Photos of Tidirine (Malaki 2006)

would create a sense of stewardship and put pressure on decision makers to conserve the heritage. But in order this happen, scientists, geologists in particular, are obliged to provide information on the distribution and value of the hidden treasures. The information will not only build awareness, but will also be used by planners and managers for formulating policies and strategies for conservation programmes.

A lot more effort is required to achieve all of this in order to put the geoheritage conservation movement on the same footing as the biological and cultural heritage conservation movements.

It is only then that we can meaningfully speak about a holistic approach to conservation.

It is important to realize more empirical studies in various geological and geomorphological contexts and to develop assessment and mapping methods. We propose to focus the scientific activities on assessment and mapping, because there is still a lack of available (published) methods.

The tourist sector is one of the economic sectors that could use the results of our researches. In this sense, we plan to develop several activities (e.g. scientific conferences, educative programs) in order to better anchor geosite research in the development of eco- and geotourism.

In most countries, protection of geosites and geomorphosites is poorly developed. On the other way, impacts and pressure of human activities on geomorphology is growing, both in developing and industrialized countries. More knowledge of geoconservation is therefore important, both at the institutional and scientific level. We plan to develop relationships with other scientific groups dealing with geosites, geotourism and geoconservation. We consider this institutional networking as a high priority.

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