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MAGNETOSTRATIGRAPHY OF NEOGENE SERIES OF THE GUERCIF BASIN (MOROCCO)

Magnetostratigrafía de la serie neogéna de la cuenca Guercif (Marruecos)

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Abstract: *This paper presents the results of paleomagnetic investigations on continental and marine Neogene deposits in the Guercif basin in northeastern Morocco. The Guercif basin is the eastern continuation of the Neogene foredeep of the Moroccan Rif Mountains, from which it has been separated by the late Neogene uplift of the Middle Atlas Mountain. Four stratigraphic sections have been analyzed on which 136 samples have been taken for the magnetostratigraphy study. The magnetic characteristics of these rocks show that the magnetization usually results from the presence of magnetite, titano-magnetite, goethite and hematite. The results demonstrate the presence of a single reverse polarity in the case of the Khendek El Ouaich section correlated with chron C3Br.2r (~ 7.3 - 7.5 Ma). Magnetostratigraphic investigations in Safsafate section in the Messinian deposits show that it could be correlated with chrons C3Br.1n - C3Ar (~ 6.7 - 7.3 Ma). The Ain Guettara and Oued Lahmar sections show a succession of at least seven polarities that are correlated with chrons C3n.4n - C3n.2n (~ 4.5 - 6.0 Ma). These results along with new biostratigraphic studies based on rodent faunas and volcanism permit to establish the age of tectonic activity and deposition.*

Keywords: *Magnetostratigraphy, Neogene, Guercif basin, Morocco.*

Resumen: *Este artículo presenta los resultados de las investigaciones paleomagnéticas sobre depósitos neógenos continentales y marinos en la cuenca Guercif en el noreste de Marruecos. La cuenca de Guercif es la continuación oriental del foredeep neogeno de las montañas marroquíes de Rif, de las cuales ha sido separado por el levantamiento neogeno tardío de la montaña media del Atlas. Se han seleccionado cuatro secciones estratigráficas en las que se han tomado 136 muestras para el estudio de magnetostratigrafía. Las características magnéticas de estas rocas muestran que la magnetización generalmente resulta de la presencia de magnetita, titano-magnetita, goethita y hematites. Los resultados demuestran la presencia de una sola polaridad inversa en el caso de la sección de Khendek El Ouaich correlacionada con el cron C3Br.2r (~ 7.3 - 7.5 Ma). Las investigaciones magnetostratigráficas en la sección de Safsafate en los depósitos de Messiniense muestran que podría correlacionarse con los crones C3Br.1n - C3Ar (~ 6.7 - 7.3 Ma). Las secciones de Ain Guettara y Oued Lahmar muestran una sucesión de al menos siete polaridades que están correlacionadas con C3n.4n - C3n.2n (~ 4.5 - 6.0 Ma). Estos resultados junto con nuevos estudios bioestratigráficos basados en las faunas de roedores y el volcanismo permiten establecer la edad de la actividad tectónica y la sedimentación.*

Palabras clave: *Magnetostratigrafía, Neógeno, cuenca de Guercif, Marruecos.*

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Introduction

The Guercif basin is the eastern extension of the Neogene foredeep of the Moroccan Rif Mountains. It covers some 6000 km^2 and is filled by Tortonian to Quaternary sediments with thicknesses locally in excess of 2000 m (Colletta, 1977). The basin is surrounded by variable high relief: the Middle Atlas to the southwest, the Masgout uplift to the north and its continuation into the Beni Snassen area to the northeast and the Taourirt-Oujda Mount and the Rekkam Plateau to the east (Fig. 1). In relation to its intra-mountainous nature, sediments were settled in different environments: continental, lagoon and marine.

The Guercif basin performed a pivotal role in the late Neogene history of the Mediterranean region. Prior to the opening of the Strait of Gibraltar, the Atlantic Ocean and the Mediterranean Sea were connected via the "Rifian corridor" (Colletta, 1977; Wernli, 1988; Benson *et al.*, 1991). This narrow seaway is constricted during the late Tortonian and early Messinian (Krijgsman *et al.*, 1999; Krijgsman and Langereis, 2000; Dayja and Bignot, 2003) and closed during the Messinian desiccation event of the Mediterranean Sea (*i.e.*, Messinian salinity crisis, MSC; *e.g.*, Hsü *et al.*, 1973, Suc and Bessais, 1990; Benammi *et al.*, 1996; Garcés *et al.*, 1998). We present in this paper new results on the Neogene tectonic history of the Guercif basin based on magnetostratigraphy and new biostratigraphic studies based on rodent faunas.

Magnetostratigraphy and correlation to the geomagnetic polarity time scale (GPTS) has become a standard tool in Earth Sciences, especially because it can be applied to a wide variety of rock types and in different (marine/continental) environments. 136 samples were collected in three geologic sections through three Neogene continental formations at Khendek el Ouaich, Ain Guettara and Oued Lahmar areas. Another geologic cross section was made across the Safsafate anticline which consists essentially of marine sediments. We interpret

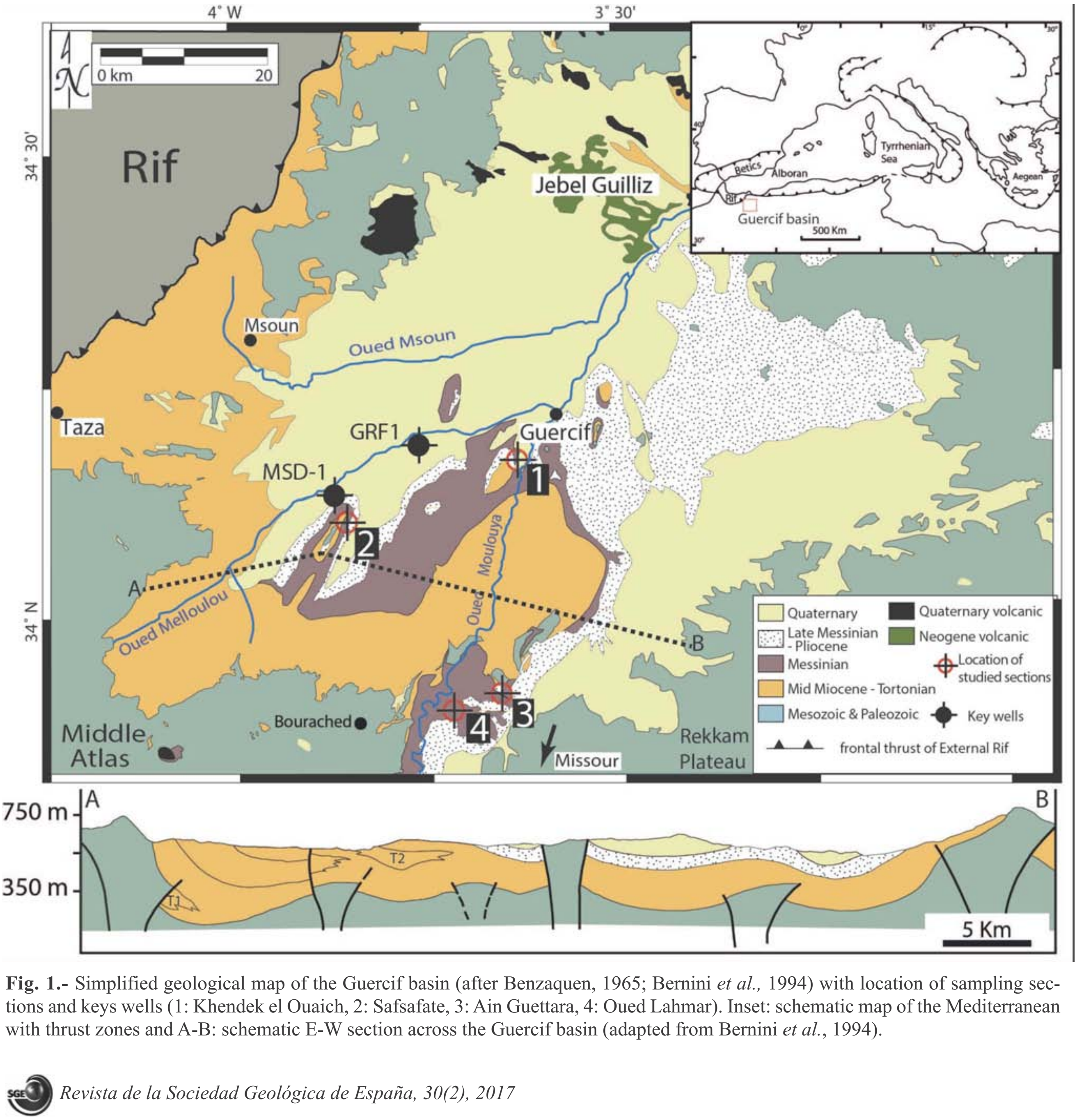

Fig. 1.- Simplified geological map of the Guercif basin (after Benzaquen, 1965; Bernini *et al.,* 1994) with location of sampling sections and keys wells (1: Khendek el Ouaich, 2: Safsafate, 3: Ain Guettara, 4: Oued Lahmar). Inset: schematic map of the Mediterranean with thrust zones and A-B: schematic E-W section across the Guercif basin (adapted from Bernini *et al.*, 1994).

these obtained results as reflecting the influence of different tectonic events that directly controlled the Guercif basin Neogene evolution.

Geological setting

The Guercif basin is divided into two geologically distinct domains: (1) the western subsiding area, with considerable thicknesses for the Jurassic-Miocene and a middle-atlasic and saliferous tectonics; and (2) the eastern platform domain, with smaller thicknesses for the Jurassic and the Triassic. The eastern domain tectonics is characterized by horst and graben structures. In this basin, Neogene series reaches up to 1800 m thick (Wernli, 1988), and are often overlaid by continental Plio-Quaternary formations.

The regional geology of the Guercif basin was mapped by Benzaquen (1965) (Fig. 1), and subsequent work by Colletta (1977) and Bernini *et al.* (1992) further defined the Neogene sedimentary geology. The recent stratigraphic advances also benefited from improved chronological constraints based on biostratigraphy (Wernli, 1988; Krijgsman *et al.*, 1999). The generalized Neogene stratigraphy and magnetostratigraphy of the Guercif basin as described by Bernini *et al.* (1992, 1994), Gelati *et al.* (2000), Gomez *et al.* (2000), Dayja and Bignot (2003), Barhoun and Bachiri Taoufiq (2008) and modified from Sani *et al.* (2000), is illustrated in Figure 2.

The exposed Neogene-Quaternary stratigraphy of the Guercif basin has been studied in the western half of the basin. In the basin, analysis of the MSD1 borehole (Dayja and Bignot, 2003; Barhoun and Bachiri Taoufiq, 2008) and GFR-1 (Sani *et al*., 2000) (Fig. 2) provided more detail about the depositional environments during this period. The base of the stratigraphic succession outcrops sporadically at the western margin of the Guercif basin. It contains continental conglomerates and breccias levels of the Tortonian Draa Sidi Saada Formation (Benzaquen, 1965) that rest with angular unconformity on the Jurassic substratum. The discordantly overlying Tortonian represents a marine transgression involving shallow-water deposits constituted of sandstones and marls (Ras El Ksar unit of Benzaquen, 1965). This series characterized a strong subsidence and its thickness exceeds 500 m. These deposits are in turn conformably overlaid by several hundred meters of open-marine sediments: the Melloulou Formation (Bernini *et al.*, 1992) including the “marnes bleues” of Benzaquen (1965) and the “marnes tortoniennes” of Colletta (1977). This series consists of three successive subunits: blue marls, two turbidite sandstone packages and gypsiferous marls on top. The Blue Marl subunit consists of thick and uniform marine marls. In the southern Guercif basin near the boundary with the Middle Atlas, the two turbidite sandstone packages interfinger with the blue marls: the finer and more thinly bedded El Rhirane turbidites and the coarser, more thickly bedded Tachrift turbidites. Current marks suggest a paleoflow from the south, indicating a source in the Middle Atlas (Gelati *et al.*, 2000). The Tortonian-Messinian boundary (*ca.* 7.2 Ma) is at or near the top of the Tachrift turbidites (Krijgsman and Langereis, 2000). The turbidites are overlaid by the Gypsiferous Marl subunit, which was deposited after rapid shallowing of the basin between 7.2 and 7.1 Ma (Krijgsman *et al.*, 1999). The post-shoaling marl contains abundant gypsum crystals indicating evaporative conditions and is several hundred meters thick, indicating the continuation of basin subsidence (Krijgsman *et al.*, 1999; Gelati *et al.*, 2000).

The Melloulou Formation is discordantly overlaid by the Kef Ed Daba unit (Bernini *et al.*, 1996), equivalent of the “laguno-lacustre of Khendek el Ouaich” of Benzaquen (1965) and the “Grès et marnes laguno-lacustres” of Colletta (1977). This formation (100 m in thickness) consists of transitional marine facies that are capped by fluvial-del-

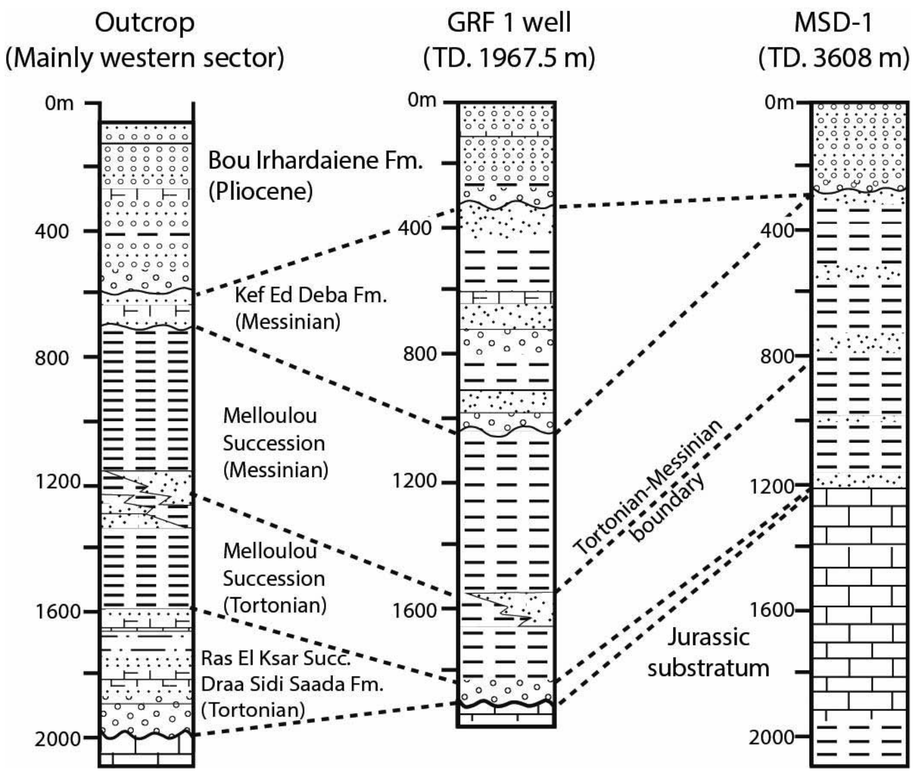

Fig. 2.- Neogene to Quaternary stratigraphic columns reconstructed from outcrop and wells (adapted from Gelati *et al.*, 2000; Gomez *et al.*, 2000; Sani *et al.,* 2000; Dayja and Bignot, 2003; Barhoun and Bachiri Taoufiq, 2008). For location of wells, see Figure 1.

taic conglomerates and fossiliferous sandstones (for more details, see Gelati *et al.*, 2000). It is truncated by a stark regional unconformity that marks the final emergence of the Guercif basin between 6.7 and 6.0 Ma (Krijgsman *et al.*, 1999). Above the unconformity, continental deposition began with the lacustrine carbonates and fluvial conglomerates of the Pliocene Bou Irhardaiene Formation, *i.e.*, “El Moungar Formation” of Benzaquen (1965) and the “Grès et conglomérats continentaux” of Colletta (1977). This situation continues in the early Quaternary by the deposition of sandstones, lacustrine limestones and sandy marls (Wernli, 1988). The Quaternary is represented by deposits of terraces and fluvial-lacustrine complex. It is formed by six levels of tiered deposits in relation to a progressive uplift of the borders and a concomitant subsidence of the basin.

Magnetostratigraphy

Sampling sites

Four profiles were sampled and studied to establish the magnetic polarity stratigraphy of the Neogene units in the Guercif basin (sections 1 to 4 in Fig. 1).

Khendek el Ouaich section. The Khendek el Ouaich section is located 17 km south of Guercif city on the left bank of the road from Guercif to Bourached. It outcrops in the east of the NNE-SSW Foum Marhrane anticline and it can be seen on both banks of Oued Khendek el Ouaich ravine (section 1 in Fig. 1). This section was first studied by Van Leckwijck and Marçais in 1935 who showed the existence of an alternation of lagoon marine and lacustrine levels. Jaeger (1977) shows the presence of lignite and cinerite layers. Lignites show a wildlife assemblage of rodents *Paraethomys miocaenicus* and *Myocricetodon ouaichi* of middle Turolian age (Jaeger, 1977). The cinerites are associated with the volcanic activity of Guilliz, located north of the Guercif basin, whose age is 7.4 ± 1.2 Ma (Choubert *et al.*, 1968). Our field observations show that this section is formed essentially by an alternation of layers of beige cinerites rich in gastropods, gray lignites and clayey marls (Fig. 3 and Plate 1A). In these deposits of the base of the Tortonian Melloulou Formation, microfauna are represented by gastropods, charophytes, ostracods and rare benthic foraminifera, which according to Colletta (1977) indicate a lagoon environment with freshwater episodes. Lignite levels are rich in micromammals and particularly rodents.

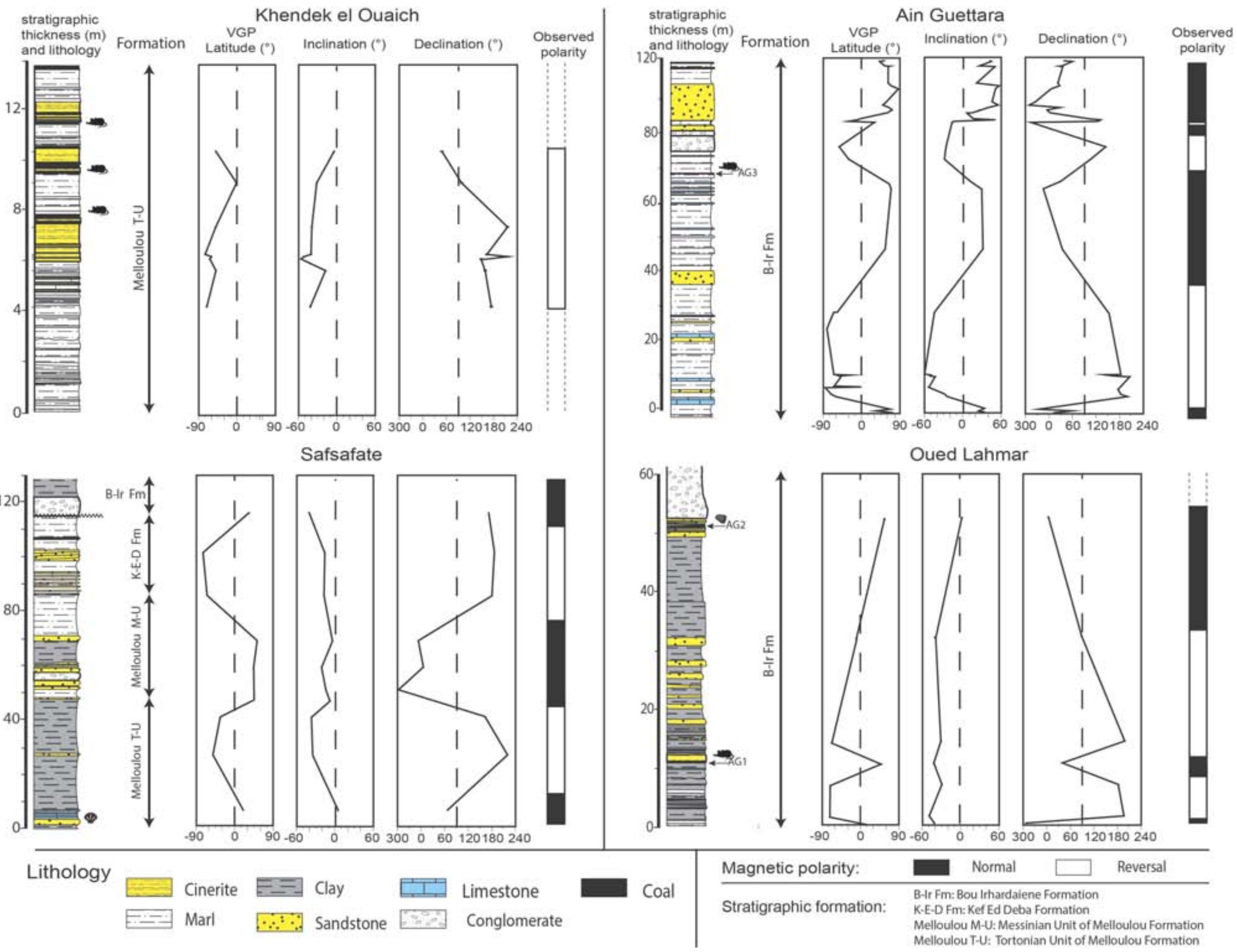

Fig. 3.- Paleomagnetic reversal stratigraphy of the four sections along the Guercif basin. Inclination (in degrees to the horizontal), declination (°E), and the virtual geomagnetic pole (VGP) paleolatitudes (°N) of characteristic remanent magnetization (ChRM) are plotted as a function of stratigraphic levels.

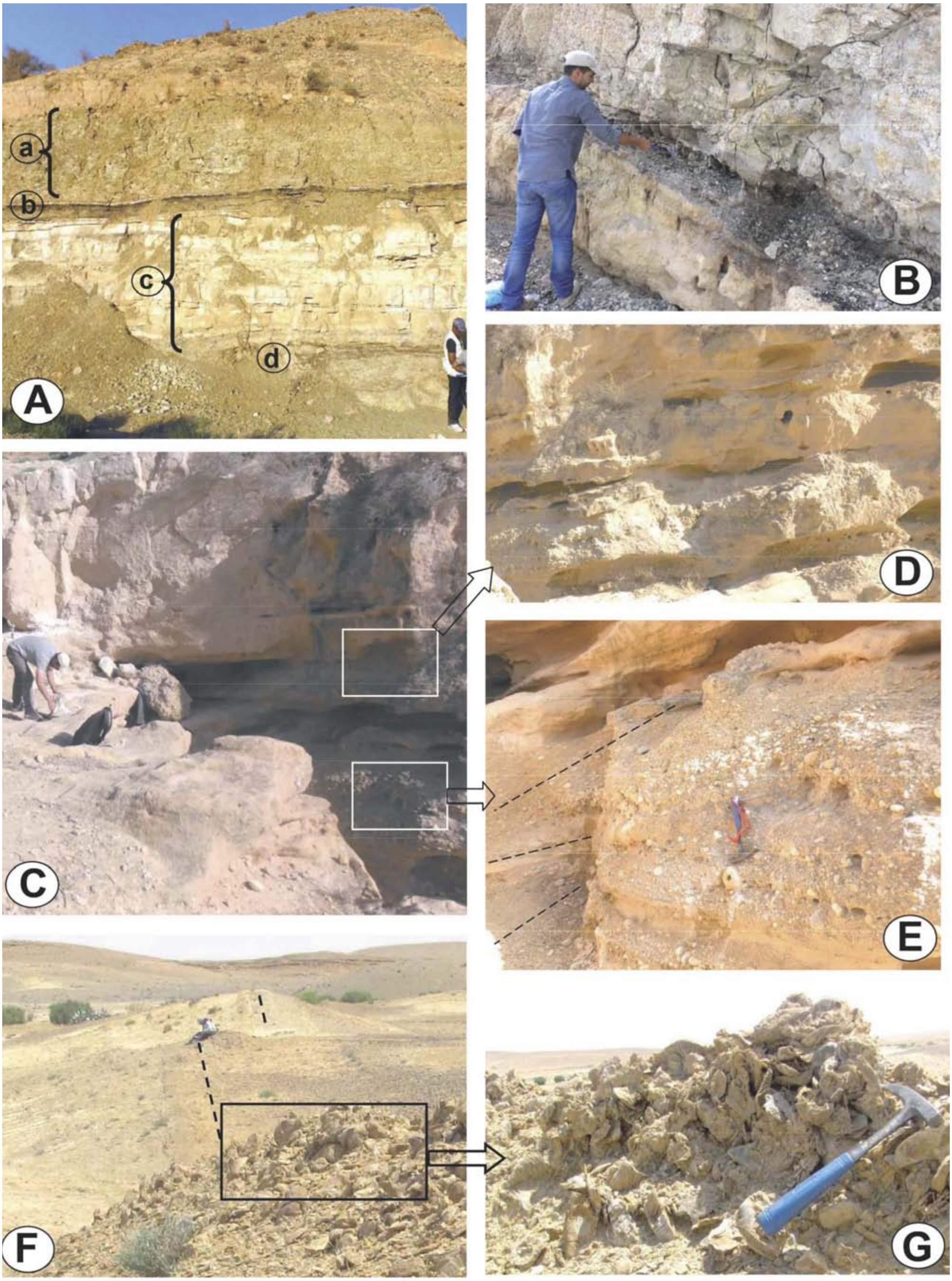

Plate 1.- Illustration of some Neogene outcrops in Guercif basin. A. Tortonian lignite levels (b and d) intercalated by cinerite beds (c) and marls (a) in the Khendek el Ouaich section. B. Subhorizontal Lignite layer (AG1) rich in Pliocene micromammals in the Oued Lahmar section. C. Pliocene channelled sandstones (D) and conglomerates (E) of the Bou Irhardaiene Formation in the Ain Guettara section. F and G. Oyster-bearing level marking the Tortonian-Messinian boundary dated 7.24 Ma in the Safsafate section.

Safsafate section. The Safsafate section is located on the western flank of Kef Ed Deba's NNE-SSW anticline, immediately south of Douar Safsafate, on the right bank of Melloulou River (section 2 in Fig. 1). It corresponds to a thick series of more than 100 m (Fig. 3). This section begins with Tortonian green marls of the Melloulou Formation, followed by ferruginous sandstone levels marking the Tortonian-Messinian boundary and then a regressive series of the Messinian represented by gray and pink ribboned marls and sandy marls with intercalated sandstones. In this section, we have located an oyster-bearing level (Plate 1F, G), marking the Tortonian-Messinian boundary dated at 7.24 Ma (Hilgen *et al.*, 1995). The upper sandy marls of Kef Ed Deba Formation provided blunted debris of lamellibranchs and suggest a sea-shift environment. These levels are unconformably overlaid by conglomerates of the Bou Irhardaiene Formation.

Ain Guettara section. The Ain Guettara's profile is located in the southern part of the Guercif basin, on the right bank of the road from Guercif to Missour. The section outcrops on both banks of Ain Guettara River, a tributary of Moulouya River, immediately south of the Jurassic anticline relief of Haloua-Richa (section 3 in Fig. 1). This site is fossiliferous and was first studied by Colletta in 1977 and Brandy and Jeager in 1980. These authors described a marine series followed by a strongly detrital lagoon-lacustrine series of Messinian age, overlaid by detritic formations attributed to the Pliocene. Brandy and Jaeger (1980) show the presence of lignite and cinerite layers in lagoon-lacustrine formations. This section of the Bou Irhardaiene Formation is about 100 m thick (Fig. 3). It shows gray-green marls and intercalated bioturbated limestones levels, followed by channelled sandstones and conglomerates (Plate 1C–E), overlaid by beige marls and marly limestones. A level of lignite (AG3) is intercalated between the marly series. This lignite level is rich in micromammals (rodents) especially *Cricetus cf. barrieri* that Brandy and Jaeger (1980) attributed to the lower Ruscinian.

Oued Lahmar section. The Oued Lahmar section is located south of the Guercif basin, a few tens of kilometers south of the Ain Guettara. This section of the Bou Irhardaiene Formation outcrops on the left bank of the Lahmar River, a tributary of the Moulouya River (section 4 in Fig. 1). The section includes clayey green and gray compact marls with intercalated sandstone levels and two levels of lignite (AG1 and AG2, Fig. 3). The top of the series is capped by conglomerates. The lignite level AG1 (Plate 1B) is rich in micromammals and especially: *Paraethomys anomalus, Cricetus cf. barrieri, Occitanomys, Prolagus* and *Ctenodactylidae indet*. The species collected are almost identical to those of the Ain Guettara deposits (AG3 level) and suggest that the two formations are contemporaneous. On AG2 lignite level, there is no trace of the micromammals, but this level has delivered abundant lacustrine gastropod fauna.

Sampling procedure

A set of 136 samples was collected in continental formations of the Khendek el Ouaich, Ain Guettara and Oued Lahmar sections and in marine sandstones of Safsafate section. The paleomagnetic sampling consists of taking several oriented samples (cores or blocks) in the layer. 25 mm diameter cores were collected using a gasoline drill. The drill is equipped with a nonmagnetic diamond drill and a water cooling system. The orientation of the core is carried out using a special tool which is inserted around the core, equipped with a magnetic compass, a solar compass and an inclinometer. The solar compass is used to verify the correct magnetic orientation. Before being broken, all cores are oriented along the dip angle of the core relative to the vertical and the azimuth of its axis. These values are then noted on the field book. On the collected core samples, the axis of its azimuth is marked using a plotter. All samples were cut into standard 22 mm long cores. Another sampling method is used for soft rocks (*e.g.*, clays) that cannot be drilled with water. It involves removing blocks in place, and with a compass equipped with a bubble level, we draw the direction of the magnetic north on the structural surface of the bench. In the laboratory, the blocks are included in a plaster support, then, they are drilled with compressed air, normal to the oriented plane. Thereafter, the samples are cut in to standard 22 mm long.

In order to identify the minerals carrying magnetization, isothermal remanent magnetization (IRM) acquisition was performed on samples from different locations and various lithologies using a pulse magnetizer (MMPM10). Samples were subjected to increasing magnetic fields up to 1 T. The intensity of the IRM was measured after each increasing step with a Spinner magnetometer JR6 (Agico).

The determination of ferromagnetic minerals was improved by stepwise thermal demagnetization of three-axis differential IRM following Lowrie's (1990) method. These IRMs have been applied along the three orthogonal axes of the samples (0.1 T along the x-axis, 0.5 T along the y-axis, and 3 T along the z-axis).

The intensity and direction of the natural remanent magnetization (NRM) were measured on a JR6 magnetometer. To isolate the characteristic remanent magnetization (ChRM), the samples were subjected to progressive thermal demagnetization from 100°C with 25–50°C increments. Magnetic susceptibility was measured after each heating step to detect any chemical or mineralogical changes in the magnetic minerals. A total of 116 from the 136 samples collected, were submitted to stepwise alternating demagnetization field with increments of 3–10 mT, up to a maximum field of 90 mT. For some samples, alternating field demagnetization was inefficient. Thus, thermal demagnetization was subsequently successfully performed. Results of demagnetization were plotted on orthogonal vector diagrams (Zijderveld, 1967) and stereograms. Finally these palaeomagnetic analyses were undertaken at the Paleomagnetism Laboratory of Poitiers University (IPHEP), France.

Paleomagnetic results

Isothermal remanent magnetization (IRM)

In most of samples, collected from marls or clay marls, the curves of the acquisition of the IRM (Fig. 4) show se-

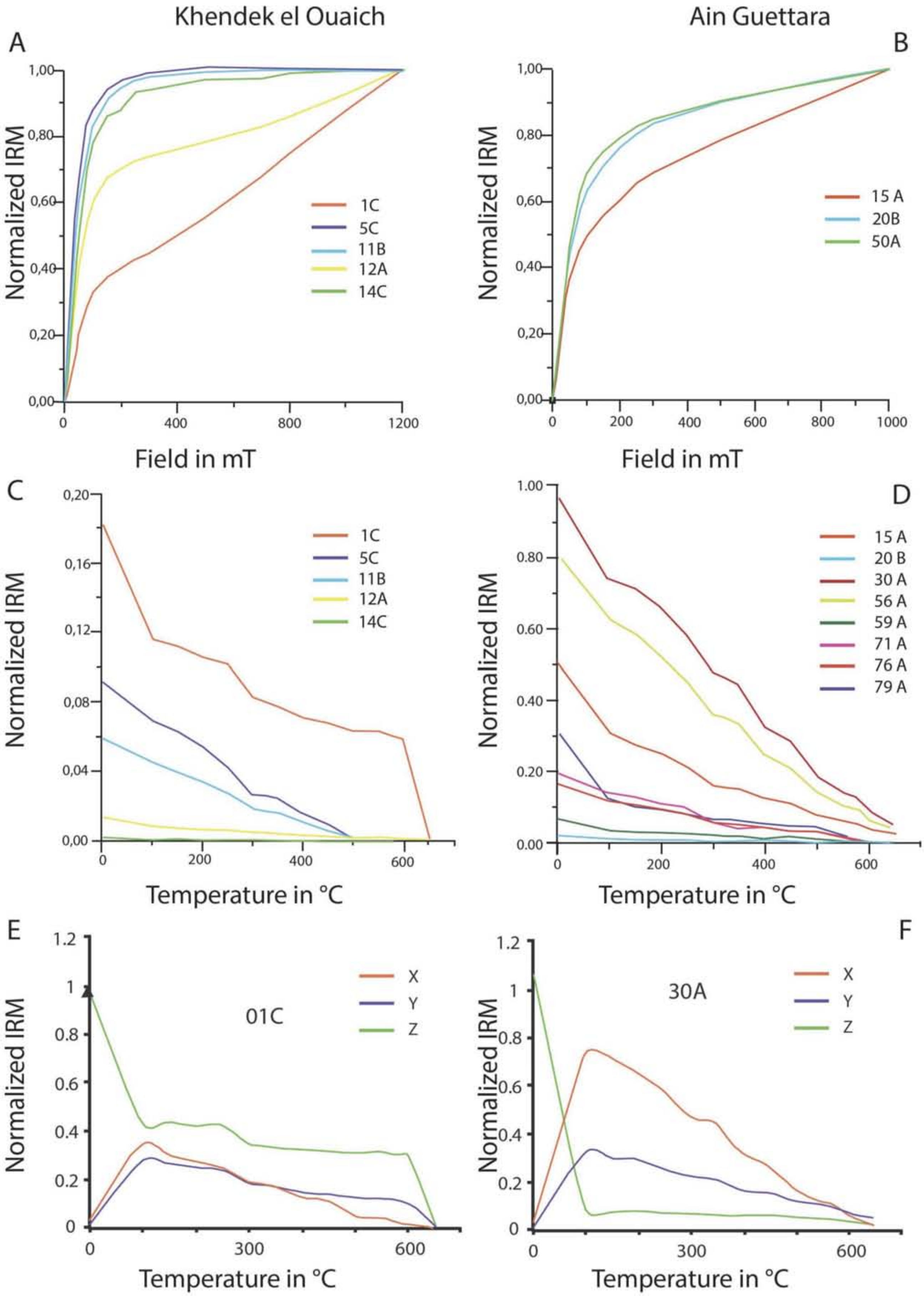

Fig. 4.- A and B. Isothermal Remanent Magnetization (IRM). C and D. Demagnetization diagrams of the components of the IRM. E and F: Examples of demagnetization diagrams of components of the IRM samples of Khendek el Oauich and Ain Guettara.

veral behaviors depending on the nature of the samples and their coercivity, indicating a diversity of the magnetic mineralogy.

In Khendek el Ouaich, the IRM acquisition curves increase rapidly in low field (samples 5C, 11B, 14C, Fig. 4A) and reach saturation at 200 mT, indicating the presence of low coercivity minerals such as magnetite or titano-magnetite. The 1C and 12A samples show that the IRM acquisition curves increase gradually without reaching the saturation at 1200 mT. The magnetic properties of these samples are probably due to the presence of high coercivity minerals, such as hematite or goethite.

A change in slope is observed on the thermal demagnetization curve at ~100°C indicating the presence of goethite (Fig. 4C and E). The total demagnetization is reached around 680°C, indicating the presence also of hematite. The three components (X, Y and Z) of sample 01C (Fig. 4E) lost their magnetization above 680°C. For the remain samples of the Khendek el Ouaich section, there is an inflexion point in the demagnetization curve observed around 300°C suggesting the presence of the titano-magnetite minerals (samples 5C and 11B, Fig. 4C).

The Ain Guettara samples (Fig. 4B) show similar IRM acquisition pattern as those of 1C and 12A samples of Khendek el Ouaich (Fig. 4A). The IRM curves increase gradually without reaching the saturation at 1T, proving that the magnetization is carried by high coercivity minerals, such as hematite and/or goethite. During the thermal demagnetization, there is a progressive decrease in the intensity without any inflection point, until the hematite unblocking temperature of 650°C (Fig. 4D and F). The combined results of the IRM and the thermal demagnetization indicate that the main minerals carrying the magnetization in the marl and clay sediments are magnetite, titano-magnetite, hematite, and a fraction of goethite.

Natural remanent magnetization (NRM)

The measured NRM intensity ranges between 10×10^{-5} A/m and $9,97 \times 10^{-5}$ A/m. Resistance to demagnetization is often discussed in terms of stability of NRM, with low-stability components easily demagnetized and high-stability components removed only at high levels of demagnetization. Most of the samples are characterized by two components magnetization: a low stability component, removed between 3 and 15 mT or between 100 and 300°C, and a high stability component (Fig. 5). The direction of the low-stability NRM is close to that of the present mag-

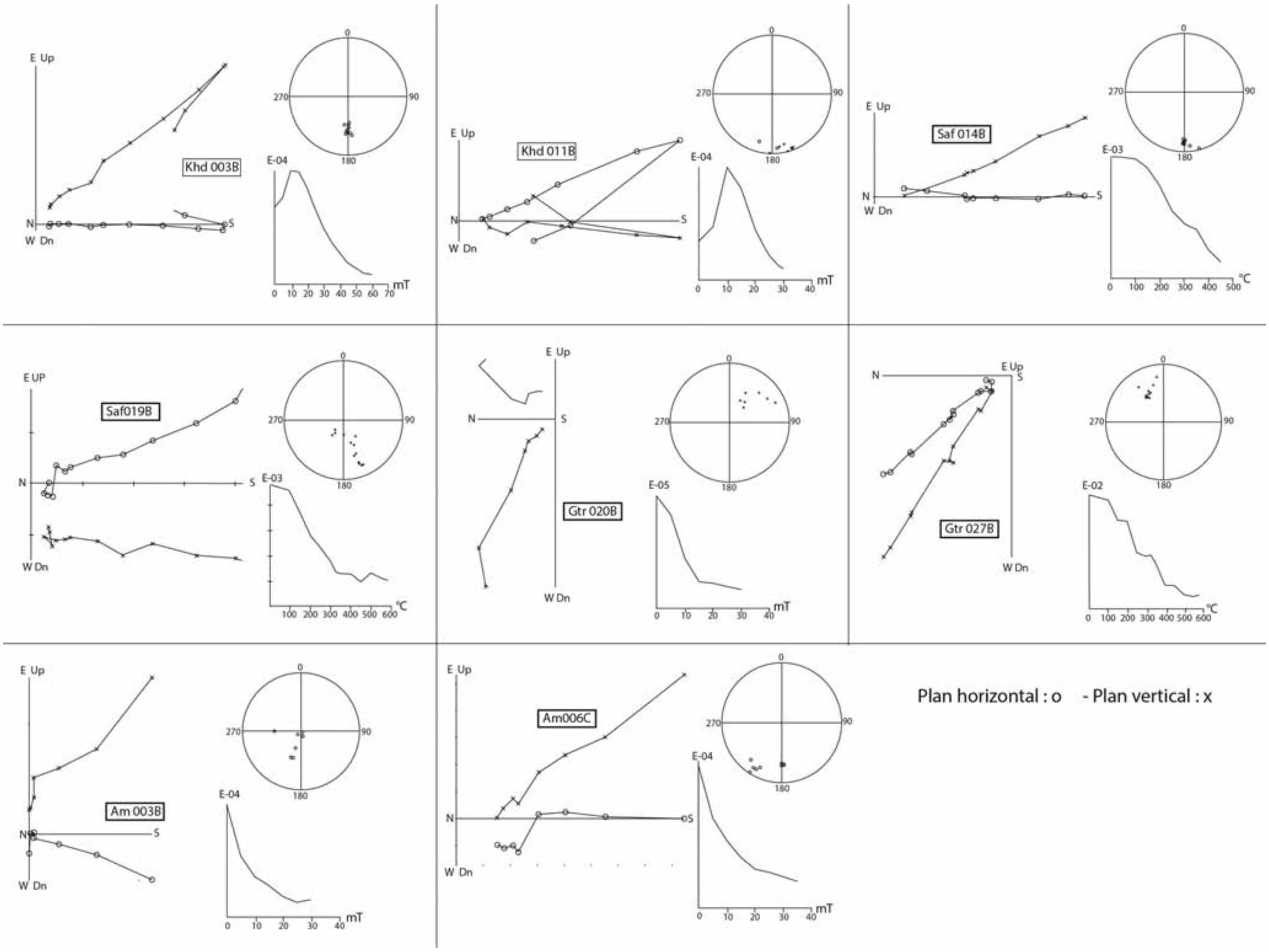

Fig. 5.- Examples of orthogonal vector diagrams of progressive thermal demagnetization. On the orthogonal patterns, cross and white dots represent horizontal and vertical components (Zijderveld, 1967). On the demagnetization diagrams, the intensity of magnetization is given in A/m.

netic field, and this component is interpreted as a viscous overprinted magnetization. For a few samples, NRM was not totally removed at temperatures greater than 600 °C. This behavior is probably due to the presence of a high unblocking temperature mineral, and the IRM analyses suggest that it may be hematite (samples Saf019B and Gtr027B, Fig. 5).

Stereographic visual analysis, orthogonal plots (Zijderveld, 1967), and statistical methods using principal component analysis (Kirschvink, 1980) were used to determine the direction of the characteristic magnetization (ChRM) from demagnetization data. The mean directions were computed using Fisher's statistics (1953) (Fig. 6). Some samples were eliminated due to inconsistent directions during the demagnetization or because of their low intensity. The presence of normal and reverse polarities at a relatively high temperature (>450°C) suggests that the NRM of the samples is primary. The declination and inclination obtained for the ChRM of each sample were used to calculate the virtual geomagnetic pole (VGP) latitude, yielding a magnetic polarity sequence in the studied sections. The angles of the virtual geomagnetic latitude (VGP) lat. (>30°) are considered a normal polarity, while < -30º angles were considered as a reverse polarity. The angle between -30° and 30° were interpreted as an intermediate polarity. The mean direction of the Khendek El Ouaich section is: declination (D) = 173.9°, inclination (I) = -30.5°, k = 5, alpha95 = 26.2°. This section provided only a reverse polarity. However, the Ain Guettara section shows normal and reverse polarities where the mean direction of normal polarities is: D =13.9°, I = 40.3°, k = 9, alpha95 = 11.4°; whereas the mean direction of all reverse sites is D = 177.9°, I = - 44.3°, k = 1.0, alpha95 = 13.9.

Because of the horizontal structure of the layers, it is not possible to perform the fold test. To evaluate our results and define the magnetization origin (primary or secondary), we applied the reverse test, which is based on comparing the normal and reverse polarity directions. At Ain Guettara site, the angle between normal and reverse directions is 12.47°. According to McElhinny and McFadden (1990) classification, this angle corresponds to C class. However, for Safsafate and Oued Lahmar sites, the recorded angles were 6.3° (B class) and 15.8° (C class), respectively. The reverse test is positive for all sections and suggests that the NRM of the samples is primary.

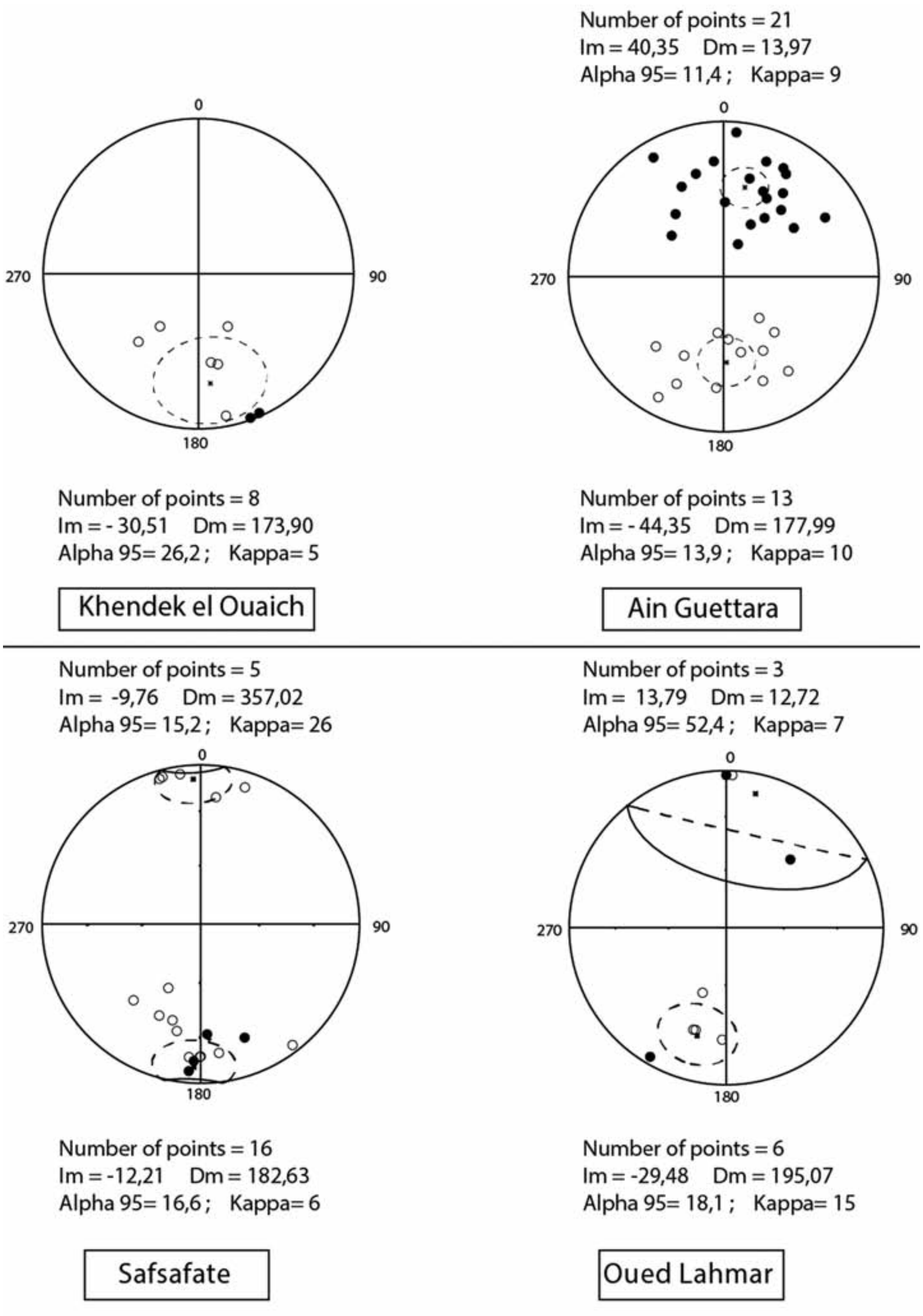

Fig. 6.- Stereographic projection of the ChRM directions of each sample after stratigraphic correction.

Correlation

The ChRM directions were converted into virtual geomagnetic pole (VGP) (Opdyke and Channell, 1996). The polarity is assigned to each level on the basis of the VGP latitude (Fig. 3). Taking into account previous work on stratigraphic and biochronological data, we try to correlate our sections with geomagnetic polarity time scale (GPTS) of Gradstein *et al.* (2012) and estimating a numerical age for each section (Fig. 7).

The Khendek el Ouaich section delivered a rodent fauna that Jaeger (1977) attributes to the middle Turolian (Fig. 7). This age was determined based on the evolutionary stage of the collected rodent fauna. The section also shows volcanic ash levels in continental sediments that may be related to Guilliz volcanic activity dated 7.4 ± 1.2 Ma (Choubert *et al.*, 1968). All the samples we analyzed of the Khendek el Ouaich section have one reverse polarity. The obtained polarity sequence could be correlated with Chron C3Br.2r of the GPTS (Gradstein *et al.*, 2012) and extends in age between 7.285 Ma and 7.489 Ma (Fig. 7).

The Safsafat section is located 20 km southwest of Khendek el Ouaich. In this section we identified a marine series at the base dated as Tortonian, and an oyster-bearing horizon, which constitutes a reliable stratigraphic marker of the Tortonian-Messinian limit dated at 7.24 Ma (Hilgen *et al.*, 1995). Towards the top of the unit, sandy marls intercalated by thin sandstones are overlapped with erosional unconformity by continental sediments. In this section, we found five polarities, two reverse (R1 and R2) and three normal (N1, N2 and an unnamed N above the unconformity) (Figs. 3 and 7). The samples below the erosional unconformity showed a succession of two normal (N1 and N2) and two reverse polarities (R1 and R2) along the 100 m thick succession (Fig. 7). This polarity sequence could be correlated with chrons C3Br.1n - C3Ar, which indicates according to GPTS of Gradstein *et al.* (2012) an age between 7.285 Ma and 6.733 Ma. The limit between the reverse polarity R1 and the normal polarity N2 coincide with the Tortonian-Messinian boundary. More precisely, the fluvio-deltaic levels could correspond to the Kef Ed Deba Formation and coincides with reverse polarity R2 and so to chron C3Ar. Magnetostratigraphic correlation reported in Krijgsman *et al.* (1999), indicates that this unit can be dated to the “pre-evaporitic" Messinian. Above the erosional unconformity, the section indicates a continental environment and shows only one normal polarity. In the absence of chronological marker, this polarity could correspond to chron C3n.4n of Krijgsman *et al.* (1999). This correlation suggests that the unconformity represents in the Safsafate area, a gap in sedimentation of about 1.26 Ma.

Ain Guettara and Oued Lahmar are located in the southern part of the Guercif basin, approximately 30 km southest of Safsafate section and 34 km south of Khendek el Ouaich profil. The correlation between the Ain Guettara and Oued Lahmar sections was carried out in the field (Fig. 7). In these sections three lignite levels (AG1 to AG3) have been identified. The association of rodent fossils collected from AG1 and AG3 lignite beds (*Paraethomys anomalus, Cricetus* cf. *barrieri, Occitanomys, Prolagus* and *Ctenodactylidae indet.*) indicates a Ruscinian age. The fauna collected are younger than those of the Khendek el Ouaich, dated according to Brandy and Jaeger (1980) to middle Turolian. Other faunas *(Cricetus* cf. *Barrieri)* are already described in Ain Guettara by Brandy and Jaeger (1980) and Benammi *et al.* (1996) and known in other Moroccan localities like Lissasfa near Casablanca in the west (Geraads, 1998; Raynal *et al.*, 1999), and Afoud 8 in the east (South High Atlas, Benammi *et al*., 1995, 1996; Gibert *et al*., 2013) are dated of late Turolian age. The fauna composition is similar to the micromammals of Spain and South of France, which allows Brandy and Jaeger (1980) to suggest a temporary connection between Europe and Africa through the Gibraltar area during the late Turolian. Other sites of the same age have been discovered in North Africa as Wanou site in Morocco (Benammi *et al.,* 1996; Benammi, 1997) and Argoub Kemellal site in Algeria (Coiffait, 1991).

The synthetic Ain Guettara-Oued Lahmar section shows seven polarity zones: four normal polarities (N1-N4) and three reverse polarities (R1-R3; Fig. 7). As the fossiliferous level of Oued Lahmar section is the same age as biochronological Afoud 8 (four common taxa) correlated with chron C3r in the Ait Kandoula basin (Central High Atlas, Benammi, 1997), we could correlate the normal polarity N2 of our synthetic section with the chron C3n.4n and the last normal polarity chron N4 with the chron C3n.2n, which indicates according to GPTS of Gradstein *et al.* (2012) an age between 6.033 Ma (base C3r) and 4.493 Ma (base C3n.2n) (Fig. 7).

Discussion

Analysis of the magnetostratigraphic data complemented by biochronological data and absolute dating in volcanic layers permit to propose a scenario of the Neogene evolution of the Guercif basin and to associate this evolution to that of western Mediterranean.

The Neogene-Quaternary stratigraphic series includes the following units from base to the top: basal Tortonian conglomerate (Draa Sidi Saada unit) outcropping at the western margin of the Guercif basin, Ras el Ksar unit representing a marine Tortonian transgression and conformably overlaid by the Melloulou Formation (Bernini *et al*., 1992), which consists of marine sediments. Within these marls, two turbidite packages have been identified (El Rhirane and Tachrift) which mark the limit between the Tortonian and the Messinian (Gelati *et al.,* 2000). The top of the Melloulou unit is characterized by gypsiferous marls levels of Messinian age. These formations are discordantly overlaid by the Kef Ed Deba Formation of Messinian age, which is discordantly overlaid by the Pliocene Bou Irhardaine Formation (Fig. 7).

The marine Melloulou upper Tortonian unit was developed in the west of the Guercif basin, in deep marine environments controlled mainly by tectonics and eustatism. Seismic profiles show that the greatest thickness of Tortonian sediments is associated with significant synsedimentary normal faults of Tortonian age (Sani *et al.*, 2000). The deposits indicate a relatively deep environment of about 600 m at about 8 Ma (Barhoun and Bachiri Taoufiq, 2008). On the northeast edges of the Guercif basin, the palaeoreliefs led to a variability of the facies. In this area, the Khendek el Ouaich section is marked by a small series with very distinct coastal facies. Lignite levels are rich in micromammals and particularly rodents dated as middle Turolian. The basis of the Melloulou unit is then correlated with

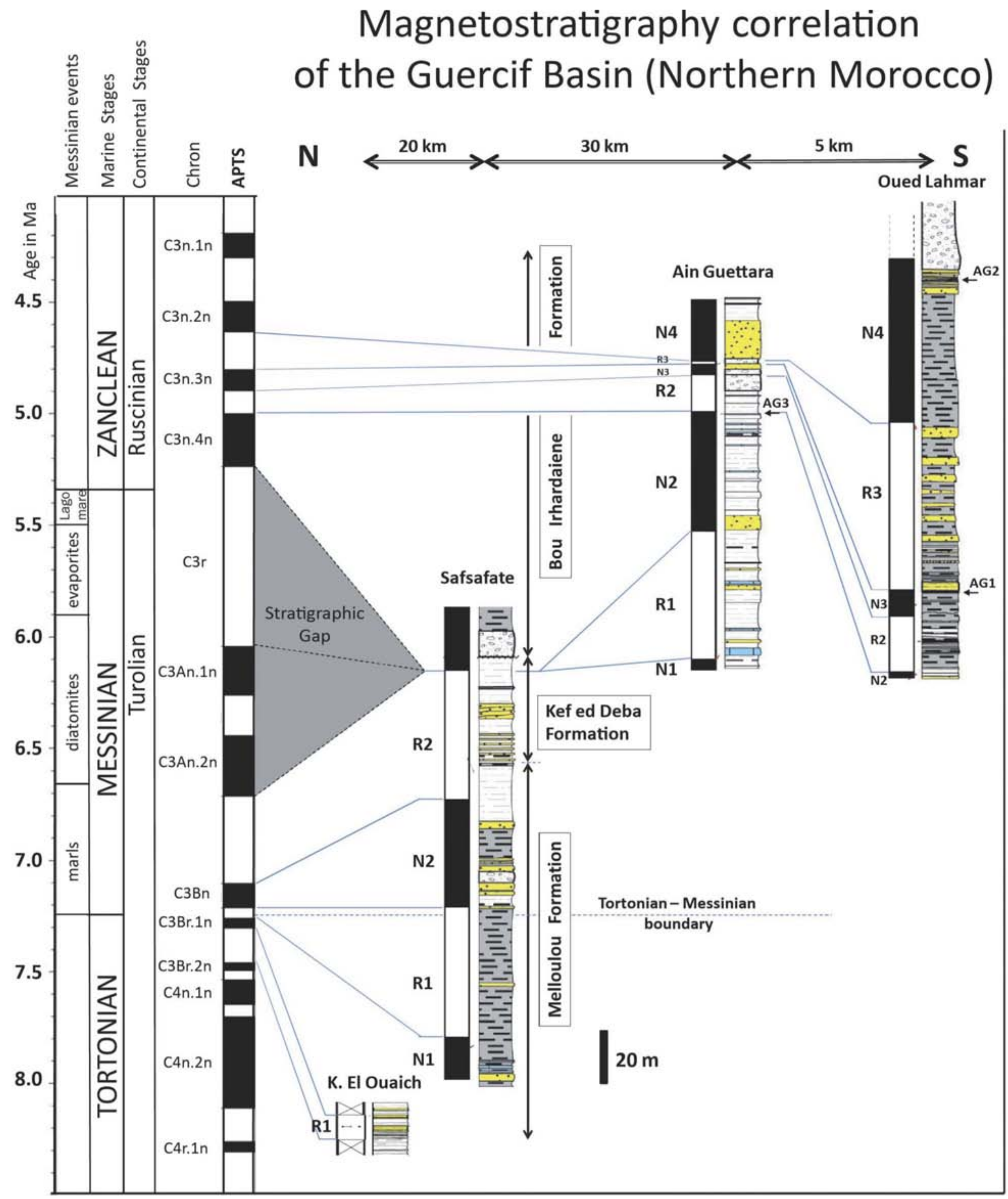

Fig. 7.- Lithology and polarity of the four sections in the Guercif basin and correlation to the APTS (Hilgen *et al.*, 1995), marine stages (Berggren *et al.*, 1995), continental stage (Gradstein *et al.*, 2012) and the chronology of Messinian facies types (Hilgen *et al.*, 1995). Chron nomenclature after Cande and Kent (1992).

Chron C3Br.2r of the GPTS (Gradstein *et al.*, 2012) and extends in age between 7.285 Ma and 7.489 Ma. Coevally, the base of the Safsatafe section shows more than 50 m of deeper marine deposits of the Melloulou unit that can be correlated to Chron C3Br.1r.

The Tortonian-Messinian (T/M) boundary, at around 7.24 Ma, is represented in the Safsafate section by an oyster-bearing horizon that underlines the passage to internal platform environments. In the deep areas of the basin, the T/M boundary is marked by a brutal impoverishment of the microfauna and the marine microflora (Barhoun and Bachiri Taoufiq, 2008). This situation of marine environment is linked to a rapid narrowing of the Rifian corridor, which accentuated the eustatic decline of the sea level in relation to tectonic activity (displacement of the Prerifian nappes) (Bachiri Taoufiq, 2000; Dayja and Bignot, 2003). The Safsafate section shows that after the T/M boundary, which coincides with the lowermost Chron C3Br.1r (7.246 Ma), the Melloulou unit starts with turbidite packages of El Rhirane and Tachrift and continues with the Gypsiferous Marl Melloulou subunit.

The Kef Ed Deba Formation was deposited during the top of the reverse event C3Br. During this early Messinian time period, the marine environment becomes more and more proximal from circalittoral to infralittoral (Barhoun and Bachiri Taoufiq, 2008). The decline in the sea level was estimated at 50 m at around 6.5 Ma (Bachiri Taoufiq, 2000). In the Safsafate section, a gap in sedimentation of about 1.26 Ma marks the unconformity between the Messinian Kef Ed Deba and Pliocene Bou Irhardaiene formations (absence of the chrons C3An.1n to C3r). More in the southwest, Krijgsman and Langereis (2000) suggest on the synthetic section of Zobzit and Koudiat Zarga, that the unconformity has a hiatus of sedimentation between the marine and continental formations of some 700 kyr. Colletta (1977) shows that the Messinian series thinned and disappeared west of the Safsafate section. The series are reduced in thickness and are represented only by sandy levels. Further to the west, the series disappears and the Late Pliocene to recent Quaternary conglomerates of the Bou Irhardaiene Formation are deposited unconformably on the Tortonian marls. They attest of a change in the general dynamics of the deposits of the Guercif basin, making an emersion of the western domain and a confinement of the eastern one, where areas of shallow water could still exist, and particularly in northeast of the basin.

This period of late Messinian coincides with disturbances in the western Mediterranean in relation to eustatism and tectonics. Eustatism is marked by decline in sea level (Haq *et al.*, 1988) and the increase in global ice volume (Hodell *et al.*, 1994). Tectonic movements along the Betic and Rifian corridors are responsible for the advancement of the Rif thrusts and olistostrome emplacement and the emersion of the Guercif basin and, on a large scale, for the isolation of the Mediterranean during the Messinian and the first Pliocene transgression (Krijgsman *et al.*, 1999; Hodell *et al.*, 2001). The Rifian Strait which formed one of the sea routes between the Atlantic Ocean and the Mediterranean at the end of the Tortonian at about 8 Ma (Benson *et al.*, 1991) was closed at 5.6 Ma (Warny, 1999) or probably before 6 Ma (Garcés *et al.*, 1998; Martín *et al.*, 2001; Braga *et al.*, 2003). Land-based wildlife exchanges between western Africa and western Europe occurred during the normal event C3An.1n. This emersion reflects the cessation of communication between the Atlantic and the Mediterranean Sea through the South Rifian Strait and the starting of outbreak of the Messinian salinity.

The closure of the thresholds of the Rifian corridor and the Betic Strait, which ensured communication between the Mediterranean basin and the Atlantic Ocean, is caused by the convergent movement of African and European plates. The Mediterranean is then in the configuration of an endorheic basin subjected to a sub-arid climate (Suc and Bessais, 1990) and a negative water balance, causing a drop in the sea level over 1500 m (Hsü *et al.*, 1973; Ryan, 1976). This drastically drop between 5.6 and 5.32 Ma is known by the Messinian salinity crisis.

Tectonic uplift generated in the Guercif basin, a rapid decrease in depositional depth. This event is associated with a restriction of the circulation of Mediterranean waters. During this period, a thick lagoon-lacustrine layer developed in the eastern domain of Guercif basin, which presupposes the presence of a small slice of water (Colletta, 1977). This layer passes laterally, on the borders of the basin, to detrital sedimentary bodies resulting from the erosion of the margins and more to the west is thinned and disappears completely. The magnetostratigraphic study of the Ain Guettara section in the southeastern part of the basin shows that the deposits of the basic series of the Bou Irhardaine unit are synchronous with the Chron C3r.

On the western margins of this restricted basin, this period of 6.0 Ma to 5.3 Ma is marked in the Safsafate section by an unconformity between the Kef Ed Deba and Bou Irhardaiene formations. In the Koudiate Zerga section, Krijgsman *et al.* (1999) showed that this basin had emerged at about 6.0 Ma, long before the time when the Mediterranean was isolated at the end of the Messinian (between 5.5 Ma and 5.3 Ma, according to Hilgen *et al.*, 1995). This period is the time of transition to an intra-continental basin (Pratt *et al.*, 2016). Further west, the Tortono-Messinian sediments are affected by a major fluvial erosion that sometimes signs the base level of Tortonian (Colletta, 1977).

During the Pliocene, the Bou Irhardaiene series evolves east and southeast of the Guercif basin in a large endorheic basin (Colletta, 1977) with a little thick and very detritic regressive series which bevels and disappears towards the west. The availability of sediments that have filled the basin seems to has been controlled by the relative elevation of the Middle Atlas Mountains (Pratt *et al.*, 2016). This series has provided a rich fauna of micromammals. The magnetostratigraphy correlates the rodent fauna harvested in the Bou Irhardaiene formation with the chrons C3n.4r and C3n.2n. On a global scale, this period of the Lower Pliocene is marked by the return of waters to the Mediterranean basins, following the opening of the Straits of Gibraltar.

While the subsidence of the Guercif basin was controlled from the late Tortonian by loading from the Rif interacting with Middle Atlas structures and then sediment loading (Pratt *et al.*, 2016), the compressional regime continued into the Plio-Quaternary and involves reactivation of the pre-existing inversion structures as well as the formation of narrow salt-cored anticlines. The same compressional regime is also responsible for the renewed uplift of the Middle Atlas and the Masgout uplift to the north of the basin.

Conclusion

This study has allowed drawing the Neogene evolution of the Guercif basin in northern Morocco from magnetostratigraphic data, supplemented by biochronological data and numerical ages derived from the radio-isotopic dating of volcanic layers. The evolution of the Guercif basin in the context of western Mediterranean has also been discussed. Four sections were selected in Guercif basin: Khendek el Ouaich, Safsafate, Ain Guettara and Oued Lahmar. By combining four sections, a complete succession of the upper Tortonian to the Pliocene has been produced with a robust calendar adapted to a global correlation. The results of this study constitute references for the Mediterranean region.

Paleomagnetic analyses show that the main magnetization of the sediments is carried by magnetite, titano-magnetite, hematite and goethite. The directions of normal and reverse polarities are antipodal and the reversal test is positive, which suggests that the remanent magnetization is primary. The polarity sequences from Neogene samples are correlated with different chrons of the upper Tortonian to Lower Pliocene, and indicates according to GPTS of Gradstein *et al.* (2012) an age between 7.5 Ma (base of reverse chron C3Br.2r) to 4.493 Ma (base of C3n.2n). Biostratigraphic data obtained from micromammals association are well correlated with chrons. The association of rodent fossils collected is dated in continental stage from middle Turolian to lower Ruscinian. Finally, the presence of volcanic ash levels related to Guilliz volcanic activity dated 7.4 ± 1.2 Ma (Choubert *et al.*, 1968) permitted a radiometric dating of continental sediments and allow us correlating them to the GPTS (Gradstein *et al.*, 2012).

In addition to the stratigraphic correlation, several non-repetitive phases can be distinguished at the end of Neogene, which can be related to the environmental changes related to the geodynamic reorganizations of the Mediterranean area caused by the convergent movement of African and European plates. We provide an astronomical age for the most pronounced lithological changes and therefore for significant environmental events occurring at: the installation of deep marine environment at about 8 Ma, the passage to internal platform at the Tortonian-Messinian boundary (around 7.24 Ma), emersion of the western domain of Guercif basin and confinement of the eastern one from 6.7 to 6.0 Ma, closure of the Rifian corridor and the Betic Strait at 5.6 Ma and cessation of communication between the Atlantic and the Mediterranean Sea, the Messinian salinity crisis between 5.6 and 5.32 Ma, development of detritic regressive series from 5.3 Ma in the Guercif basin while the return of waters to the Mediterranean basins followed the opening of the Straits of Gibraltar. These events have proved remarkably synchronous in the Mediterranean and are probably linked to a combination of geodynamic and climatic changes.

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