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GEOLOGY

Tectono-sedimentary events and geodynamic evolution of the Northern Middle Atlas Miocene basins (Morocco): impact on the NW-SE Atlantic transgression

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ABSTRACT

This paper aims to identify and map the Miocene series in the Northern Middle Atlas. This is to enhance our knowledge about its spatial-temporal variation. Field investigations mainly based on microtectonic measurements combined with structural analyses, lithostratigraphic studies and stress tensor inversion have allowed to reconstruct the genesis and geodynamic evolution of the Northern Middle Atlas Miocene basins. The lithostratigraphic analysis of the Neogene series unconformably deposed on the Jurassic formations shows a transgressive depositional evolution. Several stratigraphic levels have been identified; successively: (i) a conglomerate capped by Vallesian volcanic-sedimentary, lacustrine and palustrine continental series, (ii) Upper Tortonian sandstones, fluvio-deltaic conglomerates and sandy marls with channeled sandstone, (iii) Upper Tortonian-Messinian molasse, pink calcarenite, reef limestone, ochre sandy silt and blue marl. These formations are unconformably overlain by the Skoura puddingstones assigned to the Lower-Middle Pliocene. These deposits are synchronous with a major brittle tectonic phase divided into three episodes: (i) N120 to N140 Vallesian compression (N30 to N50 horizontal σ3 axis), (ii) Upper Tortonian – Messinian N45 extension (σ1 vertical). The history of the Middle Atlas during the Upper Miocene shows an opening megasequence which begins with continental sedimentation during the Upper Vallesian-Tortonian period evolving towards marine sedimentation associated to the NW-SE Atlantic transgression during the Upper Tortonian.

Keywords: Miocene basins; Geodynamic evolution; Tectonic events; Middle Atlas; Morocco.

Eventos tectono-sedimentarios y evolución geodinámica de las cuencas en el norte del Atlas Medio (Marruecos): impacto de la transgresión NW-SE del Atlántico

RESUMEN

Este artículo busca identificar y mapear las series del Mioceno al norte del Atlas Medio. Esto con el fin de mejorar el conocimiento de sus variaciones espacio-temporales. Las investigaciones de campo basadas en mediciones microtectónicas combinadas con análisis estructurales, estudios litoestratigráficos y de inversión del tensor de tensión han permitido reconstruir el origen y la evolución geodinámica de las cuencas en el norte del Atlas Medio. El análisis litoestratigráfico de las series del Neógeno, depuestas disconformemente en formaciones del Jurásico, muestran una evolución deposicional transgresiva. Se identificaron varios niveles estratigráficos sucesivos: (i) un conglomerado cubierto de material sedimentario volcánico del Vallesiense, series continentales lacustrinas y palustrinas, (ii) areniscas del Tortoniense tardío, conglomerados fluvio-deltáicos y margas arenosas con areniscas acanaladas, (iii) molasas del Tortoniense-Mesiniano tardío, calcarenitas rosadas, arrecifes calizos, arena ocre y marga azul. Estas formaciones cubren disconformemente las pudingas en la región de Skoura, asignadas al Plioceno temprano-medio. Estas formaciones son sincrónicas con fases tectónicas precarias divididas en varios episodios: (i) compresión del Vallesiense N120 a N140 (N30 a N50 eje horizontal σ3), (ii) extensión del Tortoniense-Mesiniano tardío (σ1 vertical). La historia del Atlas Medio durante el Mioceno tardío muestra una megasecuencia abierta que comienza con la sedimentación continental durante el período Vallesiense-Tortoniense tardío que evolucionó hacia una sedimentación marina asociada con la transgresión NW-SE del Atlántico durante el Tortoniense tardío.

Palabras clave: cuencas del Mioceno; evolución geodinámica; eventos tectónicos; Atlas Medio; Marruecos

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1. Introduction

The Middle Atlas is a NE-SW trending intracontinental mountain range. It extends over more than 400 km from the Atlas of Beni Mellal in the SW to the Guercif basin in the NE. It is framed by the South Rifain corridor to the North, the Western Meseta to the West, the High Atlas and the High Moulouya to the South and the Eastern Meseta to the East. This mountain range is divided into two zones separated by the North Middle Atlas Fault (NMAF). It is the Middle Atlas Causse in the NW and the Folded Middle Atlas in the SE (Figure 1) (Termier, 1936; Colo, 1961).

During the Neogene, the Atlas domain underwent polyphase tectonics with positive inversion, and transformation of the Jurassic basins to high orogenic zones (e.g., Laville & Piqué, 1992; Morel et al., 1993; Piqué et al., 1998; Gomez et al., 2000; Frizon de Lamotte et al., 2000; Hinaje, 2004; Ellero et al., 2020). Several studies have been carried out in the Middle Atlas and the High Atlas in order to explain the genesis of these basins and their Meso-Cenozoic evolution. Most of these works aim to propose, through regional analyses, examples of geodynamic evolution of intraplate basins.

In the Middle Atlas, the first Neogene marine deposits, first reported by Daguin (1927), were contained in outlying gulfs from the South Rifain corridor to the Skoura basin. The marine advance rounded the massif of Tazekka which was then an island (Colo & Morin, 1952; Choubert & Faure-Muret, 1960-62). Most of the synthesis studies on the Middle Atlas Miocene have been carried out using biostratigraphic studies of the Moroccan Neogene (Feinberg & Lorenz 1970, 1973; Wernli, 1987), and correlated with data from the South Rifan corridor and Skoura gulf (Taltasse, 1953; Feinberg, 1978; Jaeger, 1978; Martin, 1981; Charrière, 1990; Sabaoui, 1998; Sabaoui & Hinaje, 2000; Hinaje, 2004).

The term South Rifain Strait was first used by Gentil (1911, 1916) who thought that the Neogene formations are framed by the Rif and the Middle Atlas already outlined. It is only in 1927 that the marine Miocene was reported in the Middle Atlas in relation to gulfs from the South Rifain-Saïs Strait (Figure 2). The Middle Atlas Miocene, especially the Skoura Basin was mapped for the first time at 1/200 000 by Termier & Dubar (1937). Termier (1936) had also discovered the outcrops of Ribat Al Khayr and Tazarine. New outcrops were later recognized to the East and North of Merhraoua, and to the North of Aderj (Colo & Morin, 1952; Sabaoui, 1987,1998) (Figure 2).

The main synthesis studies carried out in the South Rifain corridor (Taltasse, 1953; Feinberg, 1978), have only focused on the extreme Northern and Western edges of the Middle Atlas. The problems of correlation between the Middle Atlas and the South Rifain corridor deposits have been highlighted by Jaeger (1978) and Martin (1981). By establishing a lithostratigraphic succession and a paleogeographic reconstruction of the Upper Miocene cycle in the Zraa basin and a large part of the Skoura basin, Charrière (1984, 1990) presented, with reservation, correlations between the Middle Atlas formations and those of the South Rifain basin. Its hypothesis is based on the synchrony of the development and invasion of pelagic fossil forms on the one hand, and the diachrony of reef forms on the other hand.

In this study, we adopted a multidisciplinary approach mainly based on field work. Lithostratigraphic and tectonic analyses, combined with geological mapping of Miocene outcrop boundaries in the Sefrou, Oued Zraa, Ribat Al Khayr, Tazarine basins and neighboring areas, have allowed to increase our knowledge about the spatial-temporal variations in the Middle Atlas Miocene series. Based on the collected data, a correlation with the South-Rifain Basin and a paleogeographic reconstruction of the Northern Middle Atlas Miocene basins were proposed.

2. Regional geological setting

The tectonic-sedimentary evolution of the Atlas domain from the Triassic to the present day has been the subject of several studies (e.g., Choubert & Faure Muret, 1960,1962; Michard, 1976; Laville,1985; Fedan, 1988; Jacobshagen et al., 1988; Charrière,1990; Sabaoui, 1998; Hinaje, 2004; Frizon de Lamotte et al., 2008). This evolution is marked by the continental rifting phase linked to the opening of the Central Atlantic and the Alpine Tethys in the framework of the Pangea supercontinent break-up. This is followed by the highly complex stages of the Atlas orogeny which led to the uplift of the High Atlas and Middle Atlas mountain ranges since the end of the Cretaceous period, in the framework of continent-continent convergence between Africa and Iberia/Europe (e.g., Mattauer et al., 1977; Aït Brahim et al., 2002; Frizon de Lamotte et al., 2009; Ellero et al., 2020; Yaagoub et al., 2022; Elabouyi et al., 2022; Laiche et al., 2025).

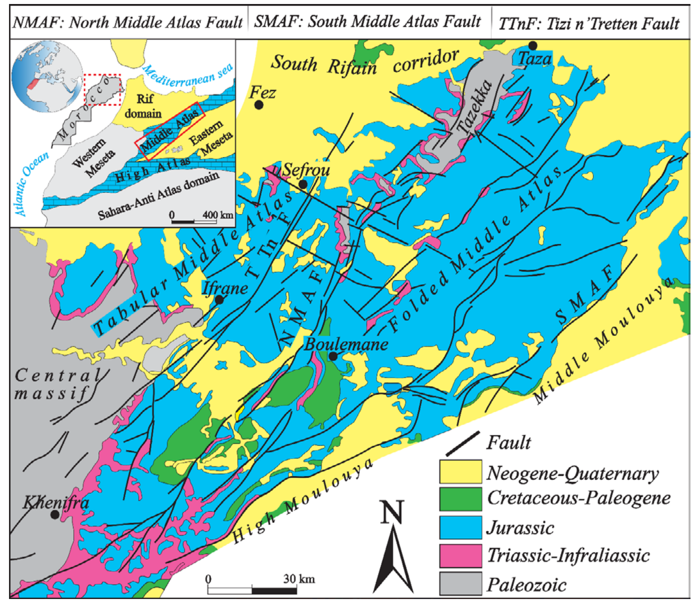

Figure 1. Geological map of the Middle Atlas (from the Geological Map of Morocco at 1:1000000, simplified and modified).

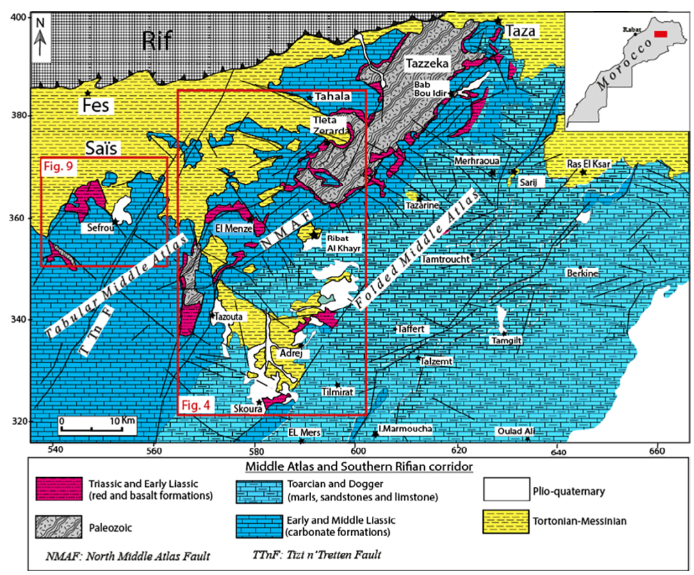

Figure 2. General geological setting of the Middle Atlas- Saïs basin and location of the studied Miocene outcrops.

The Middle Atlas stratigraphic series is mainly represented by the following formations (Figure 3):

- the folded Paleozoic basement outcropping in the Tazzeka massif and in the Bhalil, Kander, Bssabis, El Hajeb and Kerrouchene inliers;
- the Triassic-Liassic detrital, evaporitic and basaltic formations outcropping around the Paleozoic terrains of Kander, Bssabis and El Hajeb inliers, the Tazzeka massif and the Kerrouchène area;
- the Lower-Middle Jurassic carbonate and marl formations which form the most important part of the Middle Atlas terrains;
- the Cretaceous formations which appear along the edges and in the centers of the Middle Atlas range;

- the Paleogene deposits, highly diversified and outcropping to the West of the Boulemane area;
- the Upper Miocene formations outcropping in the NW part of the chain, in the Middle Atlas causse and in the Folded Middle Atlas;
- the Plio-Quaternary continental formations, represented by lacustrine, travertine, alluvial fan and volcanic deposits (Hinaje et al., 2019). They are particularly localized near major fault lines and the chain periphery.

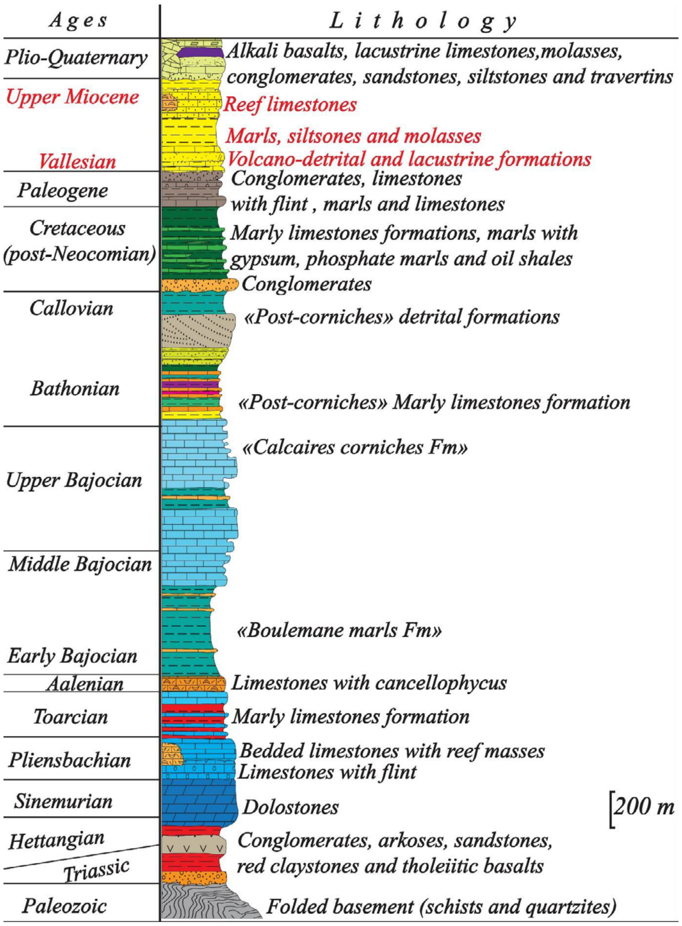

Figure 3. Synthetic lithostratigraphic column of the Middle Atlas (from Hinaje, 2004)

3. Methods

To carry out this study, we adopted a multidisciplinary approach, including lithostratigraphic analysis of the Middle Atlas Miocene terrains and their correlation with those of the Sud-Rifain trench and Saïs basin. Several cross-sections of the Miocene series allowed to specify the succession of the different lithostratigraphic terms as well as their lateral variations. This enabled to better identify correlation problems within the Middle Atlas or with other regions of the South Rifain-Saïs Strait. A tectonic and microtectonic analysis of the Vallesian, Upper Tortonian-Messinian and Pliocene formations is also carried out in order to define the tectonic framework associated with the sedimentation. In the measurement sites, the criteria used to characterize the deformation during a specific period are the following:

- the age of the fractured formations,
- the fracture offsets by others,
- the superposition of the striae on the fault slickensides,
- the presence of parallel fractures with incompatible movements,
- sealed synsedimentary faults, with slickensides showing no recrystallization,
- the elimination principle; from the most recent tectonic episode to the oldest.

Data processing is carried out using several software packages such as ARC-GIS, Adobe Illustrator and Angelier software for stress tensors inversion (Angelier, 1990). The obtained results will allow to establish the various tectonic phases affecting the study area, and to reconstruct its geological history.

4. Results

Lithostratigraphic analysis of the Northern Middle Atlas Miocene series

The Miocene outcrop deposits cover a large NW-SE trending area, located in Sefrou, Tahla, Skoura, Ribat El Khayr and Aghram Amellal (Figures 2, 4). The Skoura basin Miocene outcrops are bounded to the NW by the NMAF and to the SE by the Central Middle Atlas Fault. The Neogene deposits of this basin were guided by the normal movement of N120 to N140 synsedimentary faults (Hinaje, 2004; El Fartati, 2021).

Other outcrops with lesser extension have been studied. These are those of Sefrou, Oued Zraa, Ribat Al Khayr, Tazarine basins and neighboring areas (Figure 4). All of these Neogene deposits are related to a Neogene marine gulf open to the South Rifain corridor and bordering the Tazekka massif which formed an island. These very diversified deposits are made up of molasses and microconglomerates at the bottom, lenticular limestone, marl, reef limestone and sandy marl at the top. The basal molasse is sometimes deposited in intramontane subsiding basins. These deposits are contemporary with tectonic activity divided into several episodes, including the first, which preceded the Tortonian transgression in the Middle Atlas (Charrière, 1984), and is responsible for the emplacement of the Vallesian basalts in the Zraa fluvio-lacustrine basin (Martin, 1981; Charrière, 1990) as well as the collapse of the Guercif basin in the NE (Coletta, 1977; Hervouet, 1985; Giret, 1985).

In major angular unconformity on the Jurassic terrains, the Middle Atlas Miocene deposits show a series we subdivide into different formations correlable with the Saïs and the South Rifain corridor (Figure 4).

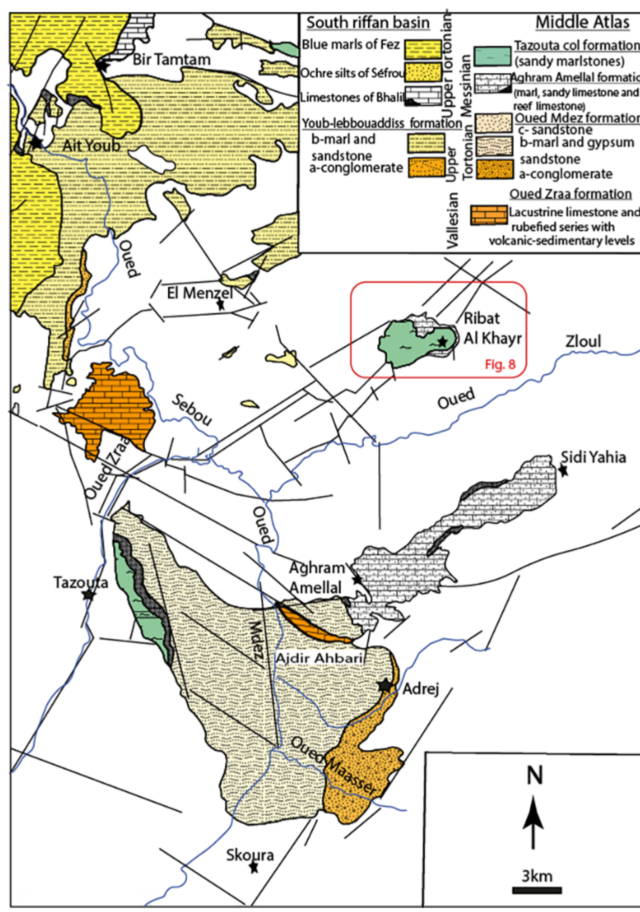

Figure 4. Geological mapping, facies repartition and correlation test of the Upper Miocene deposits in the Middle Atlas and part of the South Rifain corridor.

The paleoboulders formation or "Sefrou basal molasse"

These are deposits assigned to the Lower and Middle Miocene (Hinaje, 2004) because they are overlaid by Tortonian deposits in the Middle Atlas-Saïs junction, near the Paleozoic Bni Mellala inlier and the Sefrou basin (Figure 2). They are made up of coarse Liassic elements coming from the erosion of the neighboring reliefs. Near Sefrou city, this molasse unconformably overlay the Lower Liassic dolostone. At the bottom, it is made up of a 4 to 10 m thick coarse detrital term, with angular Liassic elements of 3 to 30 cm in size, and lenticular bedding. On this term rests a 50 cm thick beige calcarenite level with oblique bedding. On this calcarenite rests a 4 to 8 m thick grano-decreasing sequence consisting of a coarse molasse at the bottom and a microconglomerate with limestone cement at the top.

The lithostratigraphic cross-section of the Neogene deposits (Figure 5) shows two molasse and conglomerate levels representing the base of two transgressive sequences. These two undated levels can be confused because of their restricted geographical distribution.

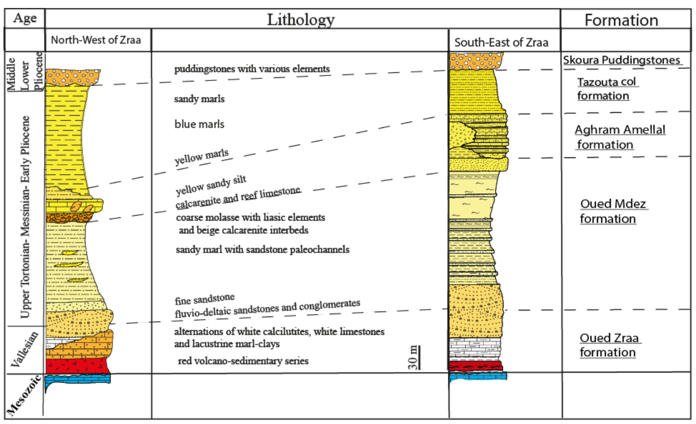

Figure 5. Stratigraphic column of the Northern Middle Atlas Neogene deposits.

The Oued Zraa formation

The Oued Zraa and Skoura basins (Figure 4) provide the first regional Neogene deposits after the paleoboulders and molasses located at the junction of the Saïs and Middle Atlas basins (Charrière, 1990; Hinaje, 2004). This formation is well developed in these two basins.

The Oued Zraa basin is located SW of the Oued Zraa-El Menzel panel which is bounded to the NW by the Median Middle Atlas Fault (MMAF) and to the SE by the NMAF. It shows three sedimentary units (Figure 4) whose first two constitute the Oued Zraa formation:

- at the bottom, there is a continental red series with volcanic and volcano-sedimentary intercalations, with a thickness of several dozen meters (Figure 5). A double geochronological dating of the volcanic flow has provided the ages of 9.7 + 0.5 Ma and 10 + 0.5 Ma (Jaeger et al., 1973). A grey clay level, overlying the dated volcanic flow, yielded Vallesian micromammals (Jaeger & Martin, 1971; Jaeger, 1978);
- on top of these clays, we find white and chalky marly limestones which constitute a relatively homogeneous lacustrine unit, 30 to 40 m thick;
- a fluvial-type lithostratigraphic assemblage covers the center of the Oued Zraa basin. This assemblage have been related to the basal member of the Oued Mdaz formation described in the Skoura basin (Sabaoui, 1998);
- these deposits are conformably capped by a lacustrine sequence constituted by calcilutites and white limestone with root traces. They are sometimes covered by conglomerates and fluvial sandstones.

In the Northern part of the Skoura basin (Figures 2, 3), on either side of the Oued Mdaz, the bottom of the Miocene series showed orange-red silt beds with volcano-sedimentary intercalations. These correspond to tuffaceous clays with 10 to 20% pyroclastic elements and also to volcanic tuff levels. All these levels have been correlated with the lower volcano-sedimentary unit of the Oued Zraa basin. On top of this, we find variegated versicolor marls. Thin white limestone benches with lumpy microfacies intersect the marly series. These deposits are equivalent to the Oued Zraa marl-lacustrine unit.

At the scale of the Middle Atlas, the extension of these lacustrine deposits is very small. They are particularly outcropping in the NE of the subsident Skoura and Oued Zraa basins (Jaeger & Martin, 1971; Jaeger, 1978; Hinaje, 2004). In the Skoura basin, 3 km East of the Oued Mdaz, these deposits unconformably overlay the Bathonian sandstone with marly interbeds. They are constituted by a clay layer with calcareous nodules more than 8 m thick. These series are surmounted by white limestones with upper vegetal traces, which thickness can reach 10 m (Figure 6) (El Fartati, 2021). Eastward, along the road leading to the Aghram Amellal village, the locality of Ajdir Ahbari displays the same deposits but with a thickness reduced to 3 m. This outcrop would represent the edge of a Vallesian lake spread over the Skoura basin (El Fartati et al., 2019, 2021, 2023).

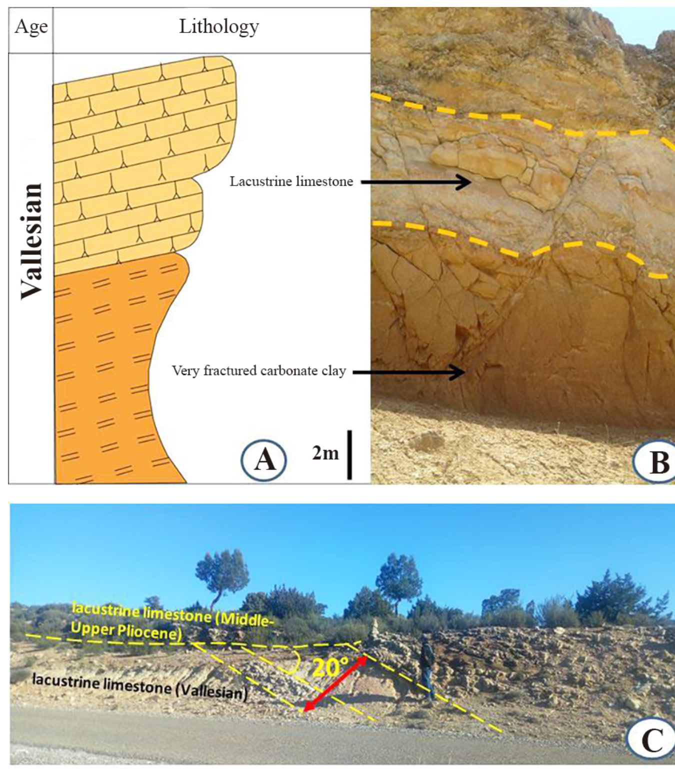

Figure 6. A- Lithostratigraphic cross-section of Vallesian lacustrine deposits East of the Mdaz bridge (Ajdir Ahbari area). B- Photo of Vallesian lake deposits, affected by N130 synsedimentary normal faults. C- Vallesian deposits at the lake basin edge unconformably deposited on the Middle-Upper Pliocene lacustrine deposits.

The Oued Mdaz formation

This formation is the equivalent of the Aït Youb-Lebbouaddis formation defined at the NW edge of the Causse (Figure 4) (Charrière, 1990). Two large outcrops are recognized in the Skoura basin. The first, which is 50 m thick, is located on either side of the Oued Mdaz where it overlies the Oued Zraa formation. The second outcrop covers the SE flank of the Skoura basin. The latter outcrop extends from the lower slope of the NE termination of the Tichoukt ridge to the Aderj proximity. On both sides of the Oued Maasser, these deposits reach 250m thickness (Figure 4). These are detrital facies where conglomeratic sedimentation is dominant. The whole shows a fluvial type sequential organization. Laterally, these deposits decrease in thickness to the N and NE where they are replaced by sandstones and marls. At the bottom, the more-least sandy marls are interbedded with small sandstone, conglomerate or microconglomerate benches. As the series rises, the marls become dominant with rare sandstone beds with oblique and intersecting bedding. In the area East of the Oued Mdaz, the thickness of this unit does not exceed 50 m. There is a progressive thinning of the deposits from SW to NE until their disappearance 1 km South of a line connecting Aderj and Aghram Amellal (Figure 4). This member is overlain by thick, poorly stratified sandstone beds with interbeds of large oyster marl (*Crassostrea*) (Figure 7). Different levels of this cross-section have yielded gastropods and rare foraminifera of the *Ammonia* genus (Sabaoui, 1998). The Oued Mdaz formation has been assigned to the Upper Tortonian (Charrière, 1990).

Figure 7. Marls with oysters in the NW of the Skoura basin.

Aghram Amellal formation and its equivalent pink limestone of Sefrou-Bhalil

This formation is recognized and studied in several outcrops of the Middle Atlas and Saïs, including Aghram Amellal, Ribat El Khayr, Tazarine and Sefrou areas (Figure 4).

In the Aghram Amellal area, Miocene outcrops have been reported by several authors (Colo, 1961; Lorenchet de Montjamont, 1963; Martin, 1981; Saint Martin, 1987; El Hamzaoui, 1994). The Aghram Amellal formation corresponds to the Upper Miocene deposits with three main facies: the basic molasses, the reef limestone and the sandstone or sandy limestone. At the Middle Atlas scale, the most important outcrop of these units is the sector of Aghram Amellal (Sabaoui; 1998), which explains its name. The reef limestones which, according to Charrière (1990), constitute the first formation of the Tazouta Pass, must be considered as one term of others which constitute this Aghram Amellal formation. The Oued Mdaz formation progressively passes to that of Aghram Amellal without sedimentation interruption. This formation is mainly composed of yellow sandy marls with sandstone inter-beds. These deposits yielded planktonic foraminifera reaching 10% of the microfauna with an association indicating the m6a subzone (Upper Tortonian-Messinian) (Sabaoui, 1998). In the Aghram Amellal area, the Upper Miocene deposits directly overlie the Triassic, Liassic or Dogger formations. Their base is generally made up of channel conglomerates and sandstones with oblique and intersecting stratification.

In addition to the known reef near Aghram Amellal (Lorenchet de Montjamont, 1963), we discovered several other coral reef outcrops (Figures 2, 8) which rest on the base molasse deposits, on the Bathonian deposits or on various Miocene terms.

In Ribat Al Khayr area, the Upper Miocene series has been known since the works of Termier (1936). Lorenchet de Montjamont (1963) indicated the reef nature of the limestone on which the village is built. In the Eastern edge of the village, there is a base conglomerate (1 m) topped by sandstone bars alternating with sandy marl layers. The whole is interlaced by conglomerate layers. Reef constructions (Figure 8) with a thickness of up to 15 m have developed on this detrital term. They are presented as lenses separated by sandstone limestones with very little coral. In the Northern part of the Ribat Al Khayr outcrop, the reef constructions are replaced by sandstone limestone and generally sparitic limestone (Figure 8). The biophase is limited to bioclasts, bryozoans and rare foraminifera. The whole of the Aghram Amellal formation deposits is surmounted by the Tazouta formation.

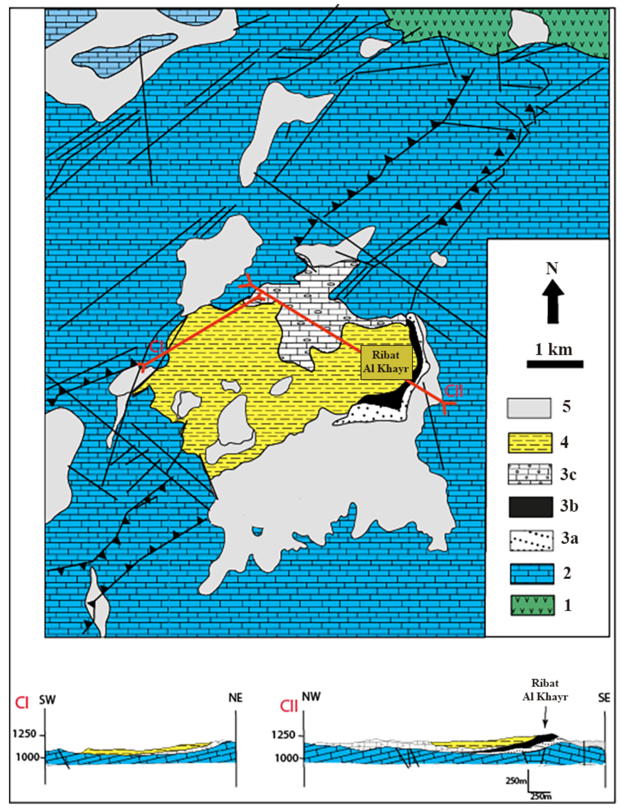

Figure 8. Geological map of Ribat El Khayr Miocene formations and orthogonal NE-SW and NW-SE geological cross-sections (from Sabaoui, 1998). 1-Paleozoic; 2- Triassic and Jurassic; 3- Aghram Amellal Formation (a-conglomerate and sandstone, b- reef limestone, c- calcarenites and sandstone limestones); 4- Tazouta formation; 5- Plio-Quaternary.

In the Tazarine area, the Miocene deposits are unconformably deposited on the Dogger marl limestone. They consist of conglomerates, calcarenite and yellow limestones rich in bioclasts and polypiers.

In the NE part of the Middle Atlas Causse, between Sefrou and Tahla, the pink limestone formation of Sefrou -Bhalil, assigned to the Upper Tortonian - Messinian, crops out (Charrière, 1990; Hinaje, 2004). It is made up at the bottom by coarse molasses with mainly Liassic elements, covered by pink limestones with *Heterostegines*, or their lateral equivalents: the pink and beige calcarenites and the reef limestones. On this term, rest the Sefrou yellowish sandy silt and the blue marls with sandstone pass. The top of the latter, NW of Fez city, is assigned to the Lower Pliocene (Wernli, 1987).

In the transition zone between the Middle Atlas-Saïs basin, especially in the center of Sefrou-Tahla gulf, the Miocene lithostratigraphic series is made up of Upper Tortonian-Messinian carbonate bar with reef layers and yellowish siltstones with sandstone-conglomerate lenses.

Tazouta Pass formation and its equivalent Fez Saïs blue marls

Charrière (1990) defined two Upper Miocene terminal formations NW of the Skoura basin. He called them the Tazouta Pass formations. The first is reef limestone and the second is oyster-white sandy marl. The extension of studies to the North showed that the reef unit must be considered as a member among others which constitute the Aghram Amellal formation (Figure 5). The second unit referred to as the Tazouta Pass Formation is the terminal Upper Miocene deposits in the Middle Atlas. Apart from the NW sector of the Skoura basin, the Tazouta Pass Formation also outcrops at Ribat Al Khayr. In this outcrop (Figure 4), we established that the different terms of the Aghram Amellal formation (molasse, reefs, sandstone limestones) pre-date the marls that must constitute the Tazouta Pass formation. Indeed, in the North and East part of this outcrop, these marls geometrically overlie the Aghram Amellal formation. To the West, Tazouta Pass marls transgress directly on the Liassic substratum. In the Ribat Al Khayr outcrop, the Tazouta Pass formation is made up of yellow to white sandy marl. In the NW of the Skoura and Saïs basins, this formation is represented by blue marls and/or white marls which sometimes directly transgress the Jurassic formations.

Tectonic and microtectonic analysis of the Northern Middle Atlas Miocene series

The Middle Atlas is the site of significant tectonic, neotectonic and seismic activity (Michard, 1976; Ramdani & Tadili, 1980; Charrière, 1990; Hinaje, 2004). Hundreds of microtectonic measurements have been collected in the Northern Middle Atlas Miocene series (Hinaje, 2004; Hinaje et al., 2015). Several tectonic phases, divided into episodes, have been revealed. We describe below the various tectonic phases which have guided basin geometry, structure and geodynamic evolution.

Tectonic phase preceding Miocene basin opening

In the Sefrou Neogene basin, located at the junction of the Middle Atlas and Saïs basin (Figure 2), the Oligocene-Lower-Middle Miocene tectonic phase, corresponds to the phase before the opening of the NW-SE Sefrou-Tahla-Tazarine-Skoura marine gulf. It is represented by two episodes (Figure 9). The first one is characterized by submeridian dextral strike-slip faults and NE-SW to ENE-WSW sinistral strike-slip faults. These faults are compatible with a stress state with N30 horizontal $\sigma1$ axis and N120 $\sigma3$ axis. The second episode is compressional and oriented NNE-SSW (vertical $\sigma3$ axis), represented by WNW-ESE trending reverse to thrust faults, metric to decimetric scale folds with N110 to N145 trending axes and WNW-ESE trending fracture cleavage. The ratio $\phi = (\sigma2 - \sigma3) / (\sigma1 - \sigma3)$ ranges from 0,02 ($\sigma2 = \sigma3$) to 0,67 ($\sigma2 \approx (\sigma1 + \sigma3) / 2$); indicating that reverse and thrust faults can be associated with strike-slip faults with reverse component. The age of this tectonic phase is assigned by analogy with work carried out in other areas where deposits are dated (Hinaje, 2004). In the Bni Mellala inlier, located in the NW edge of the Tabular Middle Atlas, this tectonic phase is represented by a NE-SW compressional episode. This is shown by N110 to N140 trending thrust faults which affect the Ordovician quartzites and schists, the Upper Triassic and Lower Liassic deposits, whereas they are missing in the Upper Miocene deposits (Figure 9). The movement of these faults is compatible with a compressional stress state characterized by N30 horizontal $\sigma1$ axis and vertical $\sigma3$ axis.

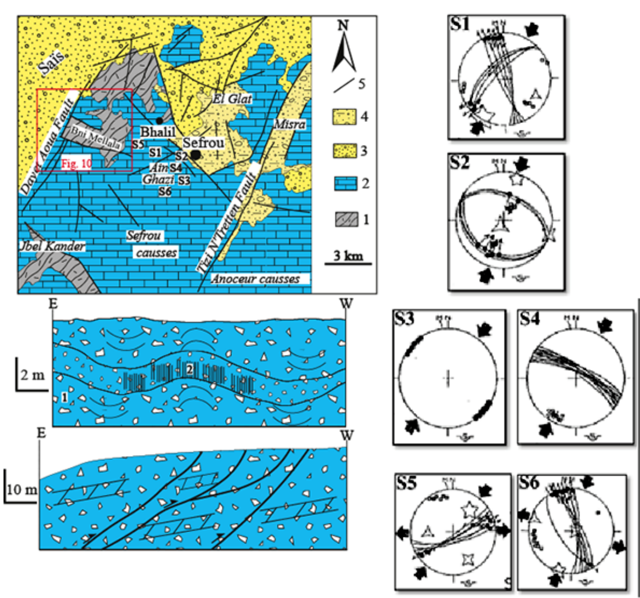

Figure 9. Microtectonic analysis of the brittle deformation and determination of the stress axes during the Oligocene-Lower-Middle Miocene tectonic phase in the Sefrou basin. A- Simplified geological map of the Sefrou-Bhalil area (from the geological map of Sefrou at 1/100 000, modified). 1- Paleozoic-Triassic; 2- Early-Middle Liassic; 3- Upper Miocene; 4- Plio-Quaternary; 5- Fault; S1-6: microtectonic measurement site. B and D- Metric fold with cleavage in the Early Liassic dolostones. 1- brecciated dolostone; 2- fracture cleavage; S3- fold axes stereoplot; S4- fracture cleavage planes stereoplot. C- thrust planes affecting Early Liassic brecciated dolostones. S5-6: strike-slip faults stereoplot.

The Bni Mellala N100 to N120 trending thrust, bordering it on the North side, corresponds to a flat surface which detaches the Triassic-Liassic cover from the Paleozoic basement (Figure 10). The contact between the Liassic dolostones and the basement corresponds to a crushed surface containing basalt levels, yellow marls and red claystones. The thrusting contact has a sinistral strike-slip component, marked by the rebound of the basement cleavage (Figure 11). The pre-Miocene age of the Bni Mellala thrust was also reported by Charrière (1990), who placed it between the deposition of the paleoboulders and the first Upper Tortonian marine deposits. This NNE-dipping thrust is reversed and tilted to the NW by the N30 Dayet Aoua normal fault with NW dipping (Figure 9). This normal movement is assigned to the Early-middle Quaternary (Hinaje et al., 2001).

To the South of the inlier, the polyphase N120 Aïn Dik fault (Charrière, 1990), offsets the Dayet Aoua fault in apparent dextral movement (Figure10). This fault also has a normal movement with dextral strike-slip component, probably of Late Miocene age. Together with the N130-trending Kandar fault and the N140-trending Sefrou-Bhalil fault, it constitutes stepped blocks with NE collapse. This collapse occurs towards the NW-SE Sefrou - Tahla - Skoura - Ribat El Khayr Upper Miocene marine gulf, and corresponds to a set of kilometer-scale subsiding grabens (Hinaje et al., 2001; Hinaje, 2004).

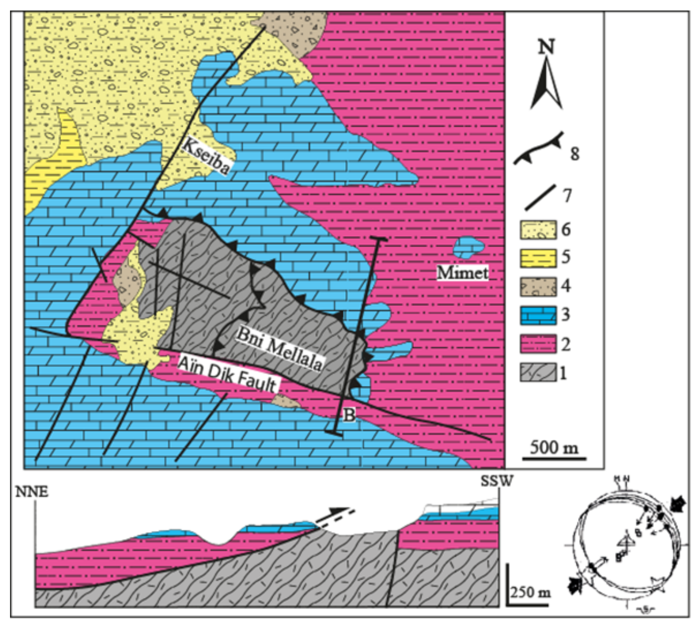

Figure 10. A- Simplified geological map of the Bni Mellala area (from Charrière, 1990 modified). 1- Paleozoic; 2- Triassic-Infra-Liassic; 3- Early-Middle Liassic; 4- Ante- Upper Miocene paleoboulders; 5- Upper Miocene; 6- Plio-Quaternary; 7- Fault; 8- thrust. B- Structural cross-section showing the N120 Bni Mellala thrust. C- Stereoplot of the thrust fault planes accompanying the Bni Mellala major thrust, and stress axes of the Ante-Upper Miocene NE-SW compressional episode.

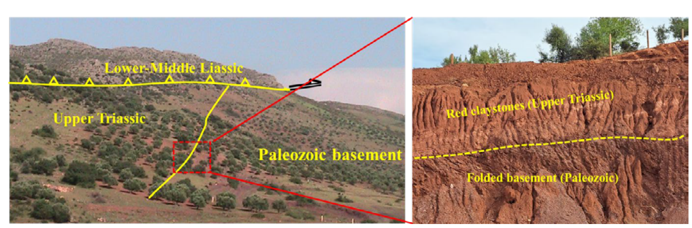

Figure 11. N110 to N120 Bni Mellala thrust putting the Early-Middle Liassic dolostones and limestones directly on the Ordovician schists.

Tectonic phase synchronous with the opening of the Miocene basins (Vallesian - Upper Tortonian - Messinian)

We have highlighted the Vallesian tectonic episode in the Oued Zraa and Oued Mdaz measurement sites. These two zones constitute the first Neogene basins with continental deposits. The bottom of these deposits is made up of a continental series with interbedded volcanic flows. On top, we find alternations of marl and limestone, white calcilutites and lacustrine white limestones, surmounted by fluvial conglomeratic deposits. The lacustrine carbonate deposits are affected by a series of sealed and striated faults, divided into two groups: N05 to N45 trending reverse faults with dextral strike-slip component, and N75 to N100 trending dextral strike-slip faults. These faults are consistent with a paleostress field with N120 horizontal σ1 axis and N30 horizontal σ3 axis. These Vallesian deposits are affected by a N130 trending major normal fault with NE collapse, whose post-Vallesian movement is assigned to the Upper Tortonian-Messinian.

The second microtectonic measurement site corresponds to the area located on the right bank of Oued Mdaz, between Tazouta and Aderj (Ajdir Ahbari). This area is part of the NW-SE Tazouta-Skoura Miocene basin. Near the Mdaz bridge, the Vallesian facies are constituted by silty, marly and calcareous lacustrine deposits with root traces. These deposits are unconformably deposited on the Bathonian formation, and they are covered by the Upper Tortonian-Messinian marls, or locally unconformably by the Lower-Middle Pliocene Skoura puddingstones (Charrière, 1990; Sabaoui, 1998). They are affected by sealed faults with planes striated by grooves and channels. These faults are oriented N120 to N145 with normal movement, consistent with an extensional paleostress field such that σ1 axis is vertical and σ3 is horizontal and striking in NE-SW direction (Figure 12). On the same outcrop, we measured N150 to N175 trending sinistral strike-slip faults; consistent with a compressional paleostress field with NW-SE horizontal σ1 axis, NE-SW horizontal σ2 axis and vertical σ3 axis. The ratio ϕ = 0,04; indicates that σ2 = σ3, and NW-SE compression is associated with NE-SW extension. The processing of all the synsedimentary normal faults and the sealed decays, results in a paleostress field with the vertical σ1 axis, NW-SE horizontal σ2 axis and NE-SW horizontal σ3 axis. In this case the ratio ϕ = 0.80, indicates that σ1 ≈ σ2. This means that the NE-SW extension is associated with a NW-SE compressional axis.

In the Bni Mellala - El Qciba valley measurement site, located in the NW limb of the Tabular Middle Atlas, the various microtectonic measurements we have carried out have allowed to highlight a Late Miocene NE-SW extensional phase. This is represented by NW-SE normal faults, compatible with a vertical σ1 axis and a NE-SW horizontal σ3 axis (Figure 13).

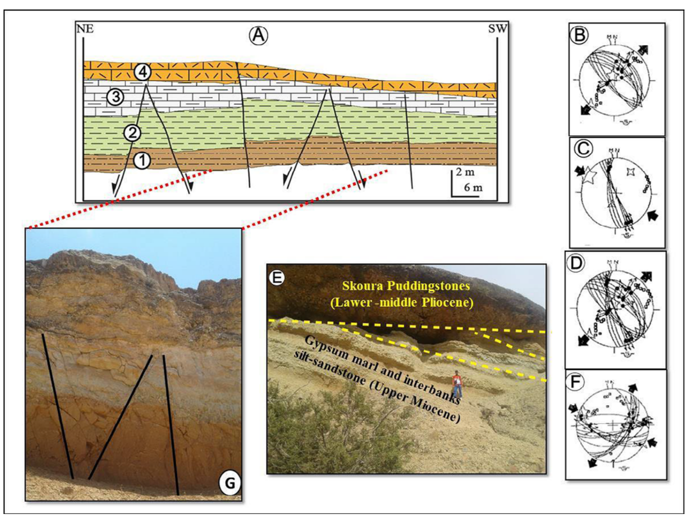

Figure 12. A- Cross-section of the Ajdir Ahbari lacustrine deposits showing sealed normal faults and strike-slip faults. 1- brown siltstone; 2- greenish carbonate marl; 3- white clayey limestone; 4- lacustrine limestone with root traces. B- Stereoplot of NW-SE synsedimentary normal faults. C- Stereoplot of the NNW-SSE sealed sinistral strike-slip faults. D- Stereoplot of normal and strike-slip faults. E- Angular unconformity of the Lower-Middle Pliocene Skoura puddingstones on the Oued Mdaz Upper Miocene deposits. F- Stereoplot of NNE-SSW reverse faults and E-W dextral strike-slip faults (ϕ ≈ 0) affecting the Vallesian lacustrine limestones in the Oued Zraa measurement site. G- Sealed synsedimentary normal faults affecting the Vallesian lacustrine deposits.

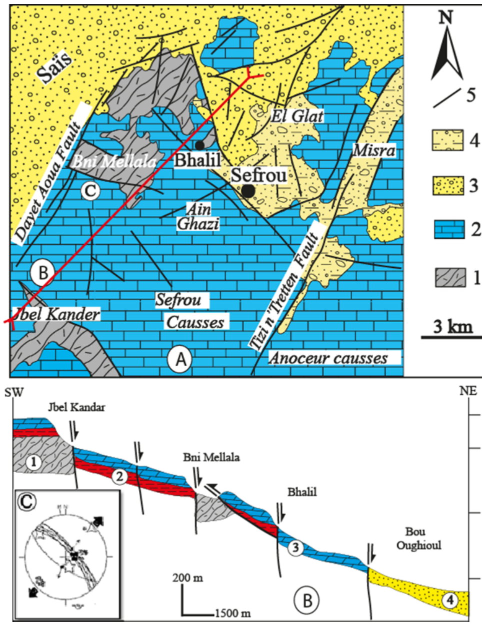

Figure 13. Tectonic analysis of brittle deformation and determination of the stress axes during the Upper Miocene extensive phase between Jbel Kandar and Bou Oughioul. A- Simplified geological map of the Sefrou-Bhalil area. 1- Paleozoic-Triassic; 2- Early Liassic; 3- Upper Miocene; 4- Plio-Quaternary; 5- fault. B- NE-SW structural cross-section showing block staging between the Kandar and Sefrou-Bhalil faults. 1- Paleozoic basement; 2- Triassic-Infra Liassic; 3- Early Liassic; 4- Upper Miocene and Plio-Quaternary. C- Stereoplot of the normal faults responsible for the NE collapsing during the Upper Miocene.

5. Discussion

Examination of Upper Miocene deposits allows us to identify the general evolutionary trend of sedimentary systems at regional scale. Two sedimentary ensembles can be identified, the first with a continental character and the second with a marine one. For each set, which raises problems of stratigraphy and correlation, we distinguish several environmental and paleogeographic events.

Vallesian continental basins

The Miocene sedimentation starts in the Zraa and Skoura basins with continental deposits which form the Oued Zraa and its equivalent Ajdir Ahbari (Figure 14). In the Zraa basin, this formation consists of red detrital deposits with volcano-sedimentary and volcanic intercalations. Its age is close to 10 Ma and it is related to lacustrine continental sedimentation associated with volcanism, in relation with a deep fracturing depending on transversal structural lines (Charrière, 1990). The study carried out just East of the Mdaz bridge, enabled of the following observations: (i) the Vallesian deposits are deposited, with angular unconformity of about 15°, on the Bathonian marl-sandstone basement, (ii) these lacustrine deposits are highly fractured and tilted towards the SW with a dip of about 20°, (iii) their depositional environment corresponds to the Oued Mdaz paleo-dam lake which natural wall is made up of the impermeable Bathonian marl layers tilted along a N130 normal fault. The intensity of fracturing recorded within these lake formations, represented by synsedimentary faults, is related to the Vallesian N120 tectonic phase.

Along the road to the Aderj village, the Upper Miocene marine deposits overlay, with angular unconformity of about 15°, the Vallesian lacustrine. This contact is particularly apparent where a N45 normal fault occurs. They also outcrop to the South of this area through the N80 normal fault, which is assigned to the Aït Chaïb-Aïchoun (SE of Tazouta) lacustrine basin formation to the Middle-Upper Pliocene.

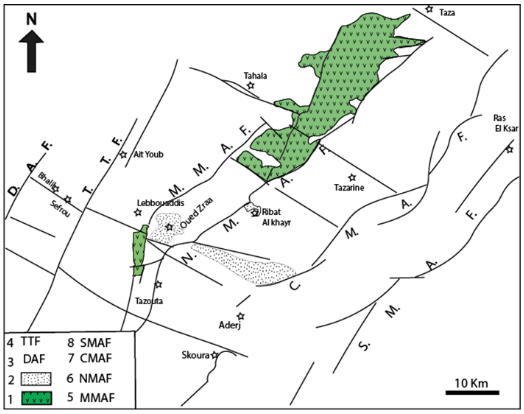

Figure 14. Paleogeographic map of the first Vallesian continental and volcanic deposits in the Middle Atlas. 1-Paleozoic; 2- Oued Zraa formation and its Ajdir Ahbari equivalent (Vallesian-Tortonian); 3- Dayet Aoua Fault; 4- Tizi N'Tretten Fault; 5- MMAF; 6- NMAF; 7- Central Middle Atlas Fault; 8- South Middle Atlas Fault.

Upper Tortonian fluvio-deltaic to lagoon-lacustrine basins

In the Oued Zraa and Skoura basins, the sedimentation is continued by coarse fluvio-deltaic facies deposits which form the base of the Oued Mdaz Formation (Figure 15). They are correlable with the basal term of the Aït Youb-Lebbouaddis formation which crops out further NW. The present outcrops show that their extension is much wider than the Oued Zraa lacustrine deposits.

The Oued Mdaz formation is continued by an essentially marl and silt sedimentation with gypsum. The biophase is essentially limited to a freshwater microfauna. All of these deposits correspond to a lacustrine to lagoon environment established in the Skoura mudflat, which underwent polyphase tectonic subsidence. At the same time, another mudflat was established to the NW, in the Aït Youb-Lebbouaddis sector (Charrière, 1990). Contrary to what has been accepted at Ribat Al Khayr, no basin existed at that time. Indeed, the first Formation to have been deposited was that of Aghram Amellal.

The Oued Mdaz formation ends with sandstone bars with facies indicating a lagoon environment with a very slight marine influence. In the Skoura basin, these sandstones have yielded a *Crassostrea* fauna, the first foraminifera of *Ammonia* genus and very rare sea urchin radioles. In the NE part of the Skoura basin, this upper term of the Mdaz Formation transgresses over the Dogger basement. This overflow indicates the impact of communication with Atlantic Ocean seawater on the NW side, on the sedimentation environment. This communication will be more important during the sedimentation of the overlying Aghram Amellal Formation.

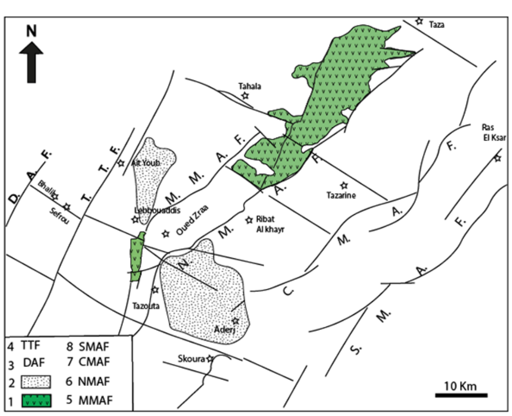

Figure 15. Paleogeographic map of the first Vallesian continental and volcanic deposits in the Middle Atlas. 1-Paleozoic; 2- Oued Zraa formation and its Ajdir Ahbari equivalent (Vallesian-Tortonian); 3- Dayet Aoua Fault; 4- Tizi N'Tretten Fault; 5- MMAF; 6- NMAF; 7- Central Middle Atlas Fault; 8- South Middle Atlas Fault.

Upper Tortonian and Messinian marine sedimentation

The Oued Mdaz formation passes to the Aghram Amellal formation without sedimentation interruption. The latter begins with a marine-facies marl-sandstone term overlying the last sandstone term of the Oued Mdaz Formation. The continuity of the sedimentation allows to confirm the idea of Charrière (1990) who questioned the presence of the "probable marine Pliocene" North of Adrej (Colo, 1961).

In the SW part of the Skoura basin, the Aghram Amellal formation begins with yellow marls with marine microfauna. The marl or marl-sandstone deposits, developed at the transition from the Oued Mdez Formation to the Aghram Amellal Formation, represent gulf-bottom facies which finds a pre-established and subsident outlet in the Skoura Basin as a result of the N120 to N140 synsedimentary normal faults and the N20 to N45 inherited reverse faults (Figure 16). The Skoura basin underwent late infilling by sandstones and marls, resulting in a bathymetric reduction favorable to coral installation. Further N and NE of this basin, the Aghram Amellal formation begins with detrital rocks representing paleo-valley filling and small paleo-depressions. This term constitutes the basement of marine deposits (sandstone, bioconstructions, calcarenite, sandstone limestone). The present distribution of the Aghram Amellal Formation outcrops highlights the NW invasion of Atlantic marine seawater into the Middle Atlas during the Upper Tortonian-Early Messinian.

The sedimentation is continued by marls constituting the Tazouta Pass formation outcropping in the NW of the Skoura basin and at Ribat Al Khayr. The first outcrop shows relatively restricted facies. The second, which we have also shown to be later than the Aghram Amellal formation, shows relatively open marine facies.

The problem of correlation between the Middle Atlasic facies and the SE part of the Saïs basin was raised by Charrière (1984,1990). Based on the synchronism of the Fez blue marls and the yellow marls overlying the Oued Mdaz formation, this author proposed a hypothesis suggesting that the Sefrou-Bhalil limestones with reef intercalations would be older than the reefs outcropping in the NW of the Skoura basin. Thus, according to this author, the former would mark the beginning of sea transgression from the South Rifain corridor onto the Middle Atlas Causse and the latter would represent the maximum sea extension in the Skoura gulf.

Field observations and cartographic surveys we have conducted in the Folded Middle Atlas to the North and NE of the Skoura basin, lead to support a correlation of the reef limestones or more generally the Aghram Amellal formation with the Sefrou-Bhalil pink limestones. This hypothesis finds its support in the following argument:

- the presence in the NW of the Skoura basin of yellow marls with a pelagic fauna of up to 10%, would represent the first clean marine facies of the Aghram Amellal formation, which developed in a pre-established mudflat, after the Upper Tortonian-Messinian transgression;
- northwest of the Skoura basin, the Tazouta Pass Formation, which is of restricted character, proved difficult or impossible to correlate with the first deposits of Fez blue marls with pelagic facies in the South Rifain corridor. The identification of the Tazouta Pass formation at Ribat Al Khayr where it shows relatively open facies with a pelagic fauna exceeding 10% allows to correlate it with the blue marls of Fez;
- the reef outcrops of Al Mahraz near Oued Zraa and El Menzel reported respectively by Martin (1981) and Chevalier (1962), would constitute intermediate markers between the Sefrou-Bhalil pink limestones and the Aghram Amellal Formation.

The present distribution of the Aghram Amellal Formation outcrops, especially the reef member, or its equivalent, indicates the installation of a marine regime with a much wider extension than the two previous lagoon-lacustrine to lagoon-marine depressions of Skoura and Aït Youb-Lebbouaddis. The passage between the Middle Atlas and South Rifain corridor marine domains, SE of Fez, is through the NW-SE Gulf of Sefrou-Tazouta-Skoura-Tahla-Tazarine (Figure 16).

The distribution of the Aghram Amellal Formation outcrops or its equivalent (the Sefrou-Bhalil pink limestones), which does not extend beyond the N130 Sefrou-Bhalil fault, suggests that, contrary to the ideas of our predecessors, the transgression tends to be oriented from East to West and from

NW to SE (Figure 17). The Atlantic transgression which allowed the deposition of Fez blue marls, could reach the core of the Middle Atlas by deposition of Tazouta marls which outcrop in Ribat Al Khayr and in the NW of Skoura basin (Figure 17). This marine intrusion occurred from NW to SE in the same-direction gulf bounded by N120 to N140 synsedimentary normal faults. The shallow facies of the Middle Atlasi deposits, in contrast to the pelagic deposits of the South Rifain corridor to the NW, is thought to be related to significant subsidence of the latter. The current outcrops of the Tazouta Pass Formation suggest a discharge of Atlantic waters into the Middle Atlas Basin from NW to SE.

The maximum sea advance could feed communication corridors with the Guercif basin. These waters penetrate the Sefrou-Tahla-Tazouta-Skoura-Tazarine gulf in a NW-SE direction, feeding the Ras El Ksar - Guercif basins during transgressive maxima.

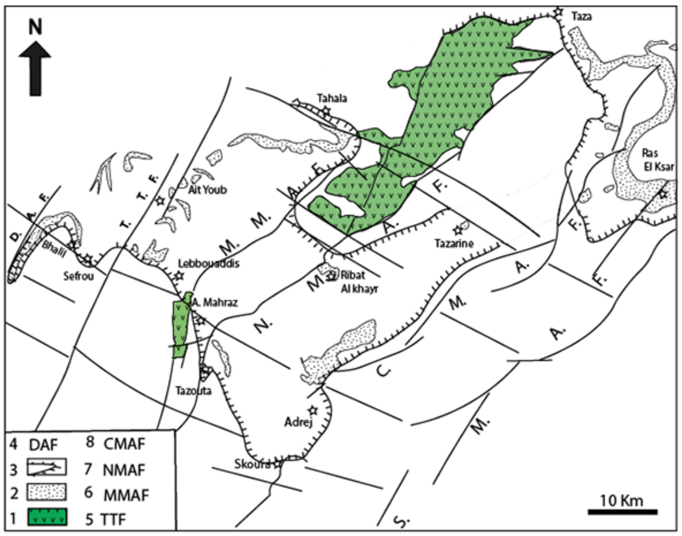

Figure 16. Paleogeographic pattern during the Upper Tortonian - Early Messinian. 1-Paleozoic; 2- Aghram Amellal Formation and its equivalent (Upper Tortonian - Early Messinian);3- probable limit of Upper Tortonian - Early Messinian Sea extension;4- Dayet Aoua Fault; 5- Tizi N'Tretten Fault; 6- MMAF; 7- NMAF; 8- Central Middle Atlas Fault.

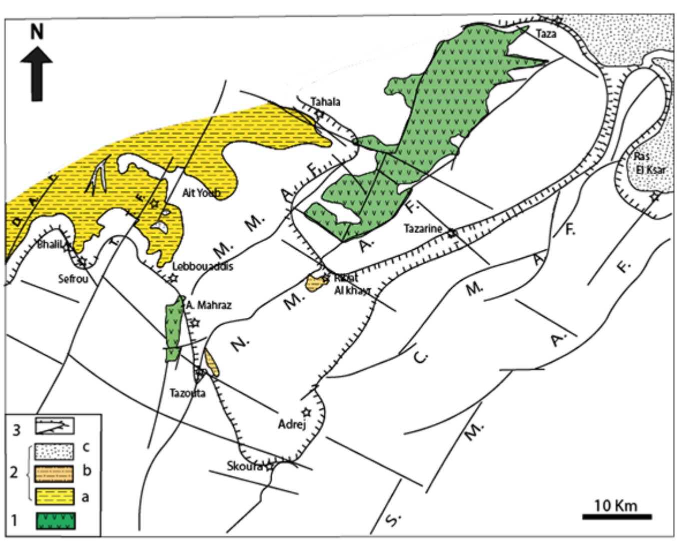

Figure 17. Paleogeographic pattern during the Messinien. 1-Paleozoic; 2- Messinian outcrop (a: Fez blue marl formation with open marine facies; b- Tazouta Pass formation with restricted marine facies; c- Melloulou succession with restricted marine-lagoon facies); 3- probable limit of Messinian sea extension.

6. Conclusion

The Northern Middle Atlas Miocene stratigraphic series are characterized from bottom to top by: (i) a conglomerate capped by Vallesian volcanic-sedimentary, lacustrine and palustrine continental series, (ii) Upper Tortonian sandstones, fluvio-deltaic conglomerates and sandy marls with channeled sandstone, (iii) Upper Tortonian-Messinian molasse, pink calcarenite, reef limestone, ochre sandy silt and blue marl. These formations are unconformably overlain by the Skoura puddingstones assigned to the Lower-Middle Pliocene. These deposits are synchronous with a major brittle tectonic phase divided into two episodes: (i) N120 to N140 Vallesian compression (N30 to N50 horizontal $\sigma 3$ axis), (ii) Upper Tortonian–Messinian N45 extension ($\sigma 1$ vertical). The history of the Middle Atlas Upper Miocene shows an opening megasequence which begins with continental sedimentation during the Upper Vallesian-Tortonian period evolving towards marine sedimentation associated to the NW-SE Atlantic transgression during the Upper Tortonian.

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