International Union of Geological Sciences
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Subcommission on Neogene Stratigraphy

THE GLOBAL BOUNDARY STRATOTYPE SECTION AND POINT (GSSP) OF THE MESSINIAN STAGE (UPPERMOST MIOCENE)

A proposal by:

F.J. Hilgen, W. Krijgsman, C.G. Langereis, W.J. Zachariasse,
S. Iaccarino, G. Villa, R. H. Benson (?) and M. Dahmani

1. BACKGROUND AND MOTIVATION

Stability in global chronostratigraphic units is needed for the construction of geological maps and to facilitate communication between earth scientists. Stability in chronostratigraphic units can be achieved by carefully selecting GSSPs following the procedures and guidelines set by the International Commission on Stratigraphy (ICS; Remane et al., 1996). During the last years, much progress has been made in the Pliocene and GSSPs have now been formally accepted for the Piacenzian (Middle Pliocene) and Gelasian (Upper Pliocene).

Much progress has also been made in establishing integrated stratigraphic frameworks for the Upper Miocene in the Mediterranean and the open ocean. The long lasting debate about the age and position of the Tortonian/Messinian boundary has finally been settled and time seems to be ripe for submitting a formal proposal of the GGSP for the base of the Messinian to the International Commission on Stratigraphy. The Oued Akrech section located on the Atlantic side of Morocco is the section most suitable for defining the Messinian GSSP. Here we present the preliminary version of the proposal to be commented and voted by members of the SNS.

1.1 Messinian stage: a brief historical review

1.1.1 Original definition of the Messinian (Mayer-Eymar, 1867)

The Messinian (after the town of Messina, Sicily, Italy) Stage was introduced by Mayer-Eymar in 1867, and more precisely defined in 1868 to fill up the gap between the Tortonian and the Astian s.l. According to Mayer-Eymar, the latter was equivalent to the entire Pliocene and included the Tabianian, Piacenzian and Astian s.s. Apparently, Mayer erected the Messinian without a (detailed) knowledge of the local stratigraphy of Sicily in order to compete with the Zanclean (= latin name of Messina) Stage introduced by Sequenza one year later (Sequenza, 1868). In his original definition, Mayer-Eymar (1867) subdivided the Messinian from top to bottom in three units (see Selli, 1971; Cita, 1975):

- Couches d'Eppelsheim ("les cailloux roulés du Tortonais et du Plaisantin, sables et cailloux à *Dinotherium* du bassin du Danube, du Jura et du bassin rhénan, et les dépôts analogues du Sud-Ouest de la France");

- Couches d'Inzendorf ("les couches à Dreissénies (ou Congéries) du bassin du Danube et de Kertsch, la région des gypses supérieurs de l'Appennin septentrional, et la molasse d'eau douce supérieure de la Suisse, etc."), and;

- Couches de Billowitz ("les couches à Cérithes et à *Mactra podolica* du bassin du Danube et de la Russie; marnes à Cérithes de Stazzano et de Ste-Agata près de Tortone, et la molasse sableuse, micacée et blanchâtre, du Nord du Suisse").

He then equates these units with the local stratigraphy of Sicily in the following terms "... *Les marnes marines miopliocènes des environs de Messine, en revanche, vu leur grande puissance, correspondront vraisamblablement aux trois niveaux à la fois*". He thus considers these marls to be time-equivalent to his three units. The lack of knowledge of the local stratigraphy becomes evident in Mayer (1868) where he subdivided the Messinian - clearly indicated as post-Tortonian and pre-Astian (s.l.) - of southern Italy more precisely in three units (from top to bottom):

- Marnes sableuses jaunâtres des envir. de Messine, de Reggio (Calàbre), de Rome, etc.

- Calcaires à polypiers des environs de Messine, gypse de Barcellona p.de Messine?, calc. caverneus du cap des Armes (Calàbre), etc.

- Marnes blanches à foraminifères des envir. de Messine, de Reggio, du cap des Armes, de Monasterace, du Val Lamato, etc.

This list includes the gypsum of the Gessoso-Solfifera Formation and possibly also diatomites of the underlying Tripoli Formation. But it contains several pertinent errors (Selli, 1960; Cita, 1975) as well, for instance the Trubi marls which are now regarded to be of Pliocene (Zanclean) age. His list of stratigraphic units from the Messinian of northern Italy, however, is more precise (see Selli, 1960). And in 1878, Mayer-Eymar states explicitly that the middle Messinian is represented by gypsum and associated limestones throughout the Apennines. In the lower Messinian, he includes "gelbliche bis schwärzliche Schiefertone" which may represent the equivalent of the Tripoli diatomite Formation of Sicily. The upper Messinian contains continental deposits, which indicate a regressive phase prior to the (basal) Pliocene transgression.

1.1.2 Messinian neostratotype section of Pasquasia-Capodarso (Selli, 1960)

During the meeting of the Committee of the Mediterranean Neogene held in Vienna in 1959, the issue of the most appropriate term to indicate the interval between the Tortonian and Pliocene was discussed at length. The majority of the participants was in favour of adopting, among other candidates, the Messinian as the standard geochronological unit for this time interval. At the same time this decision necessitated the search for a stratotype since Mayer-Eymar never actually defined one. This elaborate task was undertaken by Selli (1960), who eliminated the existing inconsistencies in the original definition of Mayer-Eymar and defined the Messinian as the "intervallo di tempo compresa fra il Tortoniano (strati di Tortona) e il Pliocene (strati di Tabiano), caracterizzato in tutto il Mediterraneo e nella Paratetide da una crisi di salinità e in Italia essenzialmente da un ambiente iperalino e da sedimenti evaporitici". He proposed the Pasquasia-Capodarso section located on central Sicily (Figs. 1 and 2) as neostratotype and argued that the Tortonian/Messinian boundary be placed 25 m. below the local base of the Tripoli diatomite Formation (Fig. 2), at the level that coincides with the first marked environmental change indicated by dystrophic faunal elements, which he interpreted as the actual beginning of the Messinian salinity crisis. But his paleoenvironmental criterion made it difficult to export the boundary, in particular to the extra-Mediterranean realm. Moreover, the position of T/M boundary became particularly unclear because the lower boundary of the Messinian as proposed by Selli differed considerably from three definitions of the upper boundary of the Tortonian (viz. that of Mayer-Eymar, 1868; Gianotti, 1953; Cita, 1965; see D'Onofrio et al., 1975 and Fig. 3).

1.1.3 The proposed boundary stratotype of Falconara (Colalongo et al., 1979)

To eliminate these apparent short-comings, a working group was established within the framework of the Italian research program on the "Geodynamic significance of the latest Miocene salinity crisis in the Mediterranean" to identify and more accurately define the lower boundary of the Messinian on the basis of planktonic foraminiferal and, subsequently, calcareous nannofossil biostratigraphy (e.g. D'Onofrio et al., 1975; Mazzei, 1977). For this purpose several Italian land-based sections were studied including the Tortonian stratotype of Rio Mazzapiedi-Castellania and the Messinian neostratotype at Capodarso. The members of the working group showed 1) that the first occurrence of *Globorotalia conomiozea* is the most reliable biostratigraphic event of those closest to the (three) proposed upper boundaries of the Tortonian, and 2) that it is impossible to detect the preferred T/M boundary at Capodarso because the lower part of the section had been burried by a landslide. Moreover, the *G. conomiozea* FO - and the *Amaurolithus delicatus* FO from a calcareous nannoplankton point of view - appeared to best approximate the beginning of the Messinian salinity crisis sensu Selli (1960). In this respect, the selection of the *G. conomiozea* FO agrees with the recommendation that the top of a stage may be defined by the bottom of the next younger one (e.g., Whittaker et al., 1991).

Because the boundary interval had been covered by a landslide at Pasquasia-Capodarso, Colalongo and others (1979) resorted to the Falconara section. They proposed to emend the Tortonian and Messinian stages and define the T/M boundary at the *G. conomiozea* FO level, 6m below the local base of the Tripoli diatomite Formation (Fig. 4). Unfortunately, the Falconara section proved unsuitable for establishing a reliable magnetostratigraphy because of secondary remagnetisations (Langereis and Dekkers, 1992) whereas tectonic deformation caused by thrust-related gravitational sliding is present, in particular directly below the diatomites. In addition, the boundary interval in the western gully complex where Colalongo and coworkers proposed to define the boundary has recently been covered by a landslide (field observations, 1997). These observations - once more - necessitated the search for an alternative T/M boundary stratotype section. It was equally clear that the *G. conomiozea* FO should be maintained as the main criterion for selecting the most suitable section and level to define the Messinian GSSP.

1.1.4 Age of the T/M boundary

The research carried out by the Italian working group led to a much more precise identification of the lower boundary of the Messinian based on calcareous plankton biostratigraphy, thus facilitating its recognition on a more global scale. And even though their proposal (Colalongo et al., 1979) was never formally accepted, consensus was nevertheless reached about the biostratigraphic criterion, the *G. conomiozea* FO in the Mediterranean, to delimit the boundary. At that time, large uncertainties in the age of Neogene stage boundaries were the result of stratigraphically correlating radiometrically dated North American mammal faunas via regional Parathethian Stages to the standard marine stages in the Mediterranean (Evernden et al., 1964; see Laurenzi et al., 1997). Subsequently, these uncertainties were considerably reduced by the publication of the first K/Ar datings of marine successions in the Mediterranean (Eberhardt and Ferrara, 1962; Tongiorgi and Tongiorigi, 1964; Charlot et al., 1967; Choubert et al., 1968). The unexpectedly young ages paved the way for more accurate and precise age determinations, which had to come from the application of the geomagnetic polarity time scale which just had become established (e.g., Heirtzler et al., 1968).

Despite the good prospects, the age of the T/M boundary remained a hotly debated issue in Neogene geochronology and chronostratigraphy. Magnetostratigraphic studies of deep-sea sediments yielded age estimates that ranged from 5.6 via 6.2 to 6.5 Ma, pending the synchroneity or diachroneity of bio-events and the exact calibration of magnetostratigraphic records to the geomagnetic polarity time scale. High-quality magnetobiostratigraphic data from late Miocene sections on Crete played a crucial role in the discussion (Langereis et al., 1984; see also Berggren et al., 1985; Hsü, 1985). The age and magnetostratigraphic calibration of the boundary remained highly controversial despite new results from ODP Leg 107 results (Channell et al., 1991; Kastens, 1992). The age problem reached a climax with the publication of a much older K/Ar age estimate of 7.26 Ma for the T/M boundary in the northern Apennines (Vai et al., 1993).

The problem was solved with the publication of the GPTS of Cande and Kent (1992). This time scale revealed two additional short normal subchrons in the critical interval. The extra subchrons allowed a straightforward calibration of the Cretan magnetostratigraphy, resulting in an age of 6.92 Ma for the T/M boundary (Krijgsman et al., 1994). The correlation of characteristic sedimentary cycle patterns to the astronomical record resulted in an astronomical age of 7.24 Ma (Hilgen et al., 1995), in agreement with the radiometric age estimates of Vai et al. (1993) and Laurenzi et al. (1997).

1.1.5 Astronomical time scales

During the last years, the application of the astronomical dating technique has resulted in astronomical time scales for the entire Plio-Pleistocene which now underly the standard geological time scale for the same time interval (Berggren et al., 1995). An important advantage of the astronomical dating technique is that the Pliocene/Pleistocene boundary as well as the more recently defined GSSPs of the Gelasian and Piacenzian are defined at lithological marker beds which are integral part of a sedimentary cyclicity that has been astronomically dated. As a consequence, the GSSPs are directly tied via first-order calibrations to the standard geological time scale. With the emergence of similar astronomical time scales for the Miocene (Hilgen et al., 1995), the same strategy is to be followed for selecting the Messinian GSSP, in addition to the conventional criteria as outlined in the revised guidelines for the establishment of global chronostratigraphic standards by the ICS (Remane et al., 1996). This implies that, other requirements being equal, cyclostratigraphy will play an important role in selecting the most suitable section and level for defining the Messinian GSSP.

1.2 Present status of the Messinian stage

A Messinian GSSP is imperative because the Messinian is still widely used, and considered valid as the standard chronostratigraphic unit for the uppermost Miocene. The Messinian was adopted as the preferred global geochronologic unit for the latest part of the Miocene during the meeting of the Committee of the Mediterranean Neogene held in Vienna in 1959. This decision was important because it marked the end of almost a century during which a multitude of names were used for this time interval. The Messinian has been since incorporated in most standard geological time scales. Its global status has recently been questioned by Benson and Rakic-El Bied (1996) who considered the Messinian merely as a regional Mediterranean stage when they proposed to define the Miocene/Pliocene boundary at the base of the Gilbert Chronozone in the Ain el Beida section on the Atlantic margin of Morocco. A clear majority of SNS members nevertheless voted - again - in favour of the Messinian as the global stage for the uppermost Miocene when they responded to the questionnaire circulated by the SNS in the spring of 1997. This outcome led to the formulation of the present proposal.

1.3 Selecting the most suitable section and level for defining the Messinian GSSP

1.3.1 Selecting the section

The selection of a section suitable for defining the Messinian GSSP is not a difficult task, despite the unsuitability of both the Falconara and Capodarso/Pasquasia sections,. At present, numerous sections are available that cover the critical interval in a continuous marine succession (Monte del Casino in northern Italy; Faneromeni, Potamida and Kastelli on Crete, Greece; Metochia on Gavdos, Greece; Oued Akrech, Morocco). All these sections have been astronomically dated and cyclostratigraphically correlated in detail, and fulfil most if not all of the requirements recommended by the ICS (Remane et al., 1996). However, considering the more important criteria for the late Neogene time interval (calcareous plankton biostratigraphy, magnetostratigraphy and astronomically dated cyclostratigraphy), the Oued Akrech section located at the Atlantic side of Morocco appears to be the most suitable section. The fact that - in that case - the GSSP will be outside its type area on Sicily and even outside the Mediterranean is not considered as a problem in view of the excellent and straightforward integrated stratigraphic correlations of Oued Akrech to sections within the Mediterranean (see further under motivations).

1.3.2 Selecting the boundary criterion

Colalongo and coworkers proposed the FO level of typical *G. conomiozea* (s.s.) to define the T/M boundary. Here we slightly deviate from this criterion by selecting the first regular occurrence (FRO) of the entire *G. conomiozea* group rather than the FO of *G. conomiozea* s.s. The FRO event marks the abrupt replacement of dextrally coiled *G. menardii* assemblages by sinistrally coiled assemblages of the *G. conomiozea* group (=*G. miotumida* group of Sierro et al., 1993), and predates the FO of *G. conomiozea* s.s. by approximately 40 kyr in most of the sections. The reason to do so is twofold.

Firstly, the event is better recognised in the North Atlantic Ocean where conical forms are typically rare or completely lacking (Sierro, 1985; Sierro et al., 1993). Secondly, the true FO of typical *G. conomiozea* coincides almost exactly with the FRO of the *G. conomiozea* group in the very high-resolution sample set from the Potamida section on Crete (Zachariasse, 1979). The *G. conomiozea* s.s. FO as reported in the literature often marks the first massive influx of conical representatives of the

G. conomiozea group. This massive influx has now been found in the Faneromeni and Potamida sections on Crete, the Monte del Casino section in northern Italy, the Gibliscemi section on Sicily and the Molinos section in southeastern Spain and slightly postdates the boundary as proposed here. The brief presence of the *G. conomiozea* group at two much older Tortonian levels in the Gibliscemi, Monte del Casino and Metochia sections is the reason to use the FRO notation for the event at the T/M boundary.

1.4 Motivations

Of all the candidate sections, Oued Akrech is the only section that has an excellent magnetostratigraphy, calcareous plankton biostratigraphy and cyclostratigraphy in the critical interval across the T/M boundary. An important additional argument for selecting Oued Akrech is to emphasise that the Messinian is a global chronostratigraphic unit and not a Mediterranean stage of regional significance only, as argued for instance by Benson and Rakic-El Bied (1996).

2. THE PROPOSED GSSP OF THE BASE OF THE MESSINIAN

Name of boundary: Base of Messinian.
Rank of boundary: Stage/Age.
Position of the unit: Uppermost part of the Miocene Series, between the Tortonian (below) and Zanclean (above) Stages.
Type locality of the Global Stratotype Section and Point: Oued Akrech, Morocco, Africa. The Oued Akrech section contains the basal part of the so-called "Blue Marls" of Atlantic Morocco and represents the lower part of the Bou Regreg composite section (Cita and Ryan, 1978; Benson et al., 1991).
Geographic location: The Oued Akrech section is located 10 km SSE of Rabat in a road-cut along a steep bluff next to the Oued Akrech ("oued" = "wadi" = valley; Fig. 5). Oued Akrech is a tributary of the Bou Regreg river that forms a deep valley in southward direction as the Bou Regreg river turns to the east (topographic map NI-29-XII-3C coordinates, 370.2 - 370 to 371).
Latitude: 33° 55′ North; **Longitude:** 6°48'45" East of Greenwich.
Map: The area is represented on topographic map NI-29-XII-3C.
Accessibility: The section is within easy reach from Rabat and Casablanca and is freely and easily accessible to scientists interested in studying the section.
Conservation: Necessary steps are being undertaken for the conservation of the section.
GSSP definition: The base of reddish layer no.15 in the Oued Akrech section is proposed as the GSSP of the base of the Messinian Stage (Figs. 6-9). This point coincides almost exactly with the First Regular Occurrence (FRO) of the *Globorotalia conomiozea* group and falls within C3Br.1r. The bed has been assigned an astronomical age of 7.242 Ma.

Identification in the field: The base of the reddish layer no. 15 is marked by a metal tag in the section. Identification and resampling of the section are greatly facilitated by the characteristic sedimentary cycle pattern.

Completeness of the section: The Oued Akrech section contains an excellent and continuous faunal and polarity record across the boundary interval. The presence of the characteristic sedimentary cycle pattern allows the section to be astronomically dated, thus providing a highly accurate age for the GSSP (Fig. 8). The section has been correlated cyclostratigraphically in detail to numerous open marine sections in the Mediterranean (Fig. 9). These correlations are confirmed in detail by the high-resolution calcareous plankton biostratigraphy, thus excluding hiatuses in the astronomically dated Blue Marl part of the section. Sediment accumulation rates can be accurately determined using the astrochronology and vary between 1.5 and 3.5 cm/kyr with an increase to 6 cm/kyr higher in the section.

Regional correlation potential: Integrated stratigraphic correlations of the proposed Messinian GSSP to the Mediterranean are straightforward and unambiguous (Fig. 9). High-resolution cyclostratigraphic correlations are confirmed in detail by the position of calcareous plankton events and magnetic polarity reversals. Biostratigraphically, this applies both to major bio-events such as the FO of *A. primus,* the FCO of *G. menardii 5* and the FRO of *G. conomiozea*, as well as to secondary events such as coiling changes in the unkeeled globorotaliids and short-term influxes of conical assemblages of the *G. conomiozea* group.

Global correlation potential: Global correlations are assured by the calibration of the Oued Akrech magnetostratigraphy to the geomagnetic polarity time scale, locating the GSSP in the middle of C3Br.1r. The characteristic polarity pattern allows identification of the boundary in continental settings lacking a direct biostratigraphic control. In the marine realm, the calcareous nannofossil genus *Amaurolithus* provides a series of extremely useful events to delimit the boundary on a global scale. The *A. primus* FO predates the boundary while the *A. delicatus* and *A. amplificus* FO's postdate the boundary (see Raffi et al., 1995; Backman and Raffi, 1997). The *Reticulofenestra rotaria* FCO is another useful nannoplankton event that predates the boundary (Negri et al., subm.).

The abrupt replacement of dominantly dextrally coiled assemblages of *G. menardii 5* by dominantly sinistrally coiled assemblages of the *G. conomiozea* group can be used to recognise the boundary in the Mediterranean and the adjacent North Atlantic (Sierro, 1985; Sierro et al., 1993).

Stable isotopes yet provide another correlation tool. The Late Miocene Global Carbon isotope shift (in $\delta^{13}C$ carbonate) straddles the boundary in the open ocean and adjacent basins such as the Mediterranean, and has been identified by Hodell et al. (1994) in the Salé drill core. In the continental realm, a significant shift in opposite direction is found in terrestrial $\delta^{13}C$. Despite being diachronous on a global scale, the shift approximates the T/M boundary better than the Miocene-Pliocene boundary as indicated by Cerling et al. (1997).

3. SUMMARY OF BACKGROUND STUDIES

The classical Blue Marls of Atlantic Morocco have been subject of numerous studies, reflecting the progress being made in Neogene integrated stratigraphy (Choubert et al., 1964; Feinberg and Lorenz, 1970; Bossio et al., 1976; Moreau et al., 1985; Wernli, 1988). The entire Oued Akrech road section was studied by Cita and Ryan (1978) and Benson and co-workers, while the Utrecht-Parma research team focussed their studies on the well exposed lower part only.

Geological setting.

The Blue Marls as exposed in the Oued Akrech section were deposited in the Gharb basin which represents the westward extension - and opening to the Atlantic - of the Rifian Corridor. The Blue Marls can easily be traced into the corridor itself and its series of smaller and interconnected basins. The corridor acted as an extensional foredeep during the late Miocene to early Pliocene, seperating the active Rif Orogen and nappe complex in the north from the Central Moroccon Meseta to the south (Benson and Rakic-El Bied, 1996). The Rifian Corridor formed one of the two Atlantic-Mediterranean connections during the Neogene. While the marine gateway was closed in the course of the Messinian, deposition of Blue Marls in the Gharb Basin continued well into the Pliocene (e.g., Benson and Rakic-El Bied, 1996).

Stratigraphic succession

The Neogene succession at Oued Akrech starts with an Upper Tortonian shallow marine glauconitic sandstone, locally referred to as "Molasse de Base". This 5m thick yellowish coloured sandstone overlies - steeply inclined - Devonian limestones with an angular unconformity and is followed by an indurated phosphatic layer. This layer, which represents a period of a strongly reduced sediment accumulation rate, is succeeded by glauconitic sandy marls and a 2m thick deep marine sandy marl with numerous biogenic components. The latter contains the solitary coral *Flabellum* and is locally termed the Coraline Zone.

The part of the Oued Akrech section that is of relevance for the Messinian GSSP starts directly above the Coraline Zone. It consists of deep marine marls known as the Blue Marls after their distinct fresh colour. The weathered colour of these marls, however, is a yellow-beige colour with reddish colour bands (colour cycles).

Depositional environment

Marine sedimentation in the Oued Akrech section starts with shallow marine beach sands. The depositional environment changed rapidly from sublittoral to upper bathyal (paleodepth 500 to 700 m.) at the level of the phosphatic layer, as indicated by the benthic microfauna (Benson and Rakic-El Bied, 1996).

Calcareous nannoplankton biostratigraphy

Calcareous nannofossils are abundant and generally well preserved. They were studied by Benson and co-workers and the Utrecht-Parma team. The GSSP falls within Zone NN11b of Martini (1971) and Zone CN9b of Bukry (1973; 1975) and Okada and Bukry (1980).

Planktonic foraminifera biostratigraphy

Planktonic foraminifera are abundant and generally well preserved. They have been studied by Cita and Ryan (1978), Benson et al. (1991) and the Utrecht-Parma team. The GSSP falls within (sub)tropical Zone M13b (*Globigerinoides extremus /Globorotalia plesiotumida-Globorotalia lenguaensis* Interval Subzone) and coincides with the transitional Mt9-Mt10 Zonal boundary (*Globorotalia conomiozea*/*Globorotalia mediterranea*-*Globorotalia sphericomiozea* Interval Subzone) of Berggren et al. (1995).

Magnetostratigraphy

The magnetostratigraphic records of Benson and co-workers (see Hodell et al., 1994; Benson and Rakic-El Bied, 1996) and the Utrecht-Parma tean are different. The reversed interval that contains the T/M boundary has been missed by Benson and co-workers apparently because of a too low sample resolution. It has been recorded in drill cores from nearby Ain el Beida and Salé (see Hodell et al., 1994). The normal interval at the base of Oued Akrech was not substantiated by the more recent paleomagnetic study because of adverse magnetic properties in this part of the section. The new magnetostratigraphy across the boundary is of excellent quality, however, and its calibration to the GPTS is straightforward through the integrated stratigraphic correlations to well-calibrated Mediterranean sections (Figs. 7 and 9). The two normal polarity intervals and intervening reversed interval thus correspond – from bottom to top - to C3Br.1n, C3Br.1r and C3Bn.

Cyclostratigraphy and astrochronology

Colour cycles in the Blue Marls of Atlantic Morocco consists of regular alternations of indurated light beige coloured marls and softer, more clayey and reddish marls. Cita and Ryan (1978) were the first to recognise the climatic significance and stratigraphic potential of the colour cycles in the Blue Marls. They interpreted the cycles as climatically modulated cold/warm oscillations and related them to sea-level changes at the time of the acme of Antarctic glaciation. Benson et al. (1995) were the first to use the cycles for high-resolution stratigraphy and applied image analyses techniques to astronomically tune the colour cycles across the lower Gilbert reversal boundary in the Bou Regreg section.

Colour cycles are also evident in the basal part of the Blue Marls - as exposed at Oued Akrech - in which 20 reddish layers of varying thickness and colour intensity have been indentified. Magnetobiostratigraphic correlations to time-equivalent sections in the Mediterranean clearly indicate a dominant precession control on the basic colour cycle thereby confirming earlier interpretations by Benson et al. (1995) for similar colour cycles at Ain el Beida. The alternation of thin(ner)/vague and thick(er)/prominent reddish layers reflect interference between precession and obliquity (cf., Hilgen et al., 1995; Lourens et al., 1996). Initially, the astronomical tuning of the colour cycles was hampered by the fact that their phase relations with the Earth's orbital cycles was not known. The characteristic interference patterns, however, allow for one possible calibration (and thus for one possible phase relation) only if the same astronomical target curve is applied as for dating time equivalent cycles in the Mediterranean.

Faunal fluctuations and stable isotopes

A relatively low resolution benthic stable isotope record has been established for Oued Akrech (Hodell et al., 1989) in which the global Chron 6 Carbon shift can easily be recognised.

Figure captions

Figure 1. Location map of relevant sections

Figure 2. The Pasquasia-Capodarso section (after Selli, 1960).

Figure 3. The position of the Tortonian/Messinian boundary in the Rio Mazzapiedi - Castellania historical stratotype of the Tortonian according to different authors.

Figure 4. The proposed T/M boundary stratotype section of Falconara (after Colalongo and Pasini, 1997; modified after Colalongo et al., 1979).

Figure 5. Location map of the Oued Akrech section.

Figure 6. Planktonic foraminiferal biostratigraphy of the Oued Akrech section, showing the position of the main events (ms. in preparation).

Figure 7. Magnetostratigraphy of the Oued Akrech section (ms. in preparation).

Figure 8. Astronomical calibration of sedimentary cycles in Oued Akrech based on the integrated magnetobiostratigraphy and colour cycle patterns. Note the registration of interference patterns between precession and obliquity in the alternation of distinct and thick and less distinct and less thick reddish marl beds.

Figure 9. Integrated stratigraphic correlations to time-equivalent sections in the Mediterranean and astronomical tuning of the colour cycles.

References

Backman, J. and I. Raffi, 1997. Calibration of Miocene nannofossil events to orbitally-tuned cyclostratigraphies from Ceara Rise. Proc. ODP., Sci. Res., 154, 83-99.

Benson, R.H., K. Rakic-El Bied, and G. Bonaduce, 1991. An important current reversal (influx) in the Rifian Corridor (Morocco) at the Tortonian-Messinian boundary: The end of Tethys Ocean. Paleoceanography, 6, 164-192.

Benson, R.H. and K. Rakic-El Bied, 1996. The Bou Regreg section, Morocco: Proposed Global Boundary Stratotype Section and Point of the Pliocene. Notes et Mém. Serv. géol. Maroc., 383, 51-150.

Berggren, W.A., D.V. Kent, C.C. Swisher and M.-P. Aubry, 1995. A revised Cenozoic geochronology and chronostratigraphy. In: Geochronology, Time Scales and Global Stratigraphic Correlation, SEPM Spec. Publ., 54, 129-212.

Berggren, W.A., F.J. Hilgen, C.G. Langereis, D.V. Kent, J.D. Obradovitch, I. Raffi, M. Raymo and N. Shackleton, 1995. Late Neogene (Pliocene-Pleistocene) chronology: New perspectives in high-resolution stratigraphy. Geol. Soc. Am. Bull., 107, 1272-1287.

Bossio, A. K., El Bied-Rakic, L. Gianelli, R. Mazzei, A. Russo and G. Salvatorini, 1976. Correlation de quelques sections stratigraphiques du bassin Méditerranéen sur la base des Foraminiferes planktoniques, nannoplankton calcaire et ostracodes. Atti Soc. Tosc. Sc. Nat. Mem., 83, 121-137.

Cande, S.C. and D.V. Kent, 1992. A new geomagnetic polarity time scale for the late Cretaceous and Cenozoic. J. Geophys. Res., 97, 13.917-13.951.

Cerling, T.E., J.M. Harris, B.J. MacFadden, M.G. Leakey, J. Quade, V. Eisenmann, and J.R. Ehleringer, 1997. Global vegetation changes through the Miocene / Pliocene boundary. Nature, 389, 153-158.

Channell, J.E.T., M. Torii, and T. Hawthorne, 1990. Magnetostratigraphy of sediments recovered at sites 650, 651, 652 and 654 (Leg 107, Tyrrhenian Sea). Proc. ODP Sci. Results, 107, 335-346.

Charlot, R., G. Choubert, A. Faure-Muret, L. Hottinger, J. Marcais, and D. Tisserant, 1967. Note au sujet de l'âge isotopique de la limite Miocène-Pliocène au Maroc. C. R. Acad. Sci. Paris, 264, 222-224.

Choubert, G., L. Hottinger, J. Marcais and G. Suter, 1964. Stratigraphie et micropaléontologie du Néogène au Maroc septentrional. Inst. "Lucas Mallada", C.S.I.C. (Espana), Curs. Y Conf., 9, 229-257.

Choubert, G., R. Charlot, A. Faure-Muret, L. Hottinger, J. Marcais, D. Tisserant, and P. Vidal, 1968. Note préliminaire sur le volcanisme messinien-(pontien) au Maroc. C. R. Acad. Sci. Paris, 266, 197-199.

Cita, M.B., I. Premoli Silva and R. Rossi, 1965. Foraminiferi planctonici del Tortoniano -tipo. Riv. Ital. Paleontol. Stratigr., 71, 217-308.

Cita, M.B., 1975. The Miocene/Pliocene boundary: History and definition. In: T. Saito, and L. Burckle (eds.), Late Neogene Epoch Boundaries. Micropaleont., Spec. Publ., 1, 1-30.

Cita, M.B., D. Rio, F. Hilgen, D. Castradori, L. Lourens, and P.P. Vergerio, 1996. Proposal of the Global Boundary Stratotype Section and Point (GSSP) of the Piacenzian Stage (Middle Pliocene).

Colalongo, M.L., A. di Grande, S. D'Onofrio, L. Giannelli, S. Iaccarino, R. Mazzei, M. Romeo, and G. Salvatorini, 1979a. Stratigraphy of Late Miocene Italian sections straddling the Tortonian/Messinian boundary. Boll. Soc. Paleont. It., 18, 258-302.

Colalongo, M.L., A. di Grande, S. D'Onofrio, L. Giannelli, S. Iaccarino, R. Mazzei, M.F. Poppi Brigatti, M. Romeo, A. Rossi, and G. Salvatorini, 1979b. A proposal for the Tortonian/Messinian boundary. Ann. Géol. Pays Hellén., Tome hors série, fasc. 1, 285-294.

Colalongo, M.L., and G. Pasini, 1997. The Messinian historical stratotype and the Tortonian/Messinian boundary. In: A. Montanari, G.S. Odin, and R. Coccioni (eds.), Miocene stratigraphy: An integrated approach. Developments in Palaeontology and Stratigraphy, 15, 107-123.

D'Onofrio, S., 1964. I foraminiferi del neostratotipo del Messiniano. Giorn. Geol., 32, 400-461.

D'Onofrio, S., L. Giannelli, S. Iaccarino, E. Morlotti, M. Romeo, G. Salvatorini, M. Sampò, and R. Sprovieri, 1975. Planktonic foraminifera of the Upper Miocene from some Italian sections and the problem of the lower boundary of the Messinian. Boll. Soc. Paleont. It., 14, 177-196.

Eberhardt, P. and G. Farrara, 1962. Confirmation of the absolute age of the granodiorite outcrop in Elba Island with potassium-argon measurements. Nature, 196, 665-666.

Evernden, J.F., D.E. Savage, G.H. Curtis, and G.T. James, 1964. Potassium-Argon dates and the Cenozoic mammalian chronology of North America. Am. J. Sci., 262, 145-198.

Feinberg, H. and H.G. Lorenz, 1970. Nouvelles données stratigraphicques sur le Miocene superieur et le Pliocene du Maroc Nord Occidental. Notes Serv. Geol. Maroc, 30, 21-26.

Gianotti, A., 1953. Microfaune della serie tortoniana del Rio Mazzapiedi-Catellania (Tortona - Alessandria). Riv. It. Paleont., Mem. VI, 167-308.

Gino, G.F., 1953. Osservazioni geologiche sui dintorni di Sant'Agatha Fossili (Tortona - Alessandria). Riv. It. Paleont., Mem. VI, 7-24.

Hilgen, F.J., W. Krijgsman, C.G. Langereis, L.J. Lourens, A. Santarelli and W.J. Zachariasse, 1995. Extending the astronomical (polarity) time scale into the Miocene. Earth Planet. Sci. Lett., 136, 495-510.

Hodell, D.A., R.H. Benson, J.P. Kennett, A. Boersma, and K. Rakic-El Bied, 1989. Stable isotope stratigraphy of latest Miocene sequences in northwest Morocco: The Bou Regreg section. Paleoceanography, 4, 467-482.

Hodell, D.A., R.H. Benson, D.V. Kent, A. Boersma, and K. Rakic-El Bied, 1994. Magnetostratigraphic, biostratigraphic, and stable isotope stratigraphy of an Upper Miocene drill core from the Salé Briqueterie (northwestern Morocco): A high-resolution chronology for the Messinian stage. Paleoceanography, 9, 835-855.

Hsü, 1986. Unresolved problem concerning the Messinian salinity crisis. G. Geol., 47, 203-212.

Kastens, K.A., 1992. Did glacio-eustatic sea level drop trigger the Messinian salinity crisis? New evidence from Ocean Drilling Program Site 654 in the Tyrrhenian Sea. Paleoceanography, 7, 333-356.

Krijgsman, W., F.J. Hilgen, C.G. Langereis and W.J. Zachariasse, 1994. The age of the Tortonian-Messinian boundary. Earth Planet. Sci. Lett., 121, 533-547.

Krijgsman, W., F.J. Hilgen, A. Negri, J. Wijbrans, and W.J. Zachariasse, 1997. The Monte del Casino section (northern Apennines, Italy): A potential Tortonian/Messinian boundary stratotype? Palaeogeogr. Palaeoclimatol. Palaeoecol., 133, 27-47.

Langereis, C.G., W.J. Zachariasse and J.D.A. Zijderveld, 1984. Late Miocene magnetobiostratigraphy of Crete. Mar. Micropaleont., 8, 261-281.

Langereis, C.G. and M.J. Dekkers, 1992. Paleomagnetism and rock magnetism of the Tortonian-Messinian boundary stratotype at Falconara, Sicily. Phys. Earth Planet. Inter., 71, 100-111.

Laurenzi, M.A., F. Tateo, I.M. Villa and G.B. Vai, 1997. New radiometric datings bracketing the Tortonian/Messinian boundary in the Romagna potential stratotype sections (northern Apennines, Italy). In: A. Montanari, G.S. Odin, and R. Coccioni (eds.), Miocene stratigraphy: An integrated approach. Developments in Palaeontology and Stratigraphy, 15, 493-530.

Mazzei, R., I. Raffi, D. Rio, N. Hamilton, and M.B. Cita, 1979. Calibration of Late Neogene calcareous plankton datum planes with the paleomagnetic record of Site 397 and correlation with Moroccan and Mediterranean sections. In: U. von Rad, W.B.F. Ryan, et al., Init. Repts. DSDP, 47, 375-389.

Mayer-Eymar, K., 1867. Catalogue systématique et descriptif des fossiles des terrains tertiaires qui se trouvent du Musée fédéral de Zürich, Zürich.

Mayer-Eymar, K., 1868. Tableau synchronistique des terrains tertiaires supérieurs, IV ed., Zürich.

Moreau, M.G., H. Feinberg and J.P. Pozzi, 1985. Magnetobiostratigraphy of a Late Miocene section from the Moroccan Atlantic margin. Earth Planet. Sci Lett., 76, 167-175.

Negri, A., S. Giunta, F. Hilgen, W. Krijgsman and G.B. Vai (subm. to Mar. Micropal.). Calcareous nannofossil biostratigraphy of the Monte del Casino section (northern Apennines, Italy) and paleoceanographic consideration on the origin of the late Miocene sapropels.

Raffi, I., D. Rio, A. d'Atri, E. Fornaciari, and S. Rocchetti, 1995. Quantitative distribution patterns and biomagnetostratigraphy of Middle to Late Miocene calcareous nannofossils from equatorial Indian and Pacific Oceans (Legs 115, 130, and 138).

Remane, J., M.G. Bassett, J.W. Cowie, K.H. Gohrbrandt, H. Richard Lane, O. Michelsen, and W. Naiwen, 1996. Revised guidelines for the establisment of global chronostratigraphic standards by the International Commission on Stratigraphy (ICS). Episodes, 19, 77-81.

Rio, D., R. Mazzei, and G. Palmieri, 1976. The stratigraphic position of Mediterranean Upper Miocene evaporites, based on nannofossils, 26 pp., Parma.

Rio, D., R. Sprovieri, and E. di Stefano, 1994. The Gelasian Stage: A new chronostratigraphic unit of the Pliocene Series. Riv. It. Paleont. Strat., 100, 103-124.

Selli, R., 1964. Il Messiniano Mayer-Eymar 1867. Proposta di un neostratotype. Giorn. Geol., 28, 1-34.

Selli, R., 1971. Messinian. Giorn. Geol., 37, 121-133.

Sierro, F.J., 1985. The replacement of the "*Globorotalia menardii*" group by the *Goborotalia miotumida* group: An aid to recognising the Tortonian-Messinian boundary in the Mediterranean and adjacent Atlantic. Mar. Micropal., 9, 525-535.

Sierro, F.J., J.A. Flores, J. Civis, J.A. González Delgado, and G. Francés, 1993. Late Miocene globorotaliid event-stratigraphy and biogeography in the NE-Atlantic and Mediterranean. Mar. Micropal., 21, 143-168.

Sprovieri, R., E. di Stefano, and M. Sprovieri, 1996. High resolution chronology for Late Miocene Mediterranean stratigraphic events. Riv. It. Paleontol. Stratigr., 102, 77-104.

Tongiorni, E. and M. Tongiorni, 1964. Age of the Miocene-Pliocene limit in Italy. Nature, 201, 365-367.

Vai, G.B., I.M. Villa and M.L. Colalongo, 1993. First direct radiometric dating of the Tortonian /Messinian boundary. C. R. Acad. Sci. Paris, 316, 1407-1414.

Wernli, R., 1988. Micropaléontologie du Néogène post-nappe du Maroc septentrional et description systématique des Foraminifères planctoniques. Notes et Mém. Serv. géol. Maroc, 331, 1-270.

Whittaker, A., J.C.W. Cope, J.W.Cowie, W. Gibbons, E.A. Hailwood, M.R. House, D.G. Jenkins, P.F. Rawson, A.W.A. Rushton, D.G. Smith, A.T. Thomas, and W.A. Wimbledon, 1991. A guide tostratigraphical procedure. J. Geol. Soc., London, 148, 813-824.

Zachariasse, W.J., 1979. The origin of Globorotalia conomiozea in the Mediterranean and the value of its entry level in biostratigraphic correlations. Ann. Geol. Pays Hellen., 3, 1281-1292.

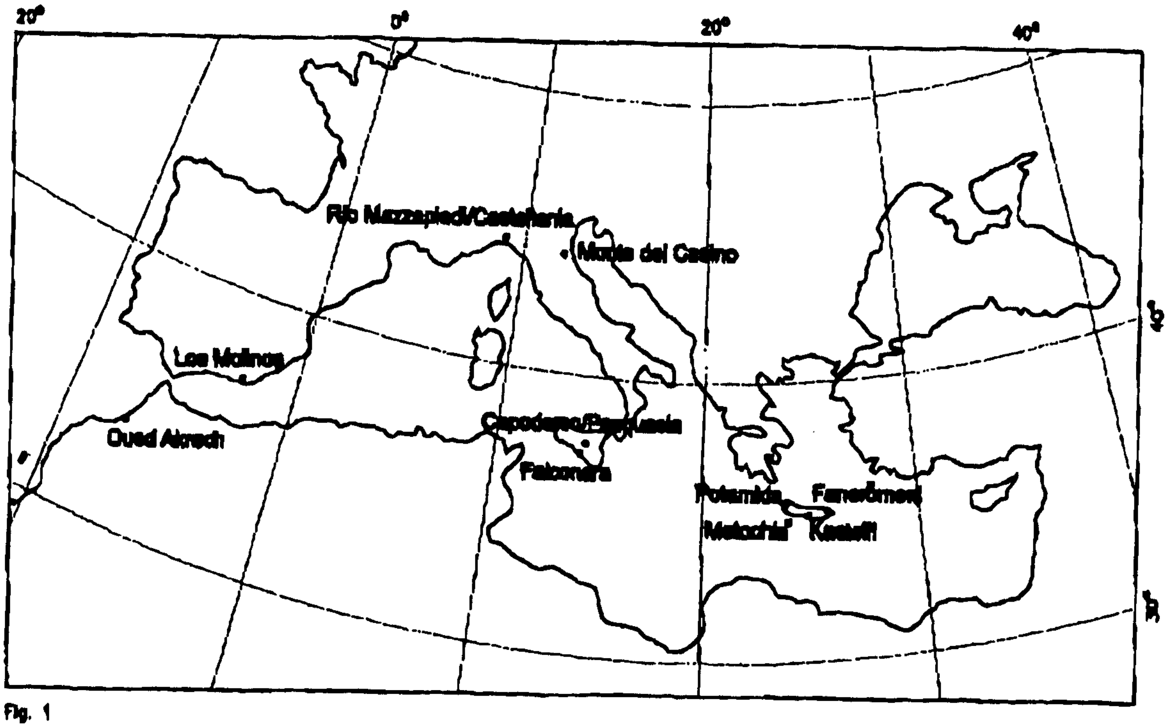


Fig. 1

Figure 1.

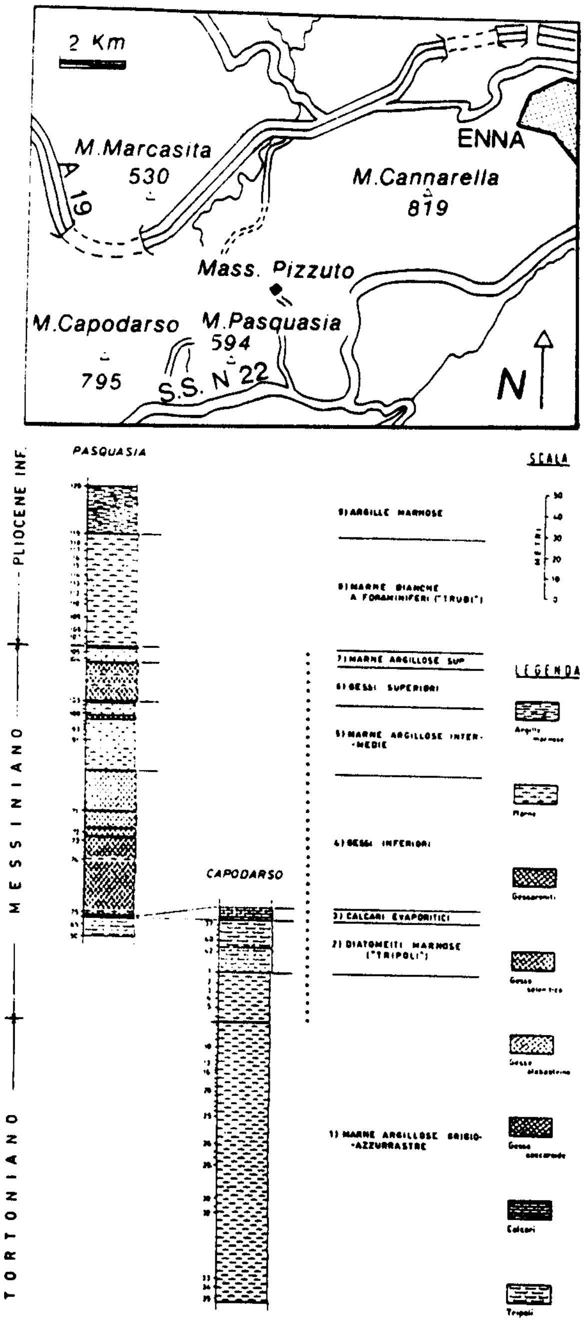
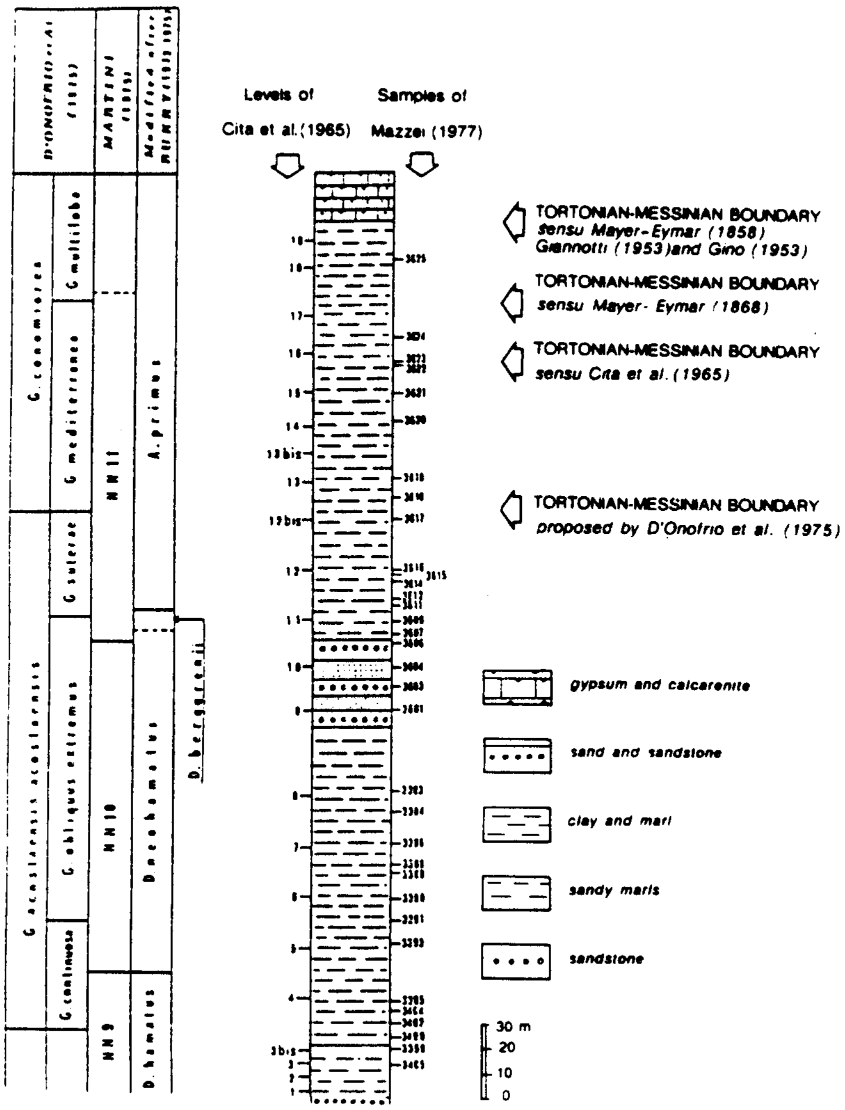

2 Km
M.Marcasita
530
A 19
ENNA
M.Cannarella
819
Mass. Pizzuto
M.Capodarso
795
M.Pasquasia
594
S.S. N 22
N
PASQUASIA
CAPODARSO
PLIOCENE INF.
MESSINIANO
TORTONIANO
SCALA
METRI
50
40
30
20
10
0
9) ARGILLE MARNOSE
8) MARNE BIANCHE A FORAMINIFERI ("TRUBI")
7) MARNE ARGILLOSE SUP
6) GESSI SUPERIORI
5) MARNE ARGILLOSE INTER-MEDIE
4) GESSI INFERIORI
3) CALCARI EVAPORITICI
2) DIATOMEITI MARNOSE ("TRIPOLI")
1) MARNE ARGILLOSE GRIGIO-AZZURRASTRE
LEGENDA
Calcari

Figure 2.



Levels of Cita et al.(1965)
Samples of Mazzei (1977)
TORTONIAN-MESSINIAN BOUNDARY sensu Mayer-Eymar (1858) Giannotti (1953) and Gino (1953)
TORTONIAN-MESSINIAN BOUNDARY sensu Mayer-Eymar (1868)
TORTONIAN-MESSINIAN BOUNDARY sensu Cita et al. (1965)
TORTONIAN-MESSINIAN BOUNDARY proposed by D'Onofrio et al. (1975)
gypsum and calcarenite
sand and sandstone
clay and marl
sandy marls
sandstone
30 m
20
10
0

Figure 3.

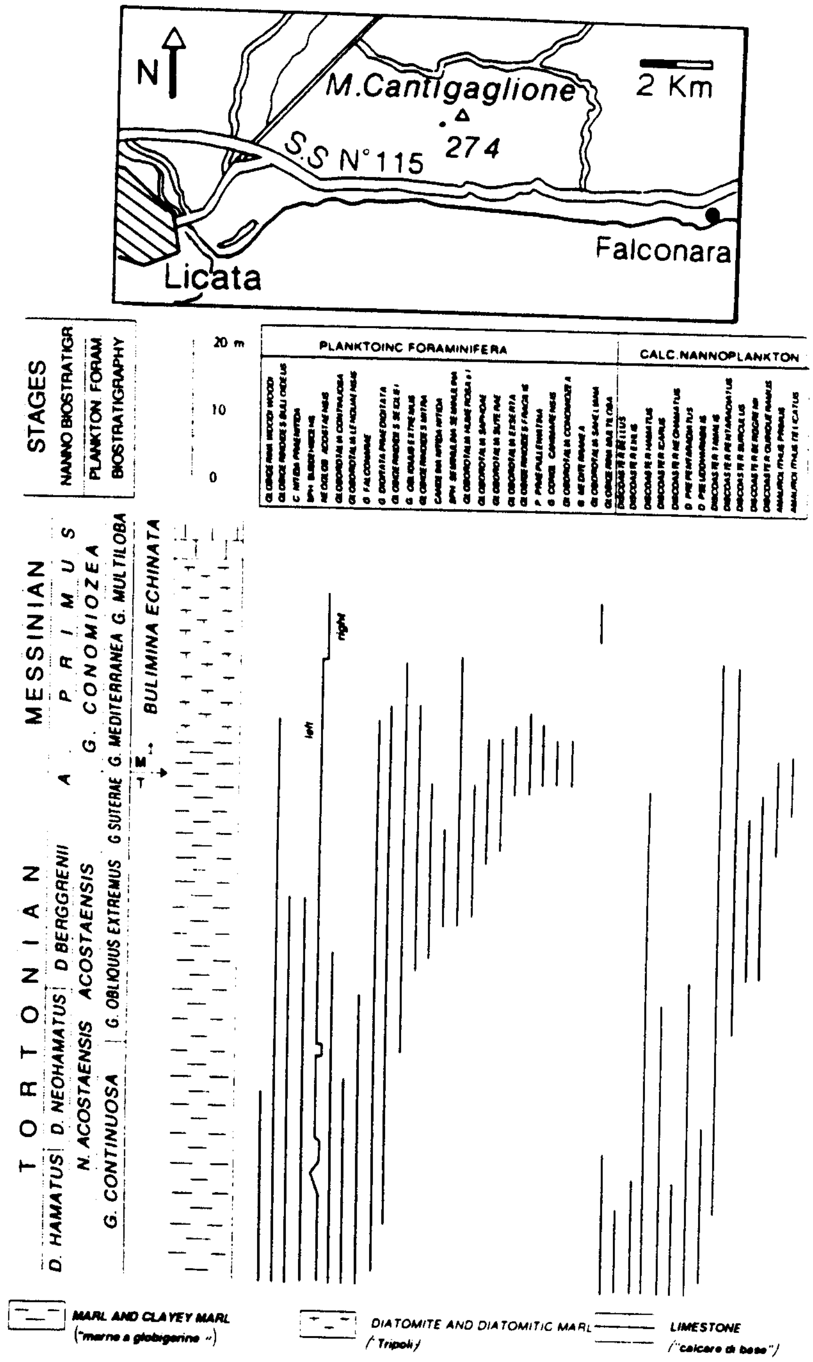
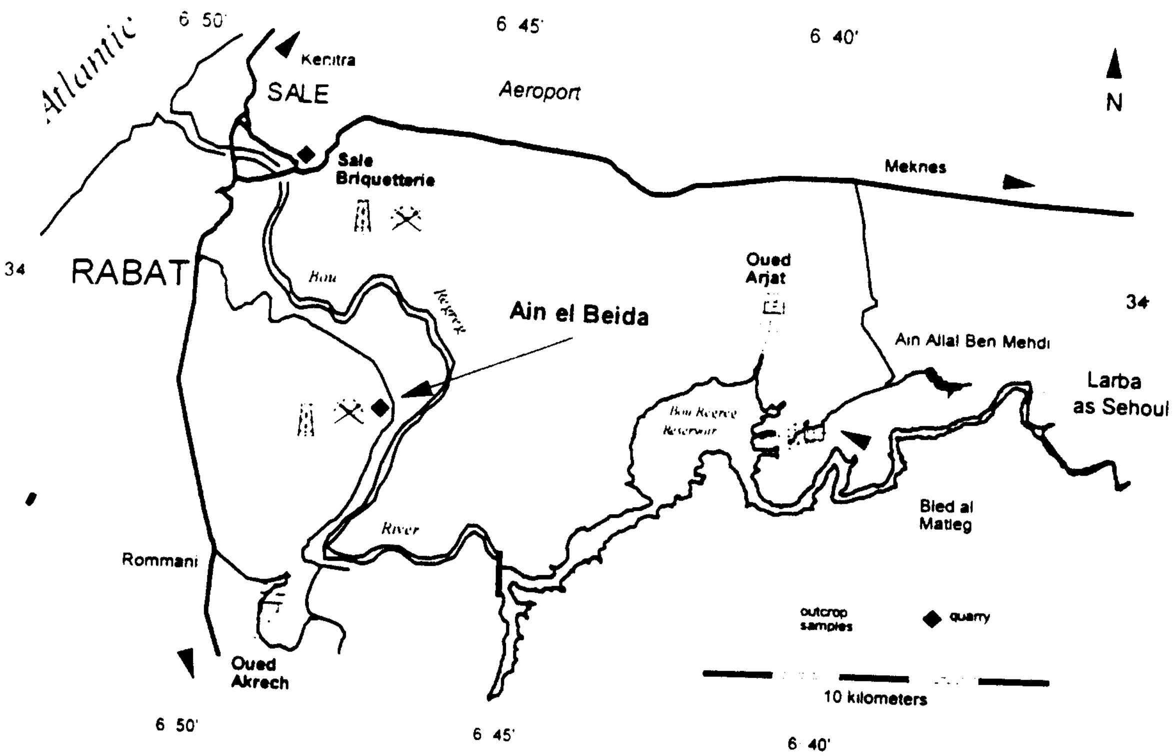
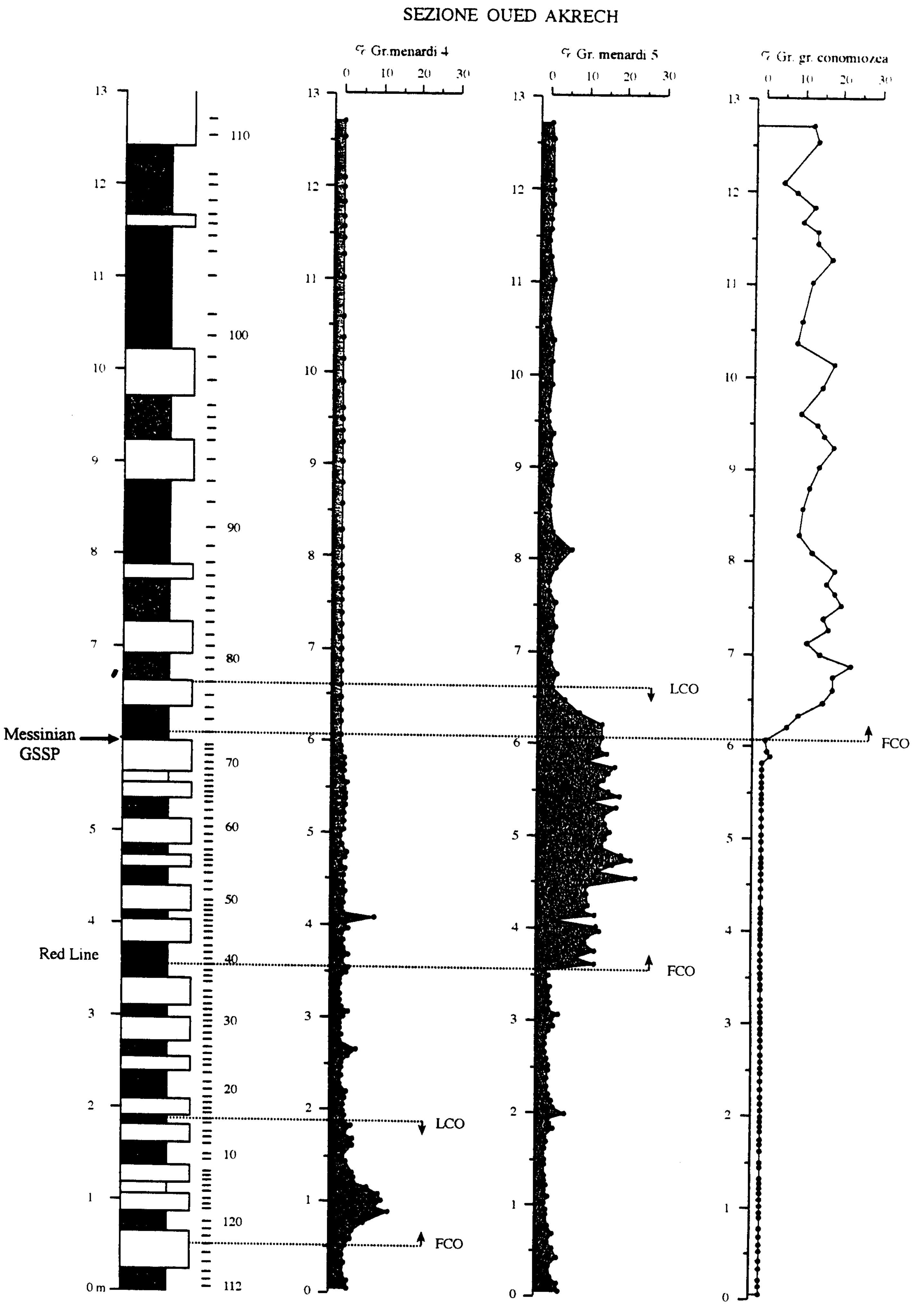

N
M.Cantigaglione
2 Km
274
S.S N°115
Falconara
Licata
STAGES
NANNO BIOSTRATIGR.
PLANKTON. FORAM.
BIOSTRATIGRAPHY
20 m
10
0
PLANKTOINC FORAMINIFERA
CALC.NANNOPLANKTON
TORTONIAN
MESSINIAN
D. HAMATUS
D. NEOHAMATUS
D. BERGGRENII
A. PRIMUS
N. ACOSTAENSIS ACOSTAENSIS
G. CONOMIOZEA
G. CONTINUOSA
G. OBLIQUUS EXTREMUS
G. SUTERAE
G. MEDITERRANEA
G. MULTILOBA
BULIMINA ECHINATA
left
right
MARL AND CLAYEY MARL
("marne a globigerine")
DIATOMITE AND DIATOMITIC MARL
(Tripoli)
LIMESTONE
("calcare di base")

Figure 4.



Atlantic
6 50'
Kenitra
SALE
6 45'
Aeroport
6 40'
N
Sale
Briquetterie
Meknes
34
RABAT
Bou
Regreg
Ain el Beida
Oued
Arjat
34
Ain Allal Ben Mehdi
Larba
as Sehoul
Bou Regreg
Reservoir
Bled al
Matleg
River
Rommani
outcrop
samples
quarry
Oued
Akrech
10 kilometers
6 50'
6 45'
6 40'

Figure 5.



SEZIONE OUED AKRECH
% Gr.menardi 4
% Gr. menardi 5
% Gr. gr. conomiozea
Messinian GSSP
Red Line
LCO
FCO
LCO
FCO
FCO
0 m

Figure 6.

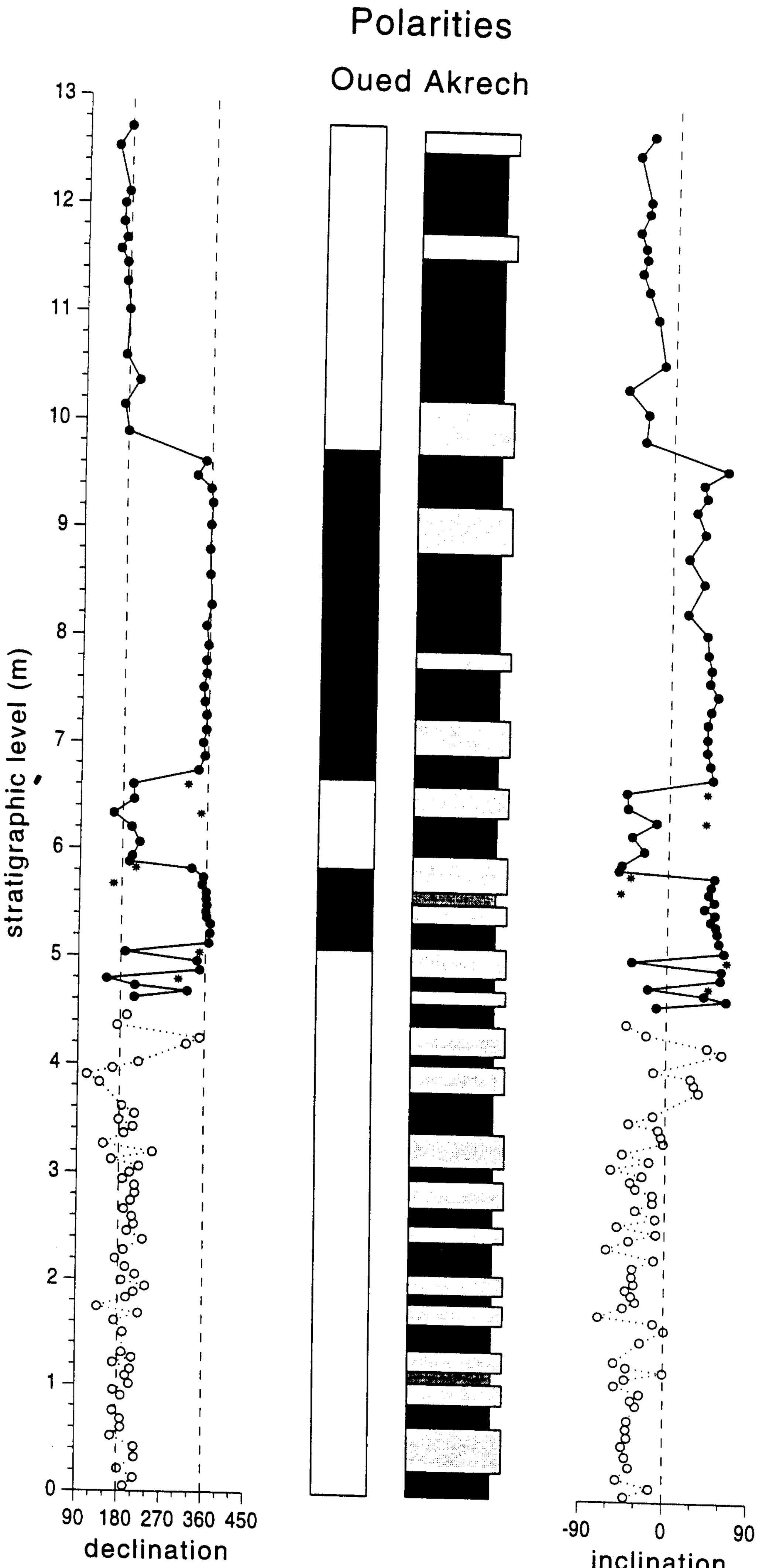

Polarities
Oued Akrech
stratigraphic level (m)
13
12
11
10
9
8
7
6
5
4
3
2
1
0
90
180
270
360
450
declination
-90
0
90
inclination

Figure 7.

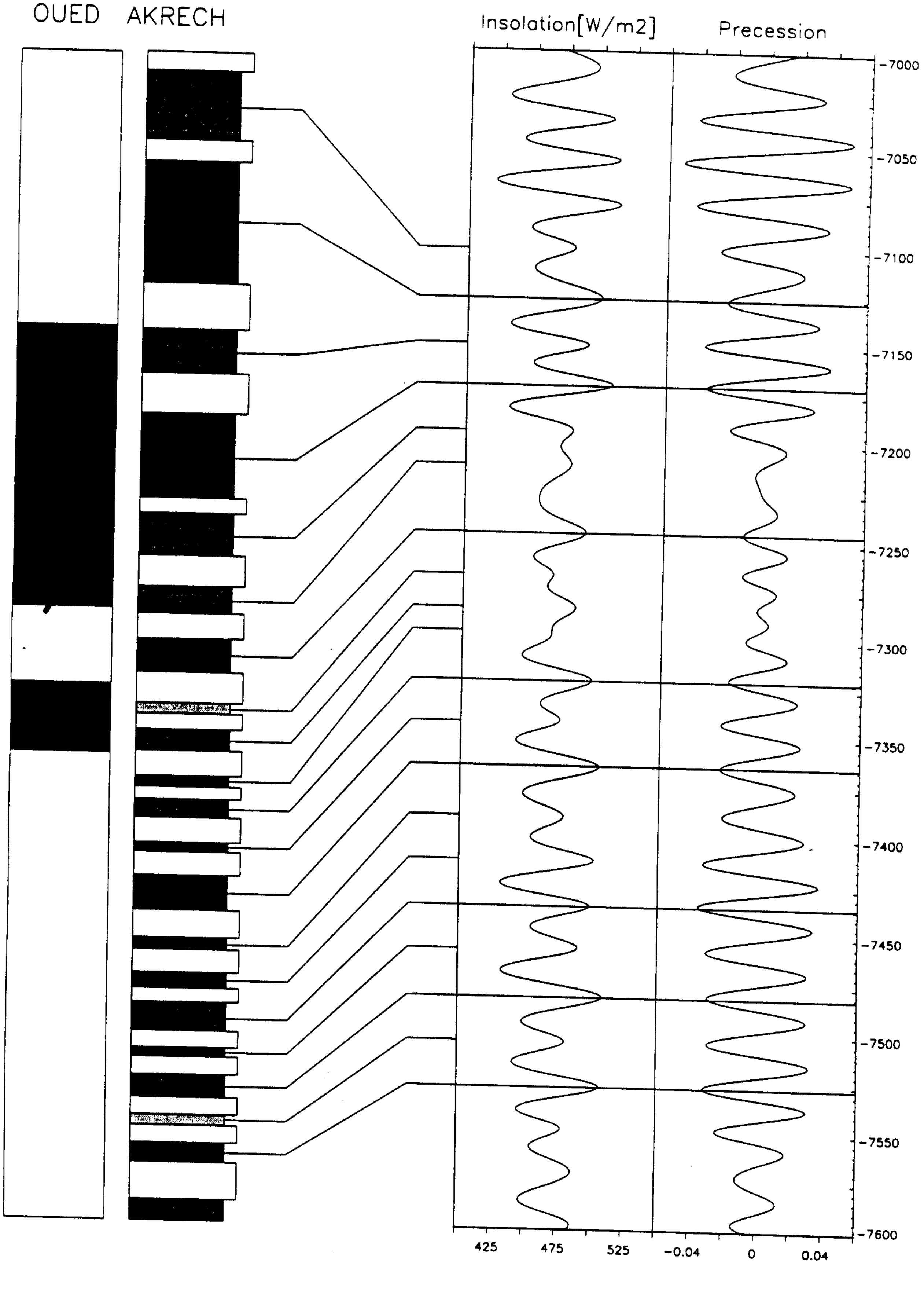

OUED AKRECH
Insolation[W/m2]
Precession
-7000
-7050
-7100
-7150
-7200
-7250
-7300
-7350
-7400
-7450
-7500
-7550
-7600
age (ka)
425
475
525
-0.04
0
0.04

Figure 8.

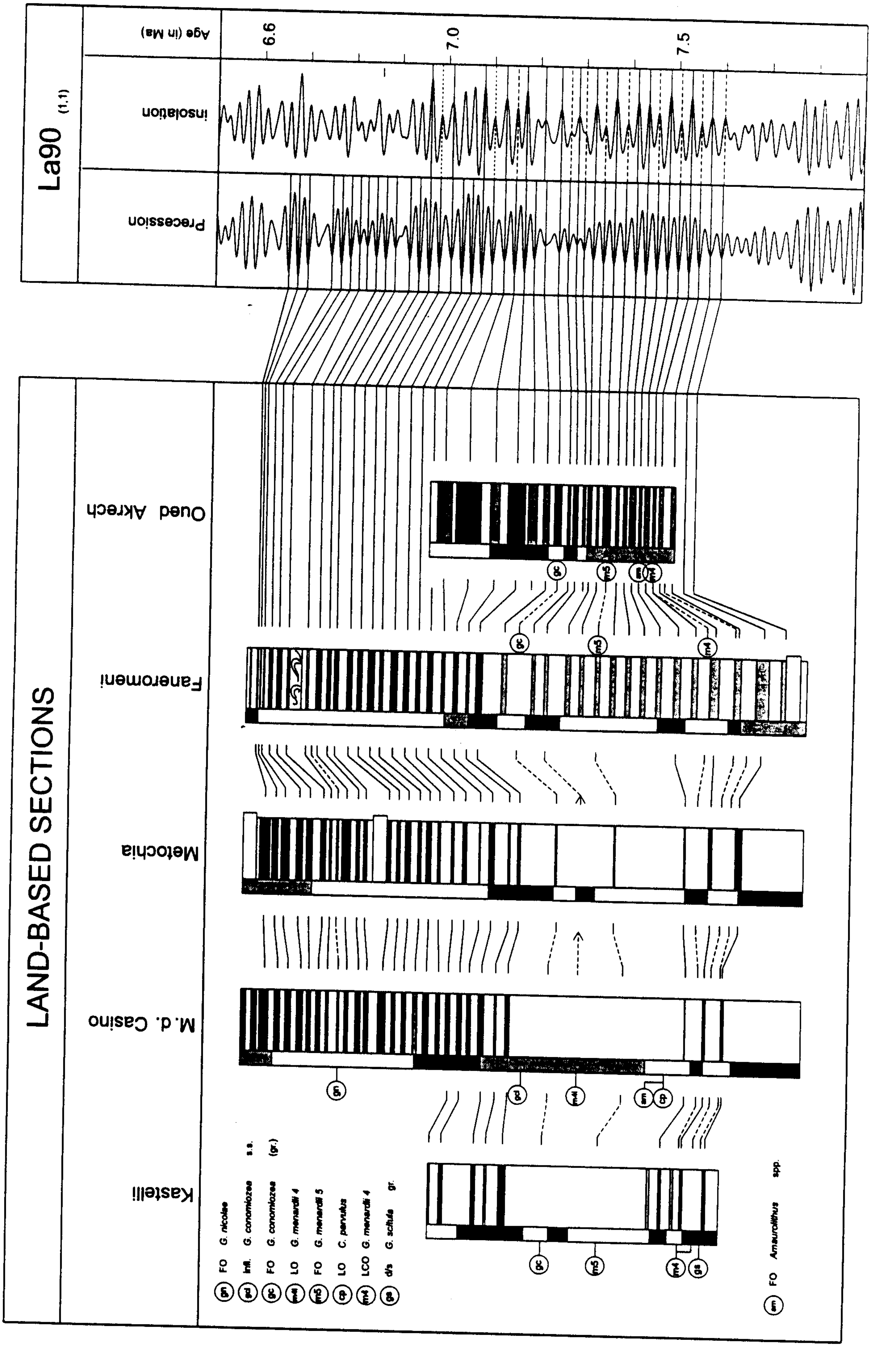

La90 (1,1)
Precession
insolation
Age (in Ma)
6.6
7.0
7.5
LAND-BASED SECTIONS
Kastelli
M.d. Casino
Metochia
Faneromeni
Oued Akrech
gn FO G. nicolae
gcl Infl. G. conomiozea s.s.
gc FO G. conomiozea (gr.)
m4 LO G. menardii 4
m5 FO G. menardii 5
cp LO C. parvulus
m4 LCO G. menardii 4
gs d/s G. scitula gr.
am FO Amaurolithus spp.

Figure 9.