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To obtain

ACADEMIC MASTER'S DEGREE

Specialty

Geology of sedimentary basins

by Rania BENAMARA

BIOCHRONOLOGICAL AND PALEOMAGNETIC STUDIES OF THE LATE MIOCENE CONTINENTAL SECTION FROM EL EULMA BASIN (SETIF, NORTHEASTERN ALGERIA)

Defended on 30 June 2025

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Dedication

To the little girl I used to be, you have made it this far. You always believed that obstacles would be defeated; you were always a believer, a dreamer. You are an alchemist.

I can't believe that I'm finally writing this part of my Master's thesis. I was always making excuses to avoid it because I thought it would make me emotional, and it did.

To every person who thinks that it's too late, there's no "the right time ", do it sick, do it tired, do it crying, do it when you are at your lowest but never give up, this was the description of my years at university, and I would have never made it without standing for myself.

Thanks to geology for giving me such beautiful friends, thank you for making it easier, funnier, and warmer. I love you guys.

Thanks to God for giving me the chance to study such a beautiful field, and for giving me the strength and patience to make it till the end.

It's always go big or go home.

Biochronological and Paleomagnetic studies of the Late Miocene continental section From El Eulma Basin (Setif, Northeastern Algeria)

Abstract

This study presents a combined biochronological and paleomagnetic analysis of Miocene continental deposits in the El Eulma Basin of northeastern Algeria. The primary goal is to establish a chronological framework and improve our understanding of the region's environmental evolution during the Upper Miocene phase.

Due to their rapid evolution and susceptibility to environmental changes, micromammal assemblages have been used as biochronological markers to determine the age of sedimentary layers relative to one another. Paleomagnetic research was conducted to identify magnetic polarity reversals in the sedimentary record and link them to the Earth's magnetic polarity.

By using a combination of biostratigraphic and magnetostratigraphic data, we were able to more accurately date the series and reveal major changes in fauna and the environment. This method revealed major faunal and environmental changes. These findings shed new light on Neogene continental dynamics in North Africa and help refine regional and interregional stratigraphic connections.

Keywords: micromammals, paleomagnetism, biostratigraphy,paleoenvironment, Miocene, El Eulma Basin, East of Algeria.

Études biostratigraphiques et paléomagnétiques de la section continentale du Miocène supérieur du bassin d'El Eulma (Sétif, nord-est de l'Algérie).

Résumé :

Cette étude présente une analyse combinée biostratigraphique et paléomagnétique des dépôts des bassins continentaux du Miocène dans le bassin d'El Eulma. L'objectif principal est d'établir un cadre chronologique et d'améliorer notre compréhension de l'évolution environnementale de la région durant la phase du Miocène supérieur.

En raison de leur évolution rapide et de leur sensibilité aux changements environnementaux, les assemblages de micromammifères ont été utilisés comme marqueurs biochronologiques pour déterminer l'âge des couches sédimentaires les unes par rapport aux autres. Des recherches paléomagnétiques ont été menées afin d'identifier les inversions de polarité magnétique dans les archives sédimentaires et de les relier à la polarité magnétique de la Terre.

En combinant des données biostratigraphiques et magnétostratigraphiques, nous avons pu dater plus précisément la série et révéler des changements majeurs dans la faune et l'environnement. Cette méthode a permis de mettre en évidence des changements faunistiques et environnementaux majeurs. Ces résultats apportent un nouvel éclairage sur la dynamique continentale du Néogène en Afrique du Nord et contribuent à affiner les liens stratigraphiques régionaux et interrégionaux.

Mots-clés : micromammifères, paléomagnétisme, biostratigraphie,paléoenvironement, Miocène, bassin d'El Eulma, est de l'Algérie.

دراسات بيولوجية زمنية ومغناطيسية قديمة للجزء القاري من العصر الميوسيني المتأخر في حوض (سطيف، شمال شرق الجزائر)العلمة

ملخص

تقدم هذه الدراسة تحليلاً بيولوجياً زمنياً ومغناطيسياً قديماً للرواسب القارية من العصر الميوسيني في حوض العلمة شمال شرق الجزائر.لهدف الأساسي هو إنشاء إطار زمني وتحسين فهمنا لتطور البيئة في المنطقة خلال مرحلة العصر الميوسيني المتأخر.

نظرًا لتطورها السريع وقابليتها للتأثر بالتغيرات البيئية، تم استخدام تجمعات الثدييات الصغيرة كعلامات بيولوجية زمنية تم إجراء بحث مغناطيسي قديم لتحديد انعكاسات القطبية .لتحديد عمر الطبقات الرسوبية بالنسبة لبعضها البعض المغناطيسية في السجل الرسوبي وربطها بالقطبية المغناطيسية للأرض.

باستخدام مزيج من البيانات البيولوجية والطباقية المغناطيسية، تمكنا من تحديد عمر السلسلة بشكل أكثر دقة وكشف تلقي هذه النتائج .كشفت هذه الطريقة عن تغيرات كبيرة في الحيوانات والبيئة .التغيرات الرئيسية في الحيوانات والبيئة ضوءًا جديدًا على ديناميكيات القارة في شمال إفريقيا خلال العصر الجيولوجي النيوجيني وتساعد في تحسين الروابط الطبقية الإقليمية والأقاليمية.

، شرق العلمة الثدييات الصغيرة، المغناطيسية القديمة، الطبقات الحيوية، العصر الميوسيني، حوض :الكلمات المفتاحية الجزائر.

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INTRODUCTION

Micromammals, which include small mammals such as rodents, shrews and certain species of bat, constitute a vital component of biochronology in continental deposits due to their capacity for rapid evolution, diverse ecological adaptations, and comprehensive fossil records. Their small size and high reproductive rates facilitate a dynamic process of speciation, enabling distinct species to develop within relatively brief geological periods. Consequently, micromammals act as reliable biostratigraphic indicators, helping to identify stratigraphic zones through characteristic species assemblages that can be correlated across different geographical areas. This correlation is vital for creating a precise chronological framework, as different micromammal species can offer insight into particular periods, especially during the Neogene and Quaternary epochs.

Additionally, the presence and variety of these small mammals reflect historical environmental conditions and climatic changes, offering insights into the past ecology of an area and helping us to understand how habitats have changed over time. Examining micromammal fossils in continental sedimentary environments, such as riverbeds, lakes and caves, enables researchers to deduce the chronological layering of these deposits, as well as to reconstruct paleoenvironments and biogeographic trends. This makes micromammals crucial for both stratigraphic and ecological research. Therefore, studying micromammal assemblages improves our understanding of ancient ecosystems, how they react to climate fluctuations, and the interactions between biodiversity, habitat, and extinction events throughout Earth's history.

Our study aims to establish a precise and reliable biochronological framework for the Miocene continental deposits from the El Eulma Basin using the small mammal dental remains that have been collected. This research objective cannot be achieved without combining it with a paleomagnetic study. Micromammal assemblages serve as biochronological markers, while magnetostratigraphy enables the correlation of sedimentary sequences with the geomagnetic polarity timescale. Together, these methods will allow us to date the Amama 1 and 2 fossil sites, as well as determine sedimentation rates and hiatuses in the depositional record.

During this Master's degree research project, we washed and sieved approximately 50 kg of sediments to extract micromammal remains. Additionally, we interpreted the results of the paleomagnetic analyses of 28 samples to identify the ferromagnetic minerals responsible of magnetization. This material was stored in laboratory No. 25 and was collected during field missions (2011, 2012, and 2016).

The integration of these data improves our understanding of the temporal and environmental dynamics of El Eulma Basin in the Miocene epoch, with the regional chronostratigraphic framework being enhanced and insights being provided into the area's paleoecological conditions.

Chapter I: Geological and Stratigraphic Context

1 Presentation of El Eulma Basin

In the East of Setif and to the North of El Eulma town (formerly Saint Arnaud), the regressive erosion of the Deheb wadi and its tributaries has undermined the Quaternary limestone shells which generally cover the high plains of Constantine, thus revealing a small Miocene continental basin preserved in a basin surrounded by the allochthonous formations of the Setifian Tell (Guiraud, 1973).

El Eulma Basin lies on the southern edge of the eastern Algerian Tell. It is a post-nappe basin of the Upper Miocene age, preserved in a basin and surrounded to the North, East, and West by allochthonous Tellian units (Djamila nappe) (Guiraud, 1973), while to the South it extends over the high plains of the Setif (Figure 1a). It is a basin that is well differentiated by the deposits of a thick series whose age ranges from the Lower Miocene to the Upper Pliocene (Guiraud, 1973; Jaeger, 1977; Ameur Chehbeur, 1988; Mahboubi, 2014; Mahboubi and Benammi, 2021).

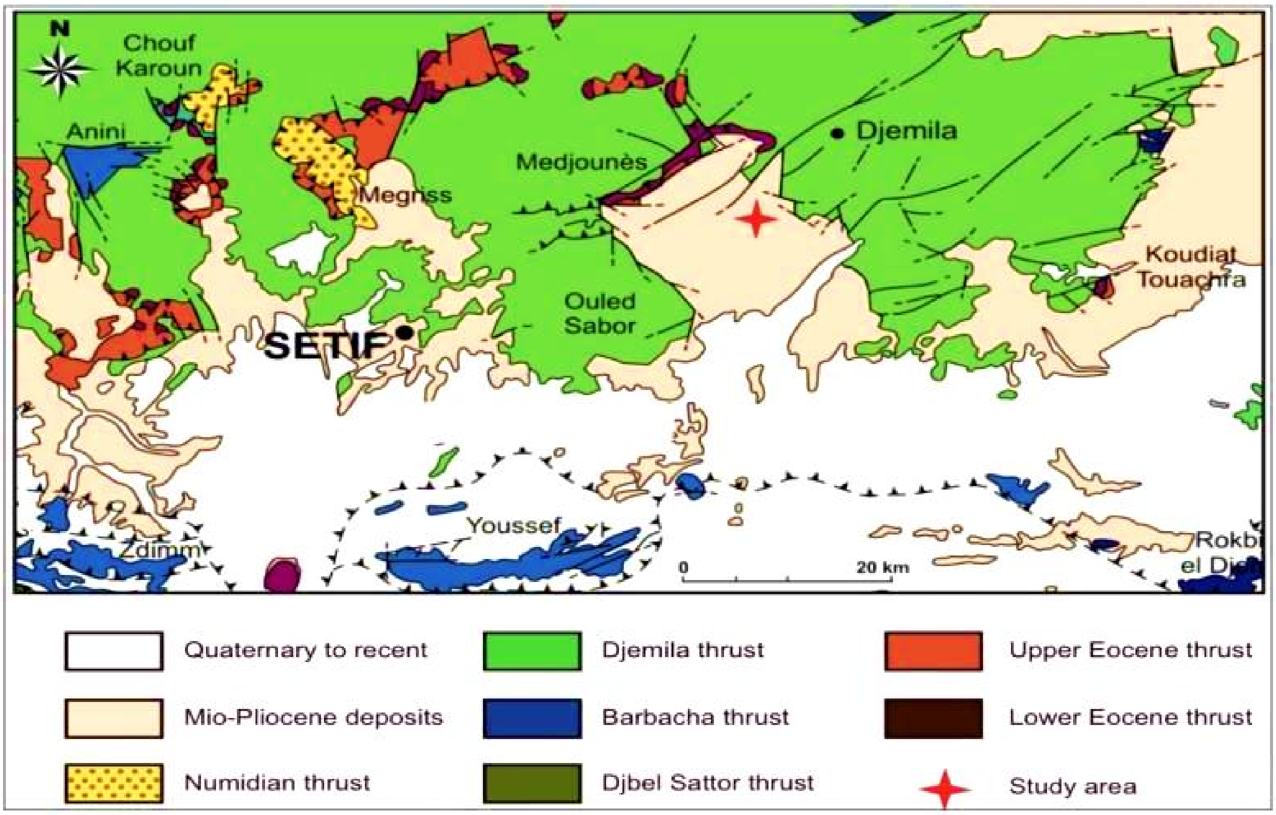

Fig. 1.- Geologic structural map of El Eulma (location of the studied area, modified from Vila,1980).

1.1 Location and geographical framework

El Eulma Basin is part of the Tell Atlas Mountain range in northeastern Algeria. It is characterized by its sedimentary deposits, which provide valuable information about the geological history of the region. The area's complex tectonics has an impact on the El Eulma basin. This is where the African and Eurasian plates meet, at the intersection of many tectonic plates. This interaction has changed the formation through faulting, folding, and uplift. The basin's hydrology and geology may be significantly impacted by seismic activity resulting from the general tectonic regime (Guiraud, 1973). El Eulma basin is located in eastern Algeria, belongs to the High Constantinian Plateaus and covers an area of 1,598 km² (Figure 1b).

Fig 1.- Location of the studied area

1.2 Tectonic and geodynamic context

The present geological structure of the Western Mediterranean region is the result of the interaction between two primary tectonic plates. Since the Late Cretaceous, the Iberian microplate and the African and European plates have been merging. This convergence has created numerous orogenic systems, such as the Maghrebian (Rif-Tell) mountains along the northern edge of the African plate and the Betic Cordillera bordering the southern edge of the

Iberian microplate (Jolivet et al., 2021). Moreover, the Western Mediterranean region is the result of the interplay between two primary tectonic units: the Atlas system and the Tell. The Flysch and the Internal Zone Domain are the other two primary tectonic units that make up the region north of Algeria. These units are divided by significant thrusts. The Tell system forms a straight east-west mountain belt and is the western extension of the Moroccan Rif. It consists of a significant accumulation of allochthonous strata known as the Tellian nappes or thrusts. These include deposits ranging from the Upper Cretaceous to the Lower Miocene and originate from the African border of the Maghrebian Tethys. (Benaouali-Mebarek et al., 2006). A series of intramontane basins with continental sedimentary infilling were created along the Tell, which extends from eastern Algeria to Tunisia, as a result of tectonic activity during the Neogene-Quaternary period. These basins are mostly continuous from east of Setif to Constantine. However, the authors have divided them into one or more basins (Melki et al., 2011).

The city of El Eulma and the town of Guelta Zerga are located towards the southeastern opening of the sub-basin and are situated between 950 and 1,000 meters above sea level. The Oued Boucherit region is situated in the El Eulma Basin, around 6 kilometers north of El Eulma and 20 kilometers east of Setif. Along the Oued Boucherit is a small, sporadic tributary of the Oued El Laatach that exposes Plio-Pleistocene sedimentary rock outcrops. This region is known to have yielded prehistoric tools from the earliest human occupation in North Africa (Sahnouni et al., 2018; Duval et al., 2021).

El Eulma Neogene Basin contains a thick, continuous series of continental formations that range in age from the Lower Miocene to the Upper Pliocene. The Neogene series begins with large red detrital deposits that are unconformably layered by Upper Cretaceous or Eocene rocks. These formations consist of alternating layers of gray to pinkish sandy marl and gypsum with irregular conglomeratic layers. Most of the formation comprises black, clayey marls that contain many gastropods. The series ends with alternating layers of white travertine limestones, black marls, and small gypsum beds. These are topped by black-to-bluish-gray gastropod marls that show small, lenticular interlayers of coarse sandstones containing vertebrate debris. The sediments then become coarser and are brown to reddish (Guiraud, 1973).

At the Koudiat El Amama area, sixty meters of gypsum beds are separated by gray clay interbeds. These gypsum beds seem to be connected laterally to lacustrine limestone and black marl. The gray clays are rich in Unionidae and contain a few sandstone layers in lenses of varying sizes. The brittle gray clays, on the other hand, contain more helicid remains. The observable thickness of this layer is about 80 meters. Reddish silts overlie the previous formations are slightly discordant and represent the base of the Miocene-Pliocene formations of the El Eulma Neogene basin.

At the top, the series becomes variable with lenticular layers of coarse puddings, friable lignite-lined clays, and gypsiferous sandstone beds containing small limestone beds. The thickness ranges from 150 to 200 meters. The series ends with fluvial-lacustrine deposits of varying composition (Figure 2). The oldest deposits of the basin would be visible on the septentrional side and could be Cretaceous or Oligocene age. The Neogene of the El Eulma basin consists of the following terms:

1) At the base, of destructive red deposits resting in discordance over Cretaceous and Eocene deposits of the Tellian units.

2) Grey to red sands (with sparse detritus) have developed over several hundred meters.
3) In the Koudiat el Amama area, there are hundreds of meters of gypsum banks separated by gray clays. This gypsy past appears to be related to lacustrine limestones and black clays.

4)The grey clays have a high concentration of Unionidae bivalves, while the encasing gray clays mostly include Helicidae gastropods. The visual thickness of this level is around 80 meters.
5) The previous formations, limons, are the base of El Eulma's Pliocene formations.

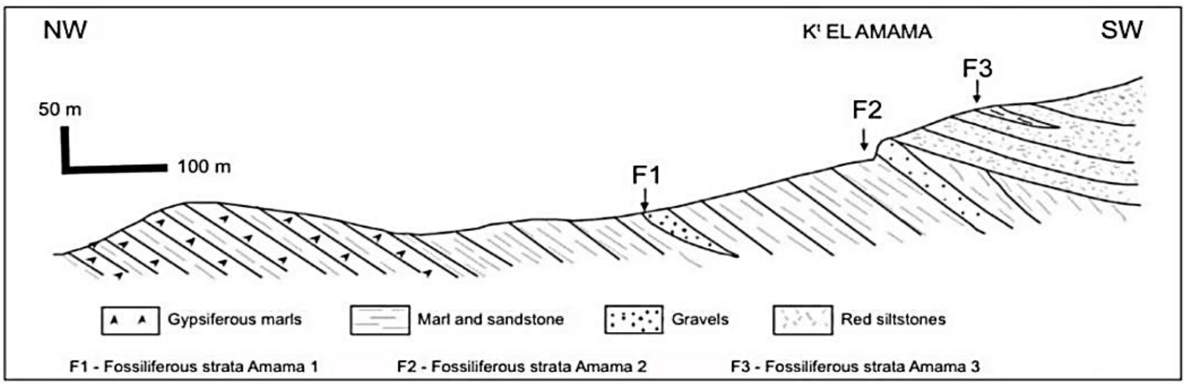

Fig. 2: A cross-section of the Mio-Pliocene deposits showing the location of the main fossiliferous strata (Jaeger, 1977).

2 Lithostratigraphical study

2.1 Description of the studied area

The Neogene deposits of the El Eulma Basin (figure 3) (Guiraud, 1973) are composed of a series of lithostratigraphic assemblages that are easy to follow laterally over long distances. According to field observations, a compressive tectonic episode occurred during the Late Miocene. The compression phase of the Burdigalian is characterized by shortening in a north-south direction (Coiffait, 1992). Based on the previous field studies (Guiraud, 1973; Jaeger, 1977; Ameur-Chehbeur, 1988; Mahboubi and Benammi, 2021), three fossil sites have allowed us to distinguish two formations: The Miocene formation is overlain by another Pliocene formation. The two are separated by an angular unconformity. The focus of this work is specifically on the Miocene formation.

Fig. 3 - Panoramic view of part of the study area.

2.2 Description of the lithological section

During our mission (28th April, 2025), we chose a section-oriented NW-SE. This section was described first by (Guiraud, 1973; Jaeger, 1975; Ameur-Chehbeur, 1988; Mahboubi and Benammi, 2022). This section presents two cineritic levels which one of which was dated at 7.7 Ma ± 0.7 Ma (Coiffait, 1991). The Miocene formation contains two fossiliferous beds (Amama 1, Amama 2). 240 m thick, exhibits lithological facies changes, and has a significant sedimentary discontinuity that is manifested by an angular discordance, allowing two formations to be distinguished from bottom to top, as mentioned earlier.

This Upper Miocene formation consists of alternating gray marls (20m) interspersed with lacustrine limestone and gypsum, as well as large packets of black gastropod marl. Three cinerite levels, the first level appears two black marl formations combined with clay (black and green) are present: the first level occupies the base of the formation and is 0.4 m thick; the other two levels appear towards the base of the last third of the formation and are 4 m and 0.8 m thick, respectively. The sandstone (10m) (yellow) levels are characterized by oblique stratification and contain pass channels, and it's formed as benches occupied by microconglomerates with vertebrate remains. This formation's depositional environment is characteristic of fluvial-type sedimentation (Figure 4).

Preliminary analysis of clays or microconglomerates in this formation revealed the presence of small mammal remains with a similar composition to the two sites (Amama 1 and Amama 2) described by previous authors (Jaeger, 1977a; Ameur-Chehbeur, 1988; Coiffait, 1991) have suggested the Upper Miocene age for this locality.

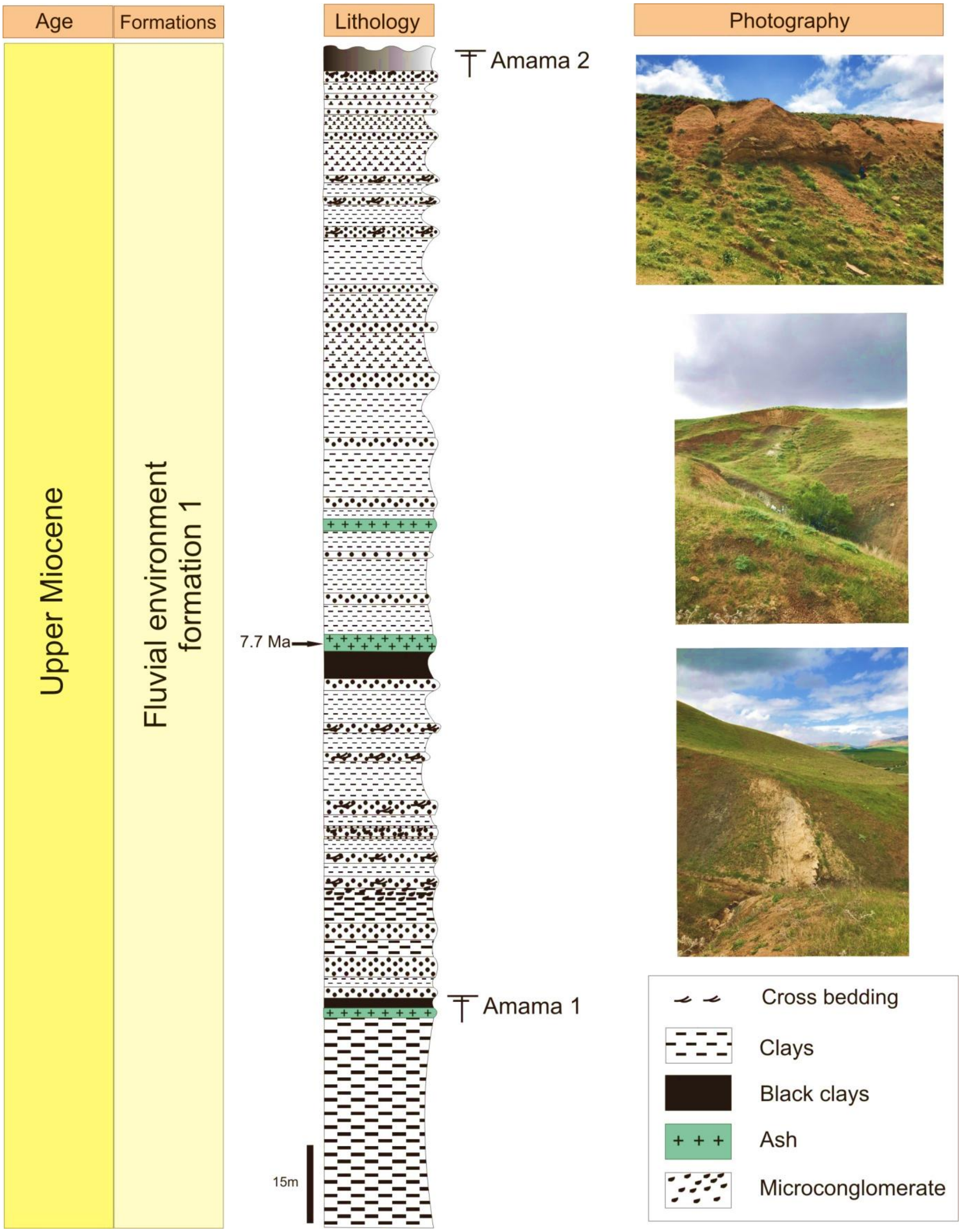

Fig. 4- Lithostratigraphic column of the continental deposits of the Miocene epoch of El Eulma Basin.

Chapter II: Biochronological study

1 The continental Miocene of North Africa: Biochronology

Small mammal fossils are a crucial tool for establishing a biochronological scale for continental deposits due to their fast evolution, abundance, and ease of collection. The development of a mammalian-based scale. However, there are other challenges, including rare ideal conditions for the preservation of their remains and inconsistent fossil records. Gisements are often isolated locations with no clear geographical relationship or separated by sterile deposits. In contrast to marine deposits, establishing boundaries between separate biostratigraphic units can be challenging (Raynal et al, 1990).

Miocene taxa in Northern Africa differ from those from Europe, making European biochronological scales unsuitable. Jaeger et al. (1977) conducted a biochronological survey of Northern Africa. The authors propose a biochronology of the Upper Miocene in Southern Europe and Northern Africa, as well as correlations with marine stratigraphy. They categorize the various faunas of the Upper Miocene of Northern Africa into three major groups:

1-The Mellalian: characterized by a fauna distinguished by the presence of Myocricetodontinae and the type species *Myocricetodon parvus*.

2-The Vallesian: characterized by the simultaneous presence of the Cricetidae*:* *Zramys*, of Muridae, *Progonomys cathalai*.

3-The Turolian: characterized by an association of faunas more evolved than those contained in the previous faunas.

Coiffait (1991) identified six zones for the Middle and Upper Miocene period. These zones are based on “guide fossils” (characteristic rodent species) (Figure 5). First appearances (FAD) and extinctions (LAD) are reported, rather than using letters or numbers to name these zones.

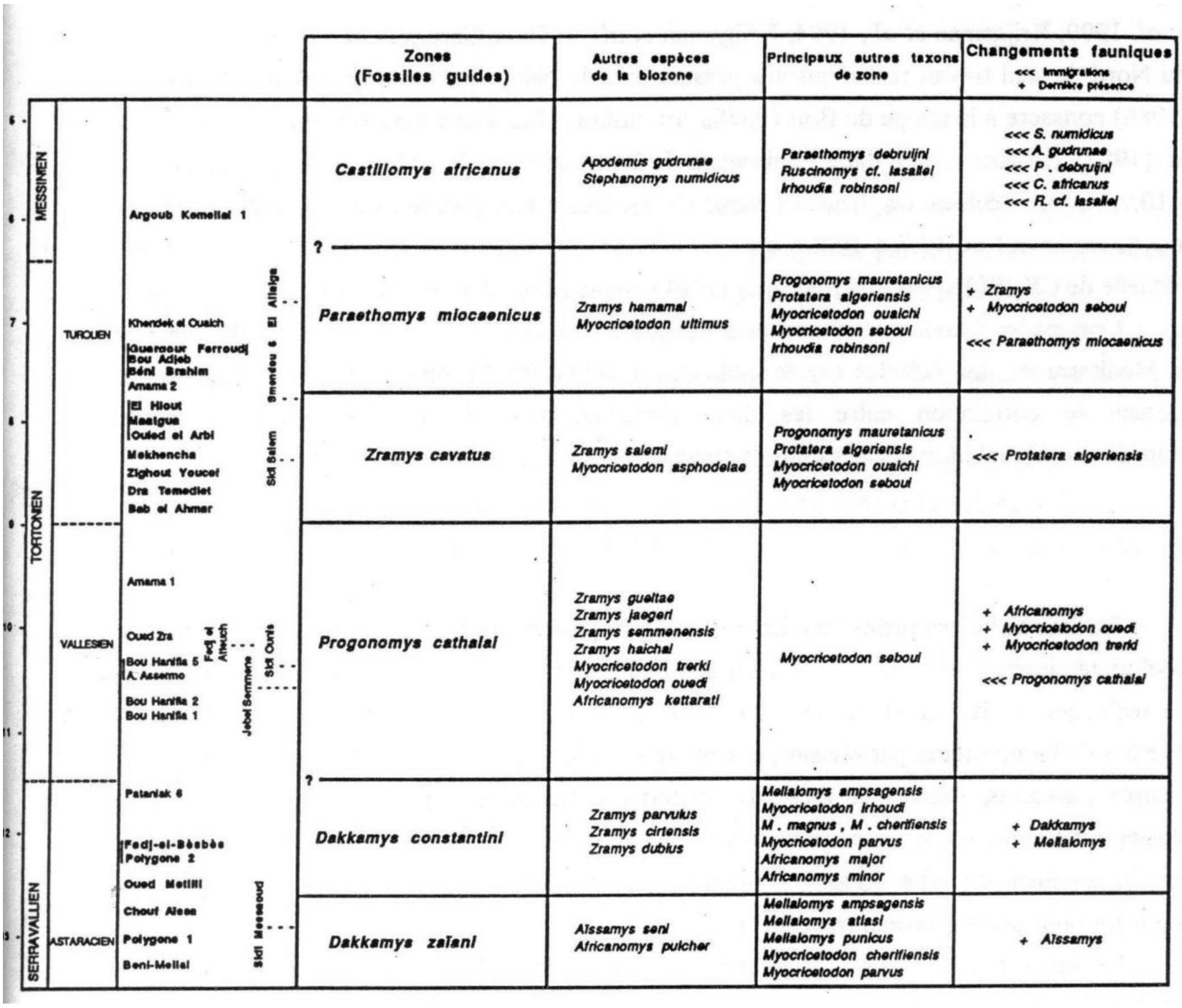

Fig. 5 -Biozonation of the Middle and Upper Miocene of North Africa (according to Coiffait, 1991).

2 Sampling and Analytical Methods of the micromammals

2.1 The use of the micromammal remains

Micromammals offer many advantages for the study of various problems, particularly those relating to the biochronology of continental deposits. The remains of the most abundant micromammals (jaw, long bone, isolated teeth) are small in size and often numerous in fossiliferous deposits. Rodent species are closely dependent on a specific type of plant cover, soil type and climate. This close dependence on the various environments they inhabit makes them, along with pollens, good indicators of the paleoenvironment and its modifications, but the changes observed in the composition of rodent faunas and that of large mammals cannot be interpreted without reference to climatic variations.

Indeed, one of the difficulties inherent in interpretation is linked to the mode of concentration of fossil rodents, due to the type of deposit, the gustatory choice of a predator, sorting. In most cases, it is small predators whose food waste, such as the regurgitation pellets of birds of prey or the faces of small carnivores, are responsible for the initial accumulation.

In flood plain-type sedimentary basins, floodwaters can wash away, dissociate and deconcentrate these remains in channel bottoms. Fossil rodents are widely distributed, with some species exceptionally spanning one or two continents. Their highly diverse deposits in continental environments (caves, fissures, continental, lacustrine, fluvial and brackish deposits) can even be found in littoral marine formations.

Because of their small size and low abundance in fluvio-lacustrine sediments, the techniques required to study fossil microvertebrates differ from those used to work with larger remains. In particular, the study of micromammal fossils is relatively new in paleontology, although rodent remains have been studied since the 19th century. These early attempts were mainly concerned with karstic fissure fills, where there may be a large concentration of fossils, sometimes mixing remains from a wide range of time periods, or as chance finds in periodic excavations. The study of fluvio-lacustrine localities implies the processing of large volumes of sediment, preferably in a short period of time. Although wet sieving techniques had been used before, the development of new methods in the 1960s allowed the discipline to progress (Daams and Freudenthal 1988). The techniques used to assemble and study the collections can be divided into three groups: field techniques, laboratory techniques, and office techniques.

2.2 Methodology

Field techniques:

Direct observation of micromammal fossils in the field is rare due to their small size and low abundance and infrequent occurrence, although vertebrate bone fragments may be found in some strata. layers. For this reason, micromammal paleontologists use indirect evidence that a particular level may yield fossil remains, such as dark coloration from organic matter and the presence of snail fossils. However, promising levels may be completely sterile, while others without snails or with a clearer coloration may be rich localities. To avoid wasting time and effort on sterile or poor levels, a sample of two or three bags of 15-20 kg each is taken. If the sample shows an acceptable fossil richness, which may vary according to the researcher's expectations, then a larger sample is taken for study.

3 Laboratory techniques

This set of techniques is used to reduce the volume of the specimen as much as possible before examining it under a binocular microscope. Ideally, only the fossils would remain, but in some cases, this requires expensive methods, such as the use of heavy liquids to eliminate quartz remnants. Therefore, we use techniques that enable us to reduce the initial concentrate to an acceptable volume.

Typically, the initial concentrate obtained in the field contains residual clays, which are removed during a second wash in the laboratory. To this end, the sample is usually washed in a sieve with a mesh size of 0.5 mm. However, each wash carries a greater risk of breaking the fossils as they are pressed against the sieve. Therefore, low water pressure is preferred when a second wash is necessary (Figure 6).

- **Sieving:**

Two sets of test sieves will be available in well-equipped laboratories: one for wet sieving with liquid assistance and one for dry sieving without liquid assistance (Figure 7). The most frequently used sieves have a diameter of 8 mm and are made of either stainless steel or brass. There are also 0.8 mm sieves, which are used in micropalaeontological processing methods. Stainless steel sieves are better suited to wet sifting, whereas brass sieves are better suited to dry screening if solutions are likely to damage the delicate brass sieve mesh. It is imperative that every sieve fits into every other sieve. Ensure that all sieves in a series ('nest') are of the same make and diameter. Note that metric diameter sieves (mm) will fit into imperial diameter sieves (inches), but will move laterally by around 5 mm. To use dry sieving, a receiver (pan) and cover must fit onto the top and bottom of the nest, respectively. The mesh of each sieve is typically made of mild steel for sieves with an aperture size larger than 1 mm, brass for sieves with an aperture size between 250 μm and 1 mm and phosphor bronze for sieves with an aperture size smaller than 250 μm. The 'cloth' or mesh is made of wire with a circular cross-section that is braided to create a square hole. Solder is used to join the mesh to the frame.

- **Sorting:**

The goal of sorting is to carefully inspect and classify the collected remains from the sieving procedure.

• Specimen Identification: To identify the bones and teeth of micromammals, researchers meticulously sort through the remnants under a microscope. For precise species identification, this calls for experience and may require comparison with reference collections.

• Quantification: Following identification, the remains are typically tallied or arranged according to size or species, which enables researchers to compile information on the demographic makeup, variety, and abundance of micromammal populations.

Recovering and examining small mammal remains from sediment samples requires the use of washing, sieving, and sorting techniques in micromammal studies (Figure 8). The evolutionary history of micromammals, community dynamics, and historical environmental conditions are all clarified by these activities. Researchers in paleontology, archaeology, and allied disciplines must become proficient in these methods in order to make a substantial contribution to our understanding of ancient ecosystems and species interactions.

- **Fractionation**

Separation of the final concentrate into fractions of different grain size facilitates the hand facilitates hand picking of fossils. Untreated concentrates in which no fractionation has taken place are much more difficult to work with and many fossils, especially the smaller ones, may go unnoticed to distinguish between different grain sizes, we used set of sieves with different mesh sizes, ranging from 2.0 to 0.5 mm. Fractionation of the the final concentrate through all the sieves in this range, starting with the largest mesh size and then then in decreasing order, produces seven concentrates (2.0 - 1.5 - 1.25 - 1.0 - 0.75 - 0.63 - 0.5) with a homogeneous particle size within each category.

- **Handpicking**

Once the volume of the sample has been reduced by field and laboratory techniques and separated into several fractions, it is time to pick out the fossils. The larger remains, those larger than 2.0 mm, can be picked out directly with the naked eye. Smaller remains, however, must be picked out under a binocular, using the appropriate magnification for each grain size. I have separated complete bones, osteoderms, and dental elements of mammals, fish, reptiles, ostracods, charophytes, not picking out very fragmented or unidentifiable remains.

- **Photography:**

All teeth and the collected fossils were photographed using an electronic balance microscope (Figure 9), with different zoom levels depending on the size of the tooth (at laboratory 25).

Fig. 6- The washing method.

Fig. 7- The sieving method.

Fig. 8- The sorting method.

Fig. 9- The binocular stereomicroscope Euromex.

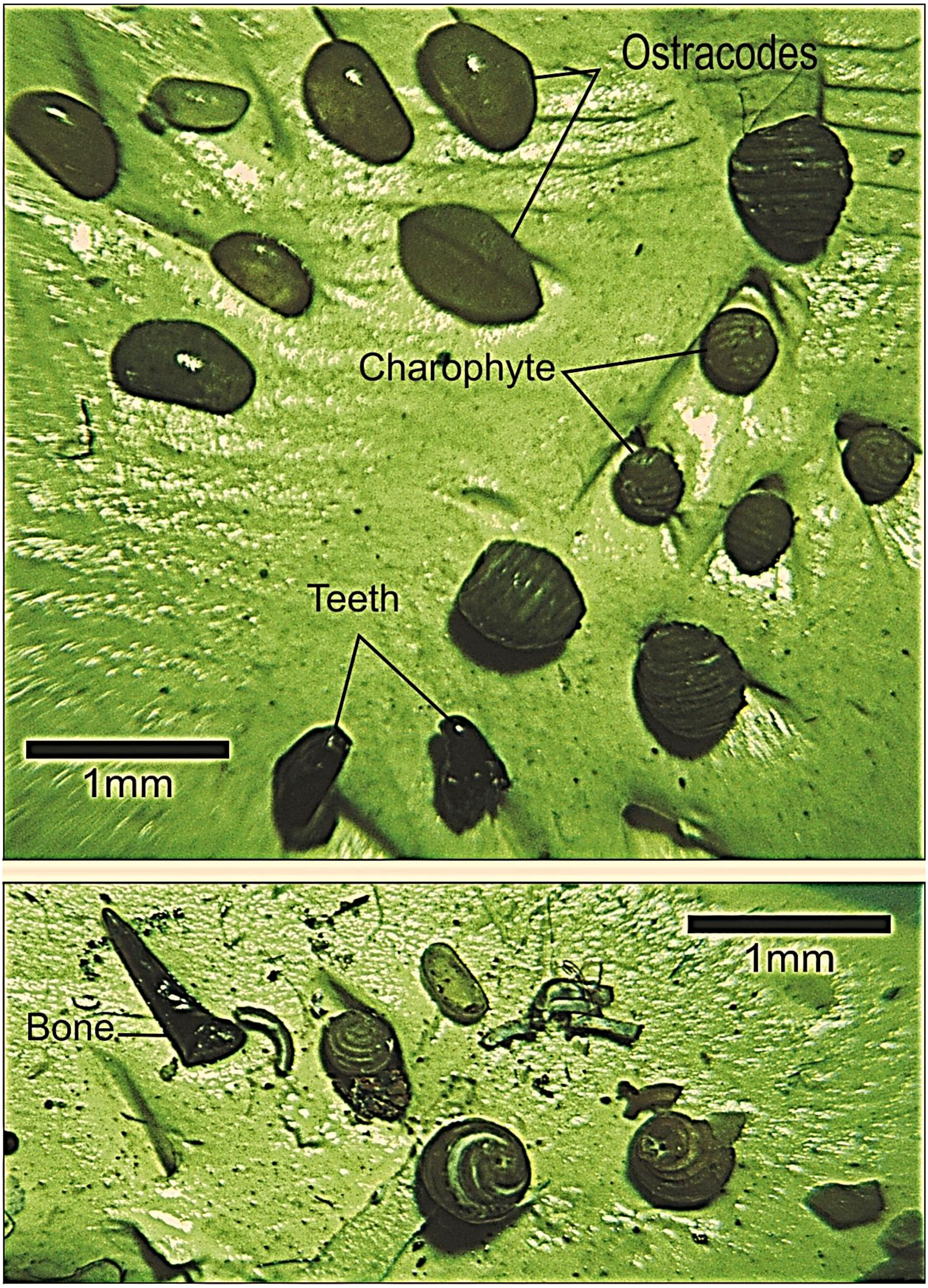

Fig. 10- Photographs of some Charophyte (Gyrogonites), ostracods, and fish teeth collected from the studied section.

4 Biochronological data:

Jaeger (1977) was the first author to attract paleontologists' attention to the continental deposits of El Eulma basin while researching the small mammal fauna in three fossiliferous localities: Amama 1, Amama 2, and Amama 3. After that, more research was done to learn more about the rodent fauna in this basin using radiometric dating, which allowed for the establishment of a correlation between the several North African continental basins (Ameur-Chehbeur, 1988; Mahboubi and Benammi, 2022). The Late Miocene to the Upper Pliocene are the ages of the small mammal fauna found in the continental layers of the El Eulma basin. The Miocene formation contains two fossil sites, Amama 1 and Amama 2. In these deposits, Guiraud (1973) and Jaeger (1977) reported *Hipparion* remains. Ameur-Chehbeur (1988) and Mahboubi (2014) carried out a detailed study of micromammal faunas.

Amama 1: This lowest locality is located approximately 40 meters above the top of the alternation of gypsum marl and limestone. The faunal list collected in this locality in the context of this work and previous work includes: *Schizogalerix* sp. (Erinaceidae), rodent species as: *Atlantoxerus* sp. *Irhoudia* sp., *Progonomys* cf. *cathalai*, and *Zramys* cf. *haichai* (Jaeger, 1977). Ameur Chehbeur conducted another paleontological investigation in 1988, adding two rodent species—*Myocricetodon* cf. *seboui* and *M*. cf. *trerki*—to the earlier faunal list.

Consequently, an age close to the Vallesian–Turolian boundary was permitted by the evolutionary stage of *Zramys* cf. *haichai* from the Amama 1 site (Jaeger et al., 1973).

Amama 2: This deposit is located in a blackish clay layer, which is rich in gastropods, and is found below the sandstone layer containing the bones of *Hipparion sitifense* (Equidae). These sandstones are at the top of the Miocene formation. The following list of small mammals remains has been found in these deposits:

Irhoudia robinsoni; *Schizogalerix* sp. (*Erinaceidae*); the rodents *Atlantoxerus* sp., *Zramys hamamai*; *Protatera algeriensis*; *Myocricetodon* cf. *seboui*; and *Paraethomys* cf. *miocaenicus*. Additionally, another species of gerbillid, *Eulmus miocaenicus*, was reported by Ameur-Chehbeur (1988).

Cricetidae includes three unique forms, while Muridae*,* Ctenodactylidae, and Sciuridae only have one species. On a quantitative level, *Protatera algeriensis* represents the

Gerbillidae and Ctenodactylidae.
Irhoudia robinsoni represents dominance. These proportions reflect the dominance of semi-arid environments in northern Africa, indicating the presence of a relatively open and dry biotope.

The position of this bearing in the biochronological scale, located within the continental formation, is not as clear as Khendek el Ouaich's. Its stratigraphic position is 50 m above the Amama 1 locality.

While only one species represents the Muridae, Ctenodactylidae, and Sciuridae, three different species represent the Cricetidae. Nonetheless, the Ctenodactylidae, represented by *Irhoudia robinsoni*, and the Gerbillidae, represented by *Protatera algeriensis*, are primarily dominant in terms of numbers. These ratios demonstrate the predominance of semi-arid environment-specific morphologies in North Africa, indicating the presence of a comparatively open and dry climate. The study of *Zramys hamamai* evolutionary degrees, which is thought to be the direct descendant of *Z. salemi* from the Lower Turolian of Sidi Salem location (Algeria), provides more accurate biochronological data. *M. ouaichi* and *P. miocaenicus* from the Khendek el Ouaich site (Morocco) (Jaeger, 1977) can be compared to *Myocricetodon* cf. *seboui* and *Paraethomys* cf. *miocaenicus*, respectively.

Compared to those outlined by Jaeger (1977) from Khendek el Ouaich, the evolutionary phases of both species from the Amama 2 site are more primitive. These data suggest that the Amama 2 locality belongs to an age that is between that of the Khendek el Ouaich deposits, which are dated to the Upper Miocene, and the Lower Turolian deposits of Sidi Salem (Algeria).

Chapter III: Paleomagnetic study

1 Determination of the paleomagnetic signal

1.1 Sampling

Samples were collected using a core drill mounted on a combustion engine driving a 2.5 cm diameter diamond drill bit, lubricated with water (Figure 11). After coring, the samples still in place were marked in the local geographic coordinate system. The generator of the meridian plane of the core was marked, and its direction and inclination were measured using a compass. Where possible, the direction of the sun and the exact time were noted to verify that no magnetic interference affected the compass measurement and to correct the azimuth of the current magnetic field declination. After orientation, the core was marked with the identified generator. The accuracy of the measurements is approximately 2°.

The number of samples collected and analyzed varies greatly from one site to another. This variability in sampling “density” is the result of two factors:

• The size of the sites determines the number of samples collected; as a general rule, the samples are spaced 20 to 40 cm apart on average;

• Sites that provided a significant proportion of samples with unstable natural remanent magnetization at high temperatures were resampled to increase the number of usable samples and give sufficient statistical weight to the interpretations.

Fig.11- Sampling method using a core driller.

2 Magnetostratigraphy

The Magnetostratigraphy is the study of the magnetic memory of rocks and how it changes over time. During the deposition of sediments or the cooling of volcanic rock, magnetic minerals acquire the characteristics of the surrounding geomagnetic field. By analyzing these rocks, the original signal can be recovered. These rocks are unique witnesses to the geomagnetic field and polarity of the Earth's dynamo at a given moment in its history. Over geological time, the Earth's magnetic field (Figure 12) has undergone a succession of normal and reverse polarities of varying duration (Gradstein, et al., 2004).

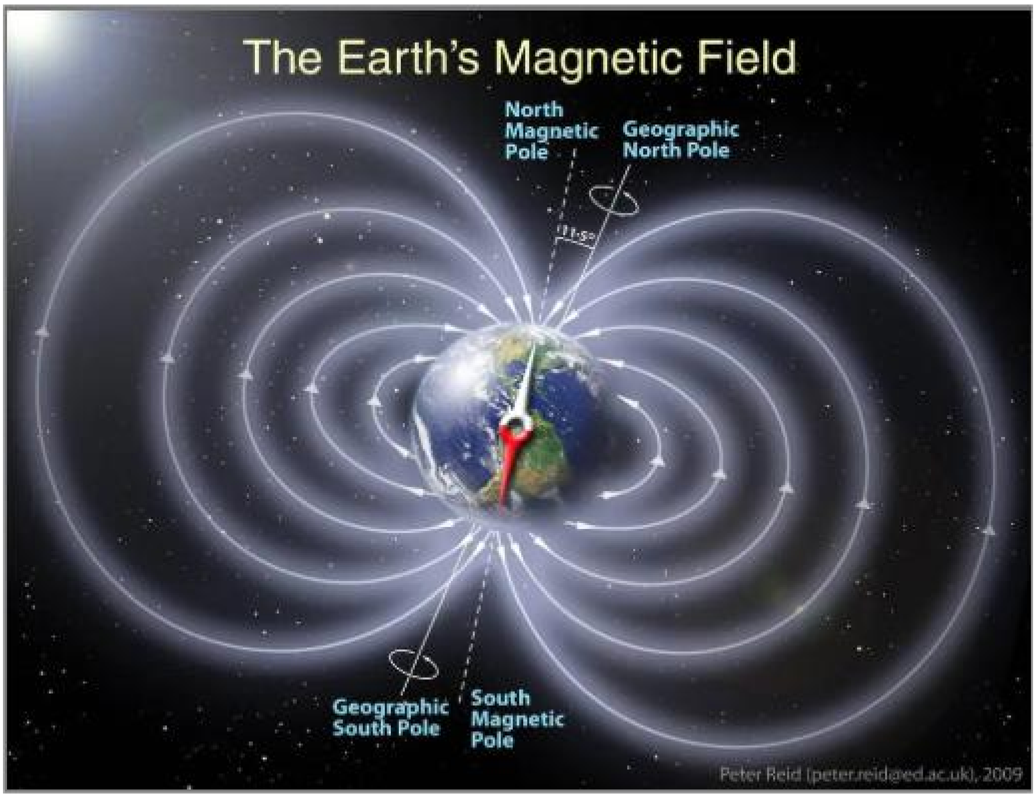

Fig. 12- Earth's Magnetic field, NASA.

This succession serves as the basis for the scale of geomagnetic reversals. Geological or biological phenomena serve as the basis for the chronology. The magnetic stratigraphy of a section must be determined as precisely as possible to compare it with the scale of geomagnetic inversions, in order for this method to be utilized as a stratigraphic tool. The specifics of the section under examination (such as sediment magnetization, sedimentation rate, thickness, and chronological data), as well as the period the section covers, determine how successful a magnetostratigraphic study is. The magnetostratigraphy of all sedimentary sequences, from the ocean floor to land masses, can now be studied thanks to this method, which has many uses. Continental deposits are also discontinuous; formations, especially those laid down in fluvial formations, frequently exhibit gaps in sedimentation. Consequently, in this type of continental deposit, the paleomagnetic record is less constant than that of the seabed, making continental deposits less suitable for this type of study. Similarly, sedimentation rates are variable and difficult to estimate. For example, the same thickness of sediment taken from two different continental basins rarely represents the same time interval, and sedimentation rates depend on many factors that are difficult to assess. Sedimentary rocks are often characterized by low magnetization, and the quality of the paleomagnetic signal is less reliable than that of volcanic rocks. Magnetostratigraphy is an invaluable tool for solving chronological problems, as it can be used to calibrate independent biostratigraphic series, such as marine and continental faunas and flora. However, a calibration is necessary to interpret the magnetic signal. Most magnetostratigraphic studies are accompanied by a biostratigraphic zonation study. The accuracy of this zonation depends on the biological species found and the sedimentary environment (Gradstein, et al., 2004).

2.1 What is paleomagnetism?

Paleomagnetism, a compound of the Greek palaeos “ancient” and ‘magnetism’, literally meaning “ancient magnetism”, is the name of an Earth Sciences discipline that studies the Earth's magnetic field in the past.

For most of us, the earth's magnetic field is the force that orients the compass needle towards the north pole. But in reality, this magnetic field is not horizontal, contrary to what the compass may lead us to believe. If we suspend the needle so that it can also rotate around a horizontal axis, we see that it tilts more or less downwards in the northern hemisphere, and upwards in the southern hemisphere. The angle between the horizontal plane and the direction of the needle is the inclination (Figure 13). With various devices, we can measure the intensity and direction of this field, but this has only been achieved with precision over the last few centuries. These quantities are not immutable and vary not only according to location, but also over time. For periods prior to these direct measurements, whether historical, prehistoric or geological, indirect methods are required. The direction and magnitude of the ancient magnetic field are inscribed in terracotta, lava and a number of other rocks, so paleomagnetism aims to extract this information from these materials,

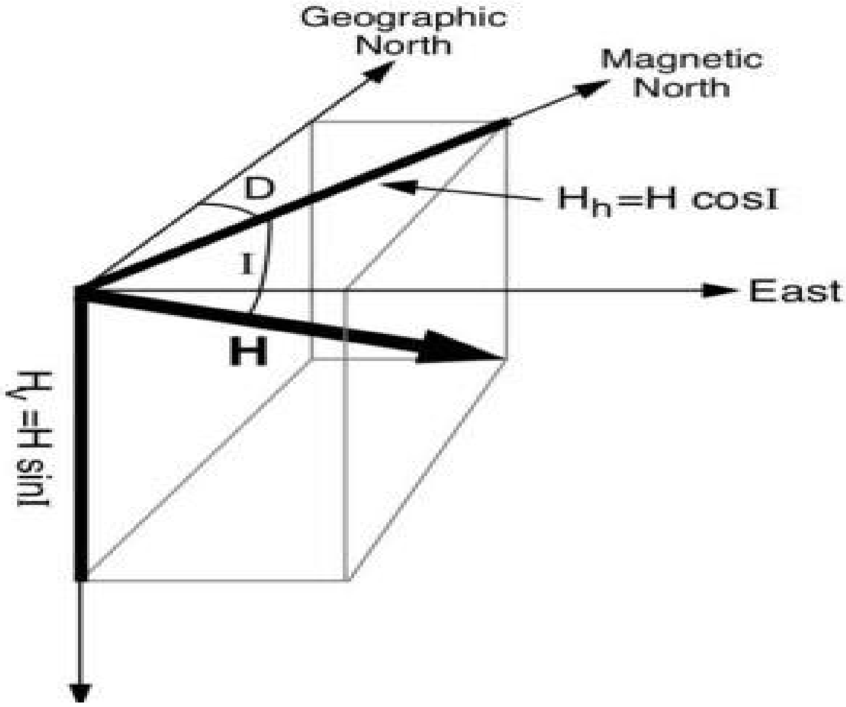

Fig. 13-The total geomagnetic field vector H can be split into a horizontal component Hh and a vertical component Hv, where Hh = HcosI, Hv = HsinI, with I representing inclination (dip), the angle between H and the horizontal. Declination D is azimuth angle between Hh and geographic north (Butler, 2004).

In the presence of certain bodies such as magnetite, magnets or electric currents, the surrounding space loses its isotropic character. A magnetic field reigns, which can be observed by the orientation of grains of iron filings along lines, by the orientation of a compass needle, by the forces exerted on circuits through which an electric current flows. This field is different from the gravitational or electrostatic field.

The magnetic field also modifies the properties of the matter it impregnates. A body subjected to the action of a magnetic field becomes itself a source of magnetic field - it has a magnetization. This magnetization depends essentially on the nature of the body and the ambient magnetic field.

3 Methodology

3.1 Acquisition of remanent magnetization (ARM)

The paleomagnetic method approach assumes that each rock sample preserves a record of the geomagnetic field it was exposed to during formation. To verify the validity of these assumptions and assess the dependability of observed paleomagnetic data. Understanding the recording process is crucial for analyzing data. Sedimentary rocks obtain their fundamental magnetization from the arrangement of detrital grains in the Earth's field. The remanent magnetization of wet sediment can be altered by chemical changes or physical disturbances to the grain alignment. Post-depositional remanent magnetization (PDRM) refers to magnetization caused by the physical movement of magnetic granules. The Controlled tests with synthetic sediments established the mechanism of PDRM. The parameters influencing PDRM in natural sediments are mostly unknown. Testing PDRM ideas requires appropriate conditions (Butler, 2004).

The process by which sedimentary rocks acquire and keep a trace of the Earth's magnetic field during or after creation is known as remanent magnetization. This record, known as natural remanent magnetization (NRM), is critical for paleomagnetism studies because it allows researchers to reconstruct historical tectonic plate placements and geomagnetic field behavior.

Natural remanent magnetization (NRM) is remanent magnetization that has been acquired naturally (not artificially acquired in a laboratory). It is the remanent magnetization of a sample (such as rock or baked archaeological material) that is present before any laboratory experiments are carried out. Magnetization is usually measured normalized to either the sample volume (units of $A\ m^{-1}$) or sample mass (units of $A\ m^2\ kg^{-1}$). NRM can be made up of one or more forms of magnetization, depending on the sample's history. Rock samples that have been exposed to the Earth's magnetic field for millions of years may have undergone numerous separate magnetization processes, resulting in multiple magnetic components. Primary components are those gained during the development of the rock, while secondary components are those acquired afterward (Butler, 1992).

3.2 Lowrie’s method (1990)

Lowrie's method is a laboratory approach for identifying ferromagnetic minerals in rocks using their coercivity (resistance to demagnetization) and thermal stability. It was created by William Lowrie in 1990 and is commonly used in rock magnetism and paleomagnetism to determine the types of magnetic minerals (such as magnetite, hematite, goethite, or maghemite) present in a sample.

The 1990 method by Lowrie is centred on the thorough examination of coercivity and unblocking temperature. Ferromagnetic minerals exhibit distinct responses to applied magnetic fields and elevated temperatures, forming their unique fingerprints. Coercivity measures the strength of the magnetic field required to demagnetize a sample, and different minerals require different field strengths. Magnetite, for instance, has a lower coercivity than hematite. Unblocking temperature, on the other hand, refers to the temperature at which a magnetic component loses its remanent magnetization when heated, indicating its thermal stability, by systematically studying these two properties, the method allows scientists to identify the types of magnetic minerals present, their relative contributions to the rock's overall magnetic signal, and their thermal stability. This differentiation is critical because different minerals carry different paleomagnetic information, and separating them helps isolate the primary magnetic signals from secondary overprints caused by later geological events.

4 The acquisition of isothermal remanent magnetization

The method involves imparting Isothermal Remanent Magnetization (IRM) along three orthogonal axes at different peak magnetic field strengths, which correspond to minerals of low, medium, and high coercivity (Figure 14). The sample is then subjected to progressive thermal demagnetization, and the decay of each magnetization component is measured to identify the magnetic mineralogy.

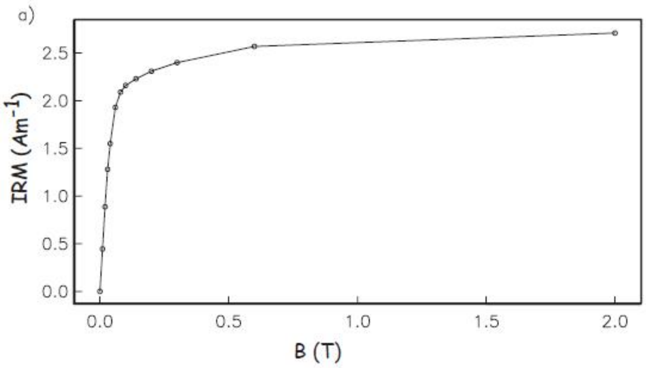

Fig. 14 - Acquisition of IRM (After applying a field of 2 T, the sample was subjected to two additional IRM: 0.4 T and 0.12 T along orthogonal axes.

The acquisition of isothermal remanent magnetization (IRM) curves allows differentiation of minerals based on their coercivity. The principle is straightforward. The sample is divided into three distinct fields along orthogonal axes:

Three-Axis IRM Imparting:

- ✓ Apply a high coercivity IRM (2.5 T) along the X-axis.
- ✓ Apply a medium coercivity IRM (0.4 T) along the Y-axis.
- ✓ Apply a low coercivity IRM (0.12 T) along the Z-axis.

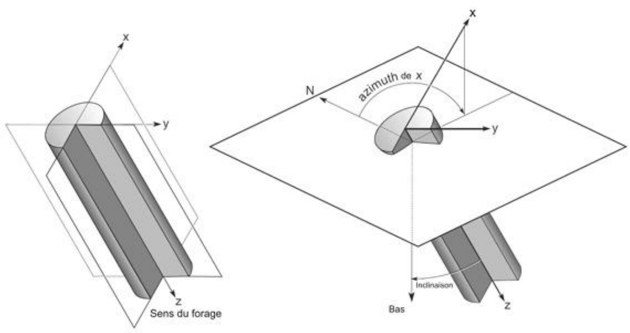

Fig.15- Representation of the 3 axes on a core sample.

Ferromagnetic minerals differ significantly in coercivity based on crystal structure, grain size, domain state, and chemical composition. Examples:

Mineral	Approx. Coercivity (Hc)	Notes on Variability
Magnetite	~20–30 mT	Single-domain grains ~20–40 mT; multi-domain often lower apparent Hc.
Titanomagnetite	~30–60 mT	Varies with Ti content; more Ti usually lowers magnetic stability.
Hematite	~150–300 mT	Fine-grained hematite can have lower Hc; crystallinity matters.
Goethite	~100–200 mT	Often unstable over geological time; variable.
Maghemite	~30–100 mT	Intermediate; can form by oxidation of magnetite.
Pyrrhotite	~50–100 mT	Depends on composition and grain size.

Fig.16-- Typical coercivity ranges of common magnetic minerals

4.1 Interpretation

Coercivity in rock magnetism refers to the resistance of a magnetic mineral grain to changes in its magnetization when subjected to an external magnetic field. More precisely, it is the intensity of the reverse magnetic field required to reduce the remanent magnetization of a sample (or of individual grains) to zero after it has been saturated in one direction.

Unblocking temperature of a magnetic mineral is the temperature at which a remanent magnetization carried by that mineral is lost (or “unblocked”) upon heating. It corresponds to the thermal energy needed to overcome the energy barriers holding magnetic moments in a stable orientation. For ferromagnetic or ferrimagnetic minerals (magnetite), the unblocking temperature for remanence typically approaches but is slightly below the Curie temperature (Tc), above which spontaneous magnetization vanishes.

For antiferromagnetic minerals (hematite), the relevant temperature is near the Néel temperature (TN), above which the antiferromagnetic order collapses.

Fig. 17- Demagnetization using an oven.

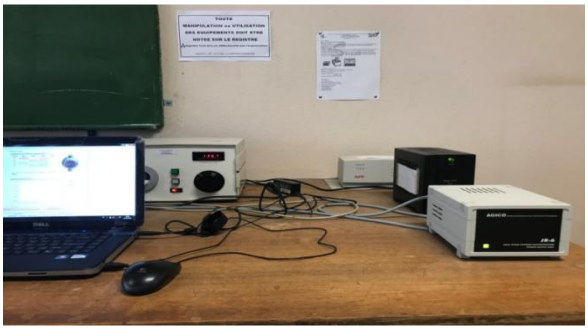

Fig. 18- Equipment of measurements, AGICO (laboratory 25).

4.2 Case of our study:

As part of this study, we submitted 28 samples that were magnetized along three axes in different fields. The results are represented in three different graphs according to the behavior observed (Figure 17, 18).

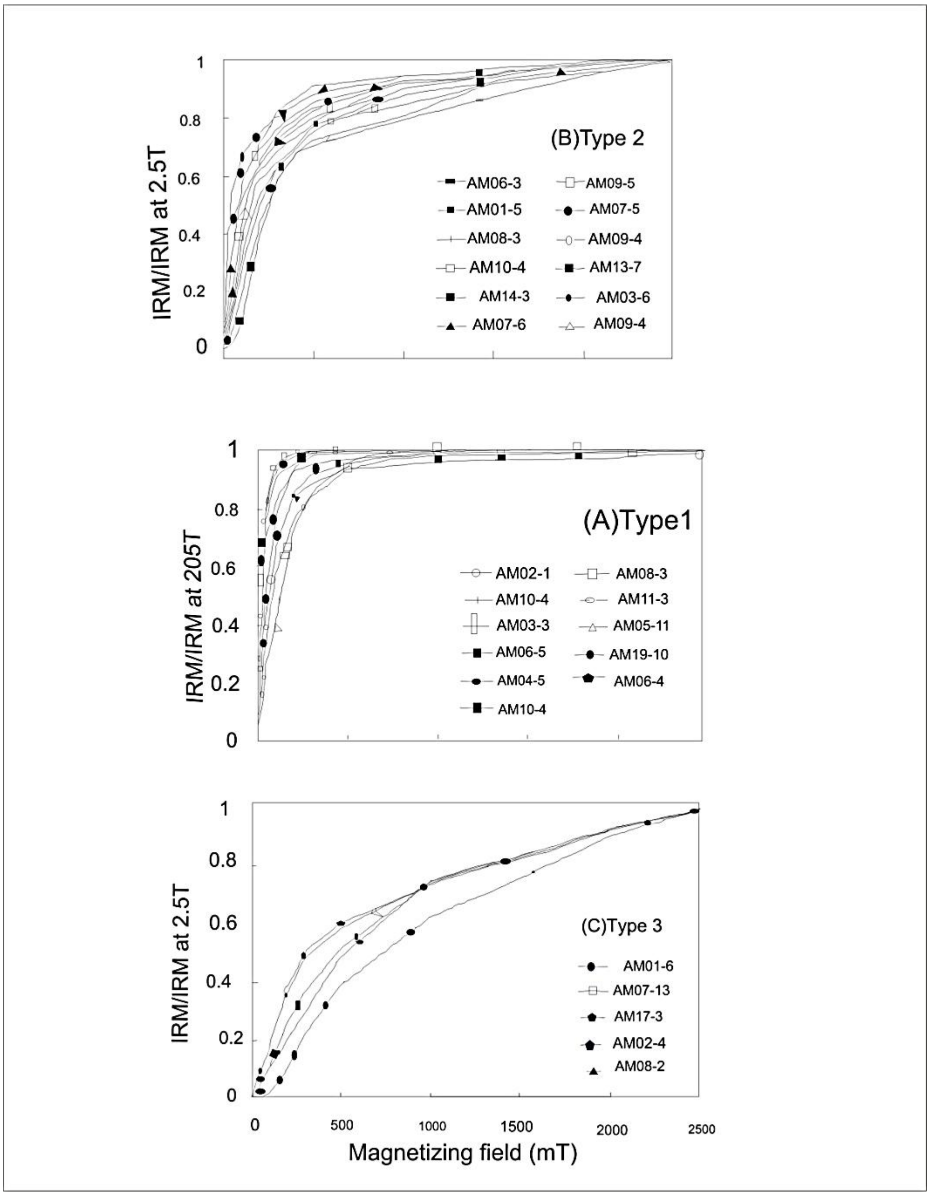

Fig. 19-Isothermal Remanent Magnetization (IRM) acquisition curves of different samples.

4.3 Observations

These graphs display Isothermal Remanent Magnetization (IRM) acquisition curves (Figure 19), normalized to their maximum value at 2.5 Tesla (T), for three different sample types: Type 1**,** Type 2, and Type 3. The X axis represents the magnetizing field (in millitesla, mT), and the Y axis is the normalized IRM (IRM at 2.5 T)**.** These graphs represent how different rock samples acquire magnetization when exposed to progressively stronger magnetic fields (up to 2.5 T). The vertical axis shows normalized (IRM at 2.5 T), making it possible to compare samples regardless of their absolute magnetization values.

type	Saturation field (approx)	Dominant minerals	coercivity	Magnetic domaine
Type (1)	200-300mT	Magnetite/maghemite	Low	MD/PSD
Type (2)	500-1000mT	Mixed (some hematite)	Medium	MD+SD/PSD
Type (3)	1500-2000mT	Hematite/goethite	High	SD/SP grains

Fig. 20-illustrating the table of the magnetic behavior.

Stepwise IRM acquisition experiments were conducted to identify the major ferromagnetic minerals in the samples. Ferrimagnetic minerals (e.g., magnetite) are typically Saturated in a field of less than 300 mT, it is canted antiferromagnetic. Minerals such as hematite and goethite require more than 2 T to become saturated (Lowrie, 1999).

Monoclinic pyrrhotite (Fe_7S_8), a ferrimagnetic mineral, is an example of single domain (SD) or pseudo-single domain (PSD) pyrrhotite generally exhibits a continuous increase in IRM intensity at relatively high fields (0.3–2.7 T) (Lowrie, 1999). IRM acquisition patterns can be grouped into three types (Fig. 20).

Type 1 shows rapid IRM acquisition in a field of less than 100 mT, reaching over 90% saturation at approximately 500 mT (Fig. 20a). This behavior suggests that ferrimagnetic minerals are a major contributor to the magnetization.

Type 2 samples reach 60-80% saturation at 300 mT, followed by the gradual acquisition of additional IRM up to 2.5 T (Fig. 20b). This behavior indicates the presence of either a mixture of ferrimagnetic and canted antiferromagnetic materials or high-coercivity SD/PSD pyrrhotite.

In the case of Type 3, the gradual acquisition of IRM up to a maximum magnetizing field of 2.5 T suggests that the canted antiferromagnetic minerals significantly contribute to IRM acquisition, possibly due to the partial effect of the SD/PSD pyrrhotite (Fig. 20c).

The classification of the IRM curves into Types 1, 2, and 3 reflects a progression from fresh detrital magnetite-bearing sediments (Type 1) to highly altered or weathered iron oxide-rich environments (Type 3). This progression is useful in:

- ✓ Reconstructing environmental changes
- ✓ Tracing sediment sources
- ✓ Assessing the degree of chemical alteration.

Chapter IV: Discussions and Conclusions

1 Discussions

An integrated biochronological and paleomagnetic analysis of the Miocene continental deposits in the El Eulma Basin revealed significant details about the sequence's age, paleoenvironmental context, and magnetostratigraphy. This multidisciplinary approach enhances geological interpretation by combining faunal dating and magnetic polarity data.

Fossil micromammals from Miocene deposits in North Africa are still poorly understood, and systematic considerations are rarely taken into account. Apart from some major works by Jaeger (1970s–1980s), Ameur-Chehbeur (1979, 1988), Coiffait (1991), and Mahboubi (2014), Mahboubi et al. (2015), few studies have been devoted to micromammal deposits in Algeria.

The rodents of the Neogene Basin of El Eulma, located in northeastern Algeria, are distinguished by African species, such as the Dendromuridae, Ctenodactylidae, and Myocricetodontinae families, as well as an Asian immigrant: Progonomys cathalai (Ameur-Chehbeur, 1988). Cricetids dominate these animals (56%). Their high frequency indicates an open, hot, and dry environment. Therefore, the vegetation must have resembled a fairly open savanna.

Based on morphological criteria, the collected charophyte gyrogonites include some species assignable to the *Chara* and *Nitellopsis* genera. This flora is also associated with microfauna assemblage rich in ostracod carapaces and fish remains. Most of these microfossils are well preserved.

The paleomagnetic study seeks to identify the ferromagnetic minerals responsible for the remanent magnetization observed in the Miocene continental layers of the El Eulma Basin in Sétif. It is crucial to understand whether magnetic minerals, such as magnetite, hematite, or goethite, are responsible for storing the natural remanent magnetization (NRM) to assess the reliability and stability of the paleomagnetic signals. This information ensures that the magnetic directions used for magnetostratigraphic correlation accurately represent the ancient geomagnetic field and have not been altered by diagenetic or post-depositional processes.
Investigations in magnetic mineralogy indicated that magnetite and hematite are the primary carriers of remanent magnetization in the El Eulma deposits. Isothermal remanent magnetization (IRM) curves, thermal demagnetization spectra, and hysteresis parameters demonstrate that low- to medium-coercivity minerals are predominant, while high-coercivity

phases are rare. This mineral assemblage favors the preservation of stable natural remanent magnetization (NRM), improving the accuracy of paleomagnetic studies.

According to Mahboubi and Benammi (2021), the magnetostratigraphic data reveal the occurrence of both normal and reversed polarity intervals, allowing for the creation of a local magnetic polarity stratigraphy for the studied section. When compared to the Global Geomagnetic Polarity Timescale (GPTS), these polarity intervals indicate that the El Eulma sequence corresponds to a piece of Chron C4-C3 (about 8.2 to 5.2 Ma), which is congruent with biochronological evidence.

The sedimentological properties the studied geological section indicate fluvio-lacustrine deposition with occasional coarser material input, most likely due to tectonic uplift and basin subsidence. The occurrence of certain taxa associated with open and semi-arid settings may indicate regional climatic conditions during the Late Miocene, a time when aridity increased in the Mediterranean.

The combination of biostratigraphic and magnetostratigraphic data contributes to a better understanding of the El Eulma Basin's tectono-sedimentary history. The accumulation of thick, magnetically well-preserved sequences indicates a subsiding basin with active sedimentation during the Mio-Pliocene transition.

2 Conclusions

This study intended to improve the chronological framework of the Miocene continental deposits of the El Eulma Basin (Setif) by combining micromammal-based biochronology and paleomagnetic stratigraphy. The combination of these two different but complementary techniques resulted in a more cohesive and exact knowledge of the chronological and geological history of the analyzed sequences.

The biochronological approach, which relied on the identification of small mammal taxa, gave useful relative age restrictions. The recovered assemblages, which contain several biostratigraphically noteworthy species, have allowed for linkage with well-known European and North African Neogene biozones. These findings support an age attribution that spans the Mio-Pliocene border and contribute to understanding faunal turnover and paleoenvironmental changes throughout this critical time.

Paleomagnetic investigations have identified a number of polarity reversals throughout the geologic succession. When associated with the global geomagnetic polarity time scale

(GPTS) (Mahboubi and Benammi, 2021), these reversals have enabled the development of a magnetostratigraphic framework that is consistent with biochronological evidence. The combined data indicate that El Eulma Basin deposits have a long and continuous sedimentary history spanning a critical time defined by substantial climatic and tectonic changes.

This comprehensive approach has revealed that the El Eulma Basin could serve as a reference location for Neogene continental sequences in North Africa. The study emphasizes the importance of micromammals as sensitive biostratigraphic indicators and the usefulness of paleomagnetism in overcoming chronological challenges in terrestrial environments.

Future research should focus on expanding the number of faunal samples and integrating sedimentological and geochemical data to more accurately reconstruct paleoenvironmental conditions and depositional dynamics. This would help us better understand the significance of the El Eulma Basin in the overall paleogeographic and paleoecological framework of the Maghreb during the Neogene period.

PLATE

1- M 1 : *Progonomys cathalai* (Amama 1)

2- M1 : *Zramys hachai*(Amama 1)

3- M2 : *Zramys hammai* (Amama 2)

4- M1 : *Paraethomys mioceanicus* (Amama 2)

5- M2: *Protatera algeriensis*(Amama 2)

6- M1: *Myocricetodon trerki* (Amama 1)

7- Bone fragment

8- Fragment of incisif


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BIOCHRONOLOGICAL AND PALEOMAGNETIC STUDIES OF THE LATE MIOCENE CONTINENTAL SECTION FROM EL EULMA BASIN (SETIF, NORTHEASTERN ALGERIA)

Rania BENAMARA

Abstract

This study presents a combined biochronological and paleomagnetic analysis of Miocene continental deposits in the El Eulma Basin of northeastern Algeria. The primary goal is to establish a chronological framework and improve our understanding of the region's environmental evolution during the Upper Miocene phase.

Due to their rapid evolution and susceptibility to environmental changes, micromammal assemblages have been used as biochronological markers to determine the age of sedimentary layers relative to one another. Paleomagnetic research was conducted to identify magnetic polarity reversals in the sedimentary record and link them to the Earth's magnetic polarity.

Using a combination of biostratigraphic and magnetostratigraphic data, we were able to more accurately date the series and reveal major changes in fauna and the environment. This method revealed major faunal and environmental changes. These findings shed new light on Neogene continental dynamics in North Africa and help refine regional and interregional stratigraphic connections.

Keywords: micromammals, paleomagnetism, biostratigraphy, Miocene, El Eulma Basin, East of Algeria.