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The Global Boundary Stratotype Section and Point (GSSP) of the Messinian Stage (uppermost Miocene)

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The GSSP of the Messinian Stage, which per definition marks the base of the Messinian and, hence, the boundary between the Tortonian and Messinian Stages of the Upper Miocene Subseries, has recently been defined and ratified by the IUGS. The boundary stratotype section is Oued Akrech (Morocco) where the Messinian GSSP is now formally designated at the base of the reddish layer of sedimentary cycle no.15. This point coincides closely with the first regular occurrence (FRO) of the planktonic foraminiferal Globorotalia miotumida *group and the first occurrence (FO) of the calcareous nannofossil* Amaurolithus delicatus, *and falls within the interval of reversed polarity that corresponds to C3Br.1r. The base of the reddish layer and, thus, the Messinian GSSP has been assigned an astronomical age of 7.251 Ma.*

Introduction

The aim of this paper is to announce the ratification of the Global Boundary Stratotype-section and Point (GSSP) of the Messinian Stage (uppermost Miocene). Together with the Tortonian, the Messinian represents the two-fold subdivision of the Upper Miocene Subseries in the Global Standard Chronostratigraphic scale. Controversies concerning the status of the Messinian as global chronostratigraphic unit and the placement of the Miocene/Pliocene boundary have now formally been settled with the official acceptance by the International Commission on Stratigraphy (ICS) and the ratification by the Executive Committee of the International Union of Geological Sciences (IUGS) of both the Zanclean (Lower Pliocene) and Messinian GSSPs.

A brief description of the stratotype-section, of the boundary itself and of the various stratigraphic tools available for global correlation of the Messinian GSSP is presented. Additional information is found in the original proposal (Hilgen et al., 1998) voted by the Subcommission on Neogene Stratigraphy (SNS) and the ICS, and in the literature referred to in the present paper. The integrated stratigraphic data and astronomical tuning of the sedimentary cycles, which underlie the selection of Oued Akrech as stratotype-section, are reported in detail elsewhere (Hilgen et al., 2000).

The original proposal (Hilgen et al., 1998) was forwarded to all SNS voting members in 1998 for postal ballot and almost unanimously accepted. Following the results of the postal ballot, a formal recommendation of SNS was submitted to the Secretary General of the ICS in March 1999. Official acceptance by the ICS and ratification by the IUGS Executive Committee were obtained in July 1999 and January 2000, respectively.

Background and motivation

Time is ripe to proceed with the definition of the GSSPs of Miocene Stages now that the GSSPs of all Pliocene Stages have been formally defined (Castradori et al., 1998; Rio et al., 1998; Van Couvering et al., 1998, 2000). Much progress has been made during the last years in establishing astronomically dated integrated stratigraphic frameworks for the Upper Miocene, both in the Mediterranean as well as in the open ocean. The Messinian GSSP is the logical first goal also because the long-lasting debate about its chronostratigraphic position and age has been settled (Vai et al., 1993; Krijgsman et al., 1994; Hilgen et al., 1995). The proven unsuitability of both the Messinian neostratotype section at Pasquasia/Capodarso as well as the Falconara section necessitated the search for an alternative boundary stratotype section. Of all candidate sections, Oued Akrech located on the Atlantic side of Morocco is the only section that provided a good to excellent magnetostratigraphy, calcareous plankton biostratigraphy and cyclostratigraphy in the critical interval across the Tortonian/Messinian boundary. An important additional argument for selecting Oued Akrech is to emphasize that the Messinian is a global chronostratigraphic unit and not a Mediterranean Stage of regional significance only, as has been argued for instance by Benson and Rakic-El Bied (1996). But before presenting the integrated stratigraphic data of Oued Akrech, we will start with a condensed review of the history of the Messinian stage concept.

The Messinian Stage: A brief historical review

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

The Messinian Stage named after the town of Messina on Sicily (Italy) 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). 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. His listing includes the gypsum of the Gessoso-Solfifera Formation and possibly the diatomites of the underlying Tripoli Formation but contains several pertinent errors (Selli, 1960; Cita, 1975) as well, e.g. 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 (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.

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

The Messinian was adopted as the standard geochronological unit for the interval between the Tortonian and Pliocene during the meeting of the Committee of the Mediterranean Neogene held in Vienna in 1959. Selli (1960) eliminated the existing inconsistencies in the original definition of Mayer-Eymar and defined the Messinian as the "intervallo di tempo compreso fra il Tortoniano (strati di Tortona) e il Pliocene (strati di Tabiano), caratterizzato in tutto il Mediterraneo ... 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 as the Messinian neostratotype and argued that the Tortonian/Messinian boundary be placed 25 m below the local base of the Tripoli diatomite Formation, at the level that coincides with the first marked environmental change which he interpreted as the actual beginning of the salinity crisis. His paleoenvironmental criterion made it difficult, however, to export the boundary, in particular to the extra-Mediterranean realm.

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

Calcareous plankton biostratigraphy was subsequently used to define the lower boundary of the Messinian more precisely (D'Onofrio et al., 1975; Mazzei et al., 1979), thus facilitating its recognition on a global scale. The First Occurrence (FO) of the planktonic foraminifer *Globorotalia conomiozea* (sensu Colalongo et al., 1979) —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). Colalongo et al. (1979) subsequently proposed to emend the Tortonian and Messinian Stages and define the T/M boundary at the *G. conomiozea* FO level, 6 m below the base of the Tripoli diatomite Formation in the Falconara section because the boundary interval had been covered by a landslide at Pasquasia-Capodarso. Unfortunately, the Falconara section proved unsuitable for establishing a reliable magnetostratigraphy (Langereis and Dekkers, 1992) and is tectonically disturbed, in particular in the interval below the diatomites. In addition, the boundary interval in the western gully complex 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, but the *G. conomiozea* FO could be maintained as guiding criterion for selecting the most suitable section and level to define the Messinian GSSP.

The age of the Tortonian/Messinian boundary

The initial large uncertainties in the age of Neogene stage boundaries had been reduced with the publication of the first K/Ar datings of marine successions in the Mediterranean (e.g., Eberhardt and Ferrara, 1962; Tongiorgi and Tongiorigi, 1964; Choubert et al., 1968). It was expected that application of the geomagnetic polarity time scale which had just become established at that time (e.g., Heirtzler et al., 1968) should even produce more accurate and precise age determinations. But despite these good prospects, the age of the T/M boundary remained a hotly debated issue in Neogene geochronology and chronostratigraphy for decades. Magnetostratigraphic studies of deep-sea sediments yielded age estimates that ranged from 5.6 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 (Langereis et al., 1984; Berggren et al., 1985; Channell et al., 1990; Kastens, 1992). The age problem culminated 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 spanning the boundary. The extra subchrons allowed a straightforward calibration of high-quality magnetostratigraphic records from Upper Miocene sections on Crete, 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 good agreement with the radiometric age estimates of Vai et al. (1993) and Laurenzi et al. (1997).

Selecting the most suitable section for defining the Messinian GSSP

Selecting a section suitable for defining the Messinian GSSP was 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, Potamidha and Kastelli on Crete, Greece; Metochia on Gavdos, Greece; Oued Akrech, Morocco). All these sections have been astronomically dated and cyclostratigraphically correlated (Krijgsman et al., 1995; 1997), and fulfil most if not all the requirements recommended by the ICS (Remane et al., 1996). Of these sections, Oued

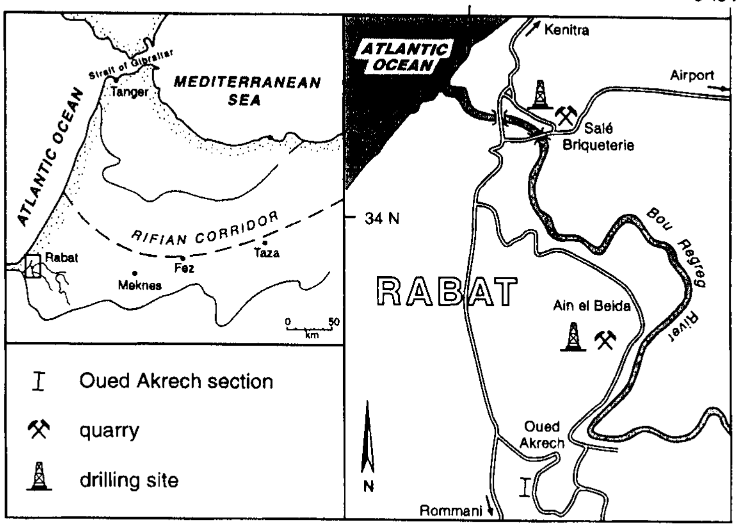

Figure 1 Location map of section Oued Akrech on the Atlantic side of Morocco (NW Africa).

Akrech located on the Atlantic side of Morocco (Figure 1) stands out as the most suitable section to define the Messinian GSSP (Hilgen et al., 1998, 2000). This section contains the lower part of the so-called "Blue Marl" of Atlantic Morocco which ranges in age from the late Tortonian to the early Pliocene.

The Messinian GSSP at Oued Akrech

The classical Blue Marls of Atlantic Morocco have been the subject of numerous studies, reflecting the progress being made in Neogene biostratigraphy and integrated stratigraphy (e.g., Choubert et al., 1964; Feinberg and Lorenz, 1970; Bossio et al., 1976; Moreau et al., 1985; Wernli, 1977, 1988; Benson et al., 1991, 1995; Hodell et al., 1989, 1994). The entire Oued Akrech road section was studied by Wernli (1977), Cita and Ryan (1978), Benson and co-workers (see Benson and Rakic-El Bied, 1996) and Barbieri (1998), while Sierro et al. (1993) and Hilgen et al. (2000) focussed their studies on the well-exposed lower part only.

The section

Location

The Oued Akrech section is located 7 km SSE of Rabat in a road-cut along a steep bluff next to the Oued Akrech ("oued" = "wadi" = valley; Figure 1), at a latitude of 33°56'13" and a longitude of 6°48'45" east of Greenwich. The exposure is along the narrow road that connects the P22 from Rabat (direction Rommani) and the S203, about 3 km from the junction with the P22 (Figure 2). Oued Akrech is a tributary of the Bou Regreg River that forms a deep valley in southward direction as the river turns to the east (topographic map NI-29-XII-3C coordinates, 370.2–370 to 371).

Stratigraphic succession and geological setting

The Neogene succession at Oued Akrech starts with an Upper Tortonian shallow marine glauconitic sandstone, locally referred to as "Molasse de Base". This 5 m-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 2 m-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 as exposed at Oued Akrech, however, is a yellow-beige with reddish colour bands (colour cycles). At the level of the phosphatic layer, the marine depositional environment changed rapidly from sublittoral to upper bathyal (paleodepth 500 to 700 m.) as indicated by the benthic microfauna (Benson and Rakic-El Bied, 1996).

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 corridor acted as an extensional foredeep during the late Miocene to early Pliocene, separating the active Rif Orogen and nappe complex in the north from the Central Moroccan Meseta to the south (Benson and Rakic-El Bied, 1996), and it 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).

Magnetobiostratigraphy, isotope stratigraphy and astrochronology

The Oued Akrech section provided a good to excellent calcareous plankton biostratigraphy, magnetostratigraphy and cyclostratigraphy across the boundary interval (e.g., Hodell et al., 1989; Sierro et al., 1993; Benson and Rakic-El Bied, 1996; Barbieri, 1998; Hilgen et al., 2000) (Figure 3). Detailed magnetobiostratigraphic correlations to time-equivalent and astronomically dated sections in the Mediterranean (Figure 4; Hilgen et al., 2000) revealed that the basic sedimentary cycles are precession-controlled but that precession/obliquity interference patterns are present as well. The characteristic cycle pattern allows the section to be astronomically tuned by matching the colour cycles (regular alternations of indurated buff coloured marls and softer, more clayey and reddish marls) to correlative patterns in the astronomical target curve (Hilgen et al., 2000; 65°N lat summer insolation), thereby providing highly accurate ages for the recorded bio-events and polarity reversals, and, as a consequence, also for the T/M boundary. This calibration is confirmed in detail by the high-resolution calcareous plankton biostratigraphy, thus excluding hiatuses in the astronomically dated 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.

Planktonic foraminifera have been studied by Feinberg and Lorenz (1970), Bossio et al. (1976), Wernli (1977), Cita and Ryan (1978), Benson et al. (1991), Sierro et al. (1993), Barbieri (1998) and Hilgen et al. (2000). The quantitative record of the most important marker species (Figure 3) allows the recognition of four distinct events which—in stratigraphical order—are the last common ocurrence (LCO) of *Globorotalia menardii* 4 of Tjalsma (1971) (= PF-Event 1 of Sierro et al., 1993), the first common ocurrence (FCO) of dextrally coiled *G. menardii* 5 of Tjalsma (1971) (= PF-Event 2 of Sierro, 1985; Sierro et al., 1993), a prominent sinistral to dextral coiling shift of the *Globorotalia scitula* group (= PF-Event A of Sierro et al., 1993) and the first regular occurrence (FRO) of the *Globorotalia miotumida*

Figure 2 Photograph of section Oued Akrech, showing sedimentary cycles OA 1–7 and the position of the Tortonian-Messinian boundary at the base of a reddish bed of cycle OA-15..

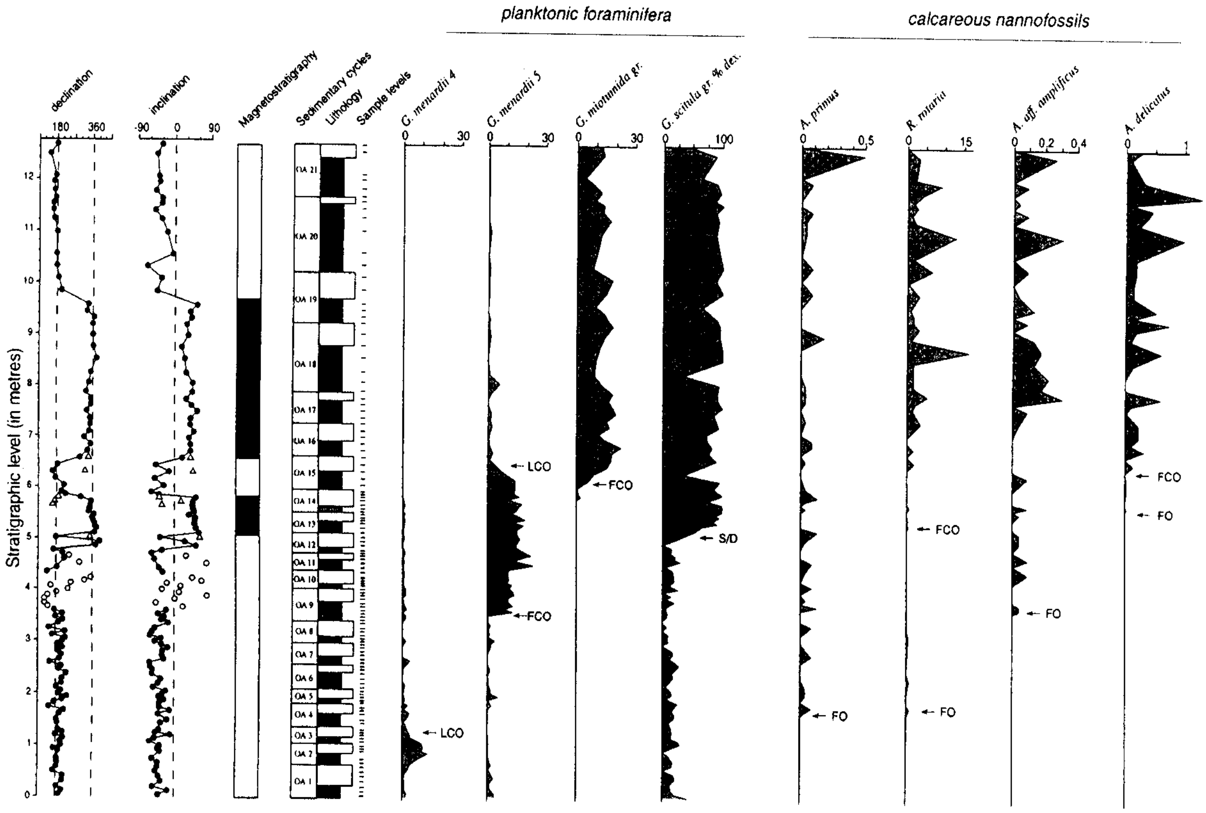

Figure 3 Integrated magnetostratigraphy, calcareous plankton biostratigraphy and cyclostratigraphy of section Oued Akrech.

group (= PF-Event 3 of Sierro et al., 1993 and *Globorotalia conomiozea* group FRO of Krijgsman et al., 1995). The GSSP falls within (sub)tropical Zone M13b (*Globigerinoides extremus/ Globorotalia plesiotumida-Globorotalia lenguaensis* Interval Subzone) of Berggren et al. (1995) and the *Globorotalia suturae* Subzone of Iaccarino (1985), and coincides with the transitional Mt9-Mt10 zonal boundary (*Globorotalia conomiozea/ Globorotalia mediterranea—Globorotalia sphericomiozea* Interval Subzone) of Berggren et al. (1995).

Calcareous nannofossils have been studied by Benson and Rakic El-Bied (1996) and Hilgen et al. (2000). Quantitative data reveal the following main events in stratigraphic order: *Amaurolithus primus* FO, *Reticulofenestra rotaria* FO, *Amaurolithus* aff. *amplificus* FO, *R. rotaria* FCO, *Amaurolithus delicatus* FO and *A. delicatus* FCO. The GSSP falls within Zone NN11b of Martini (1971) and Zone CN9b of and Okada and Bukry (1980).

Magnetostratigraphic studies were carried out by Benson and co-workers (Benson and Rakic-El Bied, 1996; see also Hodell et al., 1989) and Hilgen et al. (2000). The more recent magnetostratigraphy is of a very good quality across the boundary (Figure 3) and its calibration to the GPTS is straightforward through the integrated stratigraphic correlations to well-calibrated Mediterranean sections (Figure 4). The recorded two normal polarity intervals and intervening reversed interval correspond—from bottom to top—to C3Br.1n, C3Br.1r and C3Bn.

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 be recognized. This carbon shift can more easily be recognized in the higher resolution isotope record from the Salé drill core (Hodell et al., 1994). In addition, the $\delta^{18}C$ record from Salé reveals a first step to heavier $\delta^{18}C$ values around the T/M boundary which coincides closely with the appearance of upper psychrospheric ostracodes (Hodell et al., 1994).

The boundary ("golden spike")

Definition and age

The GSSP of the base of the Messinian Stage is now formally defined at the base of reddish layer no.15 in section Oued Akrech (Figure 2). This point coincides closely with the FRO of the planktonic foraminiferal *Globorotalia miotumida* group and the *Amaurolithus delicatus* FO, and falls within the interval of reversed polarity that corresponds to C3Br.1r. The base of the reddish layer has been assigned an astronomical age of 7.251 Ma. (Figures 3 and 4).

Correlation tools

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* and *A. delicatus* FOs predate the boundary while the *A. amplificus* s.s. FO postdates the boundary (Raffi et al., 1995; Backman and Raffi, 1997). The *Reticulofenestra rotaria* FCO is another useful nannoplankton event that predates the boundary (Negri et al., 1999). The turnover of dominantly dextrally coiled assemblages of *G. menardii* by dominantly sinistrally coiled assemblages of the *G. miotumida* 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. It has been identified in Oued Akrech (Hodell et al., 1989) and the Salé drill core (Hodell et al., 1994). In the continental realm, a significant shift in opposite direction is found in terrestrial

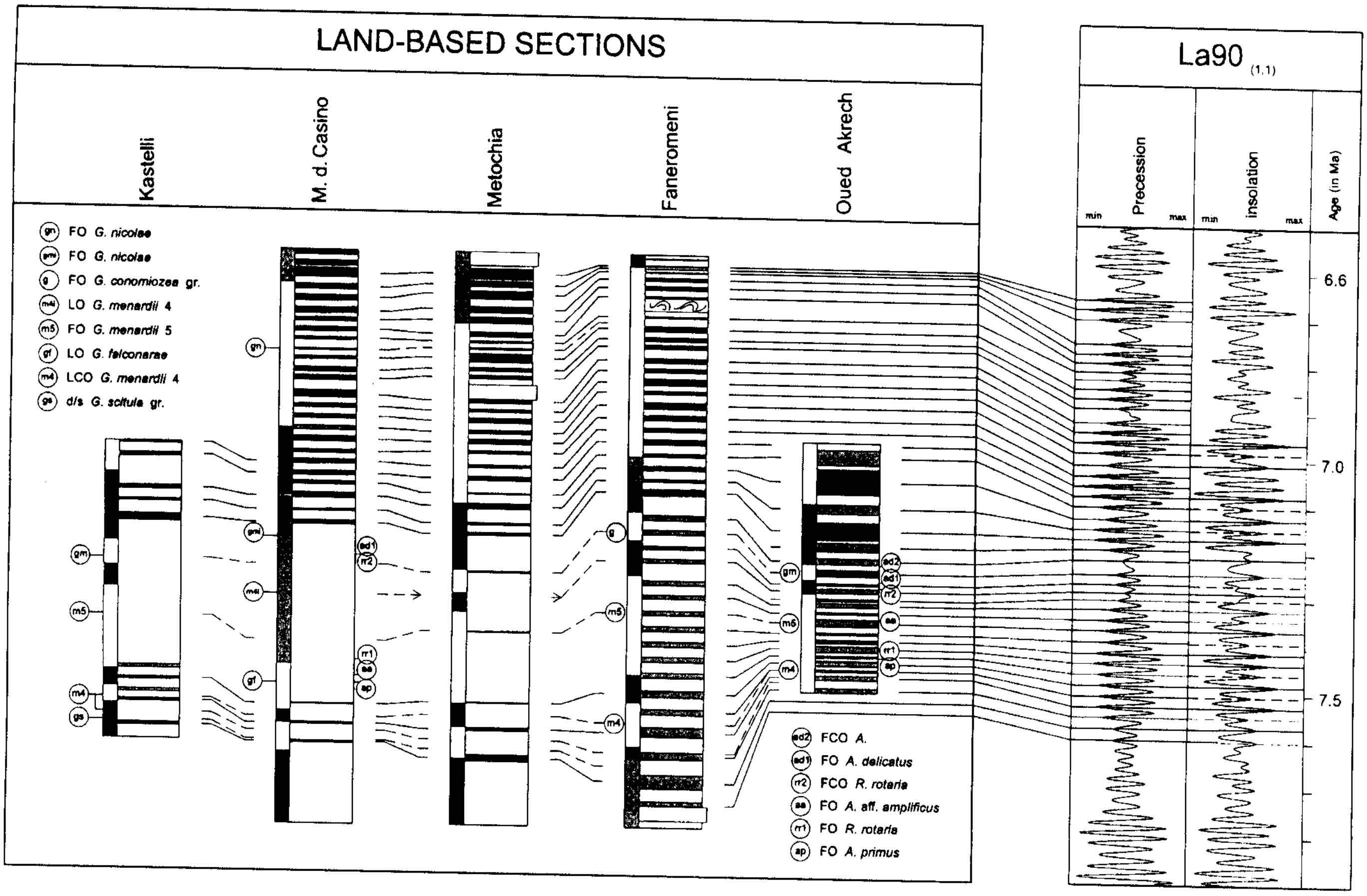

Figure 4 Astronomical tuning of sedimentary cycles OA 1–21 in section Oued Akrech and integrated stratigraphic correlations to time-equivalent and astronomically dated sections in the Mediterranean.

$\delta^{13}C$. Despite being diachronous on a global scale, the shift approximates the Tortonian/Messinian boundary better than the Miocene-Pliocene boundary as suggested by Cerling et al. (1997). The acceleration in the worldwide expansion of C4 grasses, which is associated with the terrestrial $\delta^{13}C$ shift around the Tortonian/Messinian boundary, resulted in more open habitats on most continents. Although there is no evidence for mammal turnovers exactly at the boundary, major diversity drops and/or shifts from browsing to grazing habits occurred in mammal communities in Asia, Africa and North America between 8 and 6.5 Ma (Alroy, 1992; Morgan et al., 1994).

Conclusion

The formal definition of the base of the Messinian represents an important next step towards the completion of the Global Standard Chronostratigraphic Scale for the Neogene which is directly linked to high-resolution astronomically dated integrated stratigraphic frameworks.

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The Utrecht-Parma team after sampling the Oued Akrech and Ain el Beida sections in October 1996. From left to right: Silvia Iaccarino, Wout Krijgsman, GiulianaVilla, Laura Bissoli, Fritz Hilgen, and Sandra Gaboardi.

Hutchison 'Young Scientist' Fund

William Watt Hutchison, "Hutch" to his many friends around the world, was a Scots-born Canadian geologist who served Canada and the IUGS in myriad dynamic and creative ways. Most notably, he served as the IUGS Secretary General (1976-1980) at a pivotal time in its history, and as IUGS President (1984-1987). The same boundless energy, enthusiasm, skill in communications, and ability to foster teamwork that characterized his work with the IUGS also carried him to preeminent scientific administrative positions in the Canadian Government, where he served as Director General of the Geological Survey of Canada and as Assistant Deputy Minister of Earth Sciences. His distinguished career was terminated in 1987 by his untimely death at the age of 52, following a painful struggle with cancer.

One of Hutch's last wishes was to establish under IUGS auspices a memorial foundation intended to promote the professional growth of deserving, meritorious young scientists from around the world by supporting their participation in important IUGS-sponsored conferences. The first 3 beneficiaries of the Hutchinson "Young Scientist Foundation" attended the 28th International Geological Congress (IGC) in Washington, D.C., in 1989.

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