PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
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Phil. Trans. R. Soc. Lond. A 1999 **357**, 1931-1947
doi: 10.1098/rsta.1999.0408

THE ROYAL SOCIETY

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Present status of the astronomical (polarity) time-scale for the Mediterranean Late Neogene

By F. J. Hilgen[1], H. Abdul Aziz[1], W. Krijgsman[2], C. G. Langereis[2], L. J. Lourens[1], J. E. Meulenkamp[1], I. Raffi[3], J. Steenbrink[1], E. Turco[1], N. van Vugt[2], J. R. Wijbrans[4] and W. J. Zachariasse[1]

[1] *IPPU, Faculty of Earth Sciences, Utrecht University, The Netherlands*
[2] *Paleomagnetic Laboratory 'Fort Hoofddijk', Faculty of Earth Sciences, Utrecht University, The Netherlands*
[3] *Dipartimento di Scienze della Terra, Facoltà di Scienze, Università 'G. D'Annunzio', Chieti, Italy*
[4] *Department of Isotope Geology, Institute of Earth Sciences, Free University, Amsterdam, The Netherlands*

Sedimentary cycles may reflect orbitally induced climate oscillations and can then be used to construct astronomical time-scales. Following the initial tuning of the Late Pleistocene, the 'anchored' astronomical time-scale was extended to the base of the Pliocene, using palaeoclimatic records from Ocean Drilling Project (ODP) sites in the eastern equatorial Pacific and North Atlantic and sedimentary cycle patterns in marine successions exposed onland in the Mediterranean. In this paper we present a review of the progress subsequently made in establishing a Late Neogene astronomical (polarity) time-scale (A(P)TS) in the Mediterranean region. Major steps forward are (1) the evaluation of the initial time-scale, using high-resolution climatic proxy records, different astronomical solutions and the additional influence of obliquity on sedimentary cycle patterns, (2) the extension of the A(P)TS into the Middle Miocene, i.e. back to about 12 Ma, (3) the closure of the Messinian gap in the A(P)TS, (4) the incorporation of the continental record, and (5) the intercalibration of astronomical and radioisotopic time.

Keywords: astronomical time-scale; Mediterranean; Neogene; orbital forcing; sedimentary (Milankovitch) cycles; palaeoclimate

1. Introduction

Time is an indispensable tool in Earth sciences for understanding all kinds of processes and for determining rates of change. More than a century ago, just before the invention of radiometric dating, Gilbert (1895) already realized that astronomically forced cyclicity in marine sedimentary archives could be used to estimate the duration of (parts of) the geological record. His estimates were in favour of a much older age of our planet than the age of 100 (or even 20) million years, then calculated on the basis of a conductive cooling model of the Earth (e.g. Kelvin 1899). Gilbert linked his sedimentary cycles to perturbations in the Earth's orbit and rotation axis which are caused by gravitational interactions of our planet with the Sun, the Moon and the other planets of our Solar System. These interactions give rise to cyclic changes in the eccentricity of the Earth's orbit, with main periods of 100 000 and 413 000 years, and in the tilt (obliquity) and precession of the Earth's axis with main periods of 41 000, and 21 000 years, respectively (Berger 1977). These perturbations in the Earth's orbit and rotation axis are climatically important because they affect the global, seasonal and latitudinal distribution of the incoming solar insolation.

Orbitally forced climate oscillations are recorded in sedimentary archives through changes in sediment properties, fossil communities, chemical and isotopic characteristics. While Earth scientists can read these archives to reconstruct palaeoclimate, astronomers have formulated models based on the mechanics of the solar–planetary system and the Earth–Moon system to compute the past variations in precession, obliquity and eccentricity of the Earth's orbit and rotation axis. As a logical next step, sedimentary archives can be dated by matching patterns of palaeoclimate variability with patterns of varying solar energy input computed from the astronomical model solutions. This astronomical tuning of the sedimentary record results in time-scales based on measurable physical parameters that are totally independent from those underlying radioisotopic dating and that are tied to the Recent through a direct match with astronomical curves.

Initially, research focused mostly on the inferred orbital forcing of the Pleistocene ice ages, resulting in the astronomical calibration of Late Pleistocene palaeoclimatic records which mainly reflect glacial cyclicity (e.g. Hays *et al*. 1976; Imbrie *et al*. 1984). Following earlier attempts (Pisias & Moore 1981; Ruddiman *et al*. 1989; Raymo *et al*. 1989), the astronomical time-scale was extended to the base of the Pliocene, using palaeoclimatic records from Ocean Drilling Project (ODP) sites in the eastern equatorial Pacific and North Atlantic (Shackleton *et al*. 1990) and sedimentary cycle patterns in marine successions exposed onland in the Mediterranean (Hilgen 1991*a*, *b*). Despite age discrepancies of up to 10% with conventional time-scales, the astronomical time-scale became the preferred time-scale because its validity was soon confirmed by radioisotopic dating using the new $^{40}Ar/^{39}Ar$ laser fusion technique. Independent support of the APTS came from a study by Wilson (1993), who showed that the astrochronology resulted in a more consistent and steady history of seafloor spreading rates. In this paper we will review the progress subsequently made in constructing an astronomical time-scale for the Mediterranean Neogene following the publication of the initial A(P)TS for the Pliocene and earliest Pleistocene in 1991.

2. Evaluation of the initial Pliocene astronomical time-scale

In the Mediterranean, marine successions of Neogene age are often characterized by the cyclic recurrence of dark coloured, sometimes laminated beds enriched in organic carbon, termed sapropels. Hilgen (1991*a*) used the standard oxygen isotope stratigraphy to arrive at a sapropel chronology for the last 0.5 Ma. Comparison of this sapropel chronology with the astronomical time-series revealed that individual sapropels correspond to minima of the precession index, and that small-scale and large-scale sapropel clusters correspond to 100 and 400 ka eccentricity maxima, respectively. Application of these relationships to older sapropels exposed in land-based sections (see figure 1 for locations) resulted in the construction of the initial A(P)TS for the Mediterranean Pliocene and earliest Pleistocene (Hilgen 1991*a*, *b*). This time-scale was based on correlating sedimentary cycle (sapropels and related carbonate cycles) patterns to the precession and eccentricity time-series of astronomical solu-

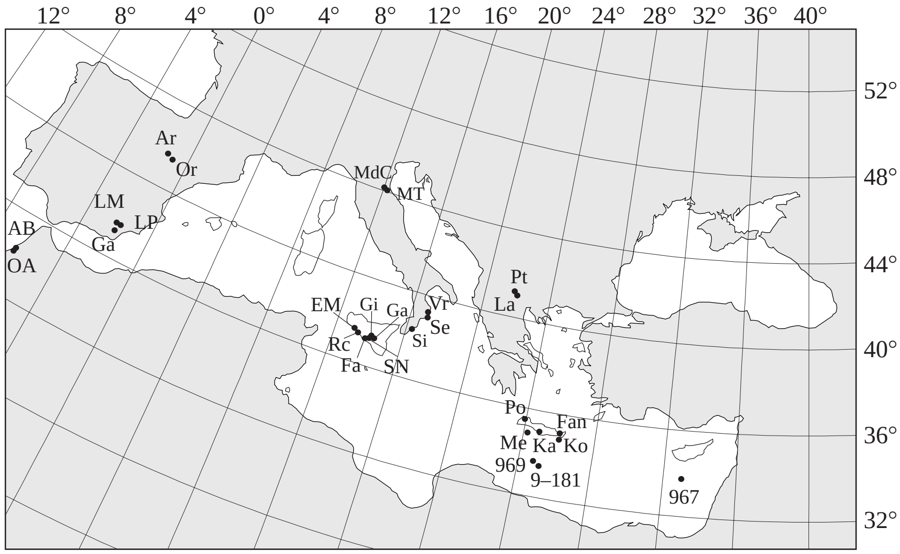

Figure 1. Location of sections used in astronomical time-scale work in the Mediterranean Late Neogene. Morocco: OA, Oued Akrech, AB, Ain el Beida; Spain: LM, Los Molinos, LP, Los Perales, Ga, Gafares (marine), Ar, Armantes, Or, Orera (continental); Italy: MdC, Monte del Casino, MT, Monte Tondo, Vr, Vrica, Se, Semaforo, Si, Singa, EM, Eraclea Minoa, Rc, Rossello Composite, Fa, Falconara, SN, San Nicola, Ga, Giammoia, Gi, Gibliscemi; Greece: Pt, Ptolemais, La, Lava, Po, Potamidha, Me, Metochia, Ka, Kastelli, Ko, Koufonisi, Fan, Faneromeni; ODP sites 967, 969; piston core RC 9-181.

tion BER90 (Berger & Loutre 1991). But soon afterwards, two other astronomical solutions became available (La90: Laskar 1990; Laskar *et al*. 1993; QTD90: Quinn *et al*. 1991). The La90 solution included two parameters, the tidal dissipation by the Moon and the dynamical ellipticity of the Earth, which are important because they affect the Earth–Moon system and are reduced relative to their present-day value (set at 1) when entering an ice age. Both the La90 and QTD90 solutions show small but significant differences with BER90 over the last 3.0 Ma (Berger & Loutre 1992) whereas La90 is in excellent agreement with the direct numerical QTD90 solution after introduction of the same tidal dissipation term (see Laskar *et al*. 1993).

Application of BER90 gave rise to unacceptably large time lags between obliquity and glacial-bound variations recorded in Late Pliocene proxy records from the Mediterranean (Hilgen *et al*. 1993). But, apart from dominantly controlling glacial cyclicity at that time, obliquity also exerted a marked influence on regional climate and thus on sedimentary cycle patterns in the Mediterranean. Lourens *et al*. (1996*a*) modified the earlier astronomical time-scale of Hilgen (1991*a*, *b*) by using different astronomical solutions and the 65° N summer insolation curve that included the influence of both precession and obliquity. Details in the sedimentary cycle patterns, in particular those caused by interference between precession and obliquity, in combination with results of a cross-spectral comparison between obliquity-related components in insolation and palaeoclimatic records, allowed them to determine which astronomical solution is the most accurate from a geological point of view (Lourens *et al*. 1996*a*; see figure 2). This appeared to be the solution formulated by Laskar, with (close to) present day values for the dynamical ellipticity of the Earth and the tidal

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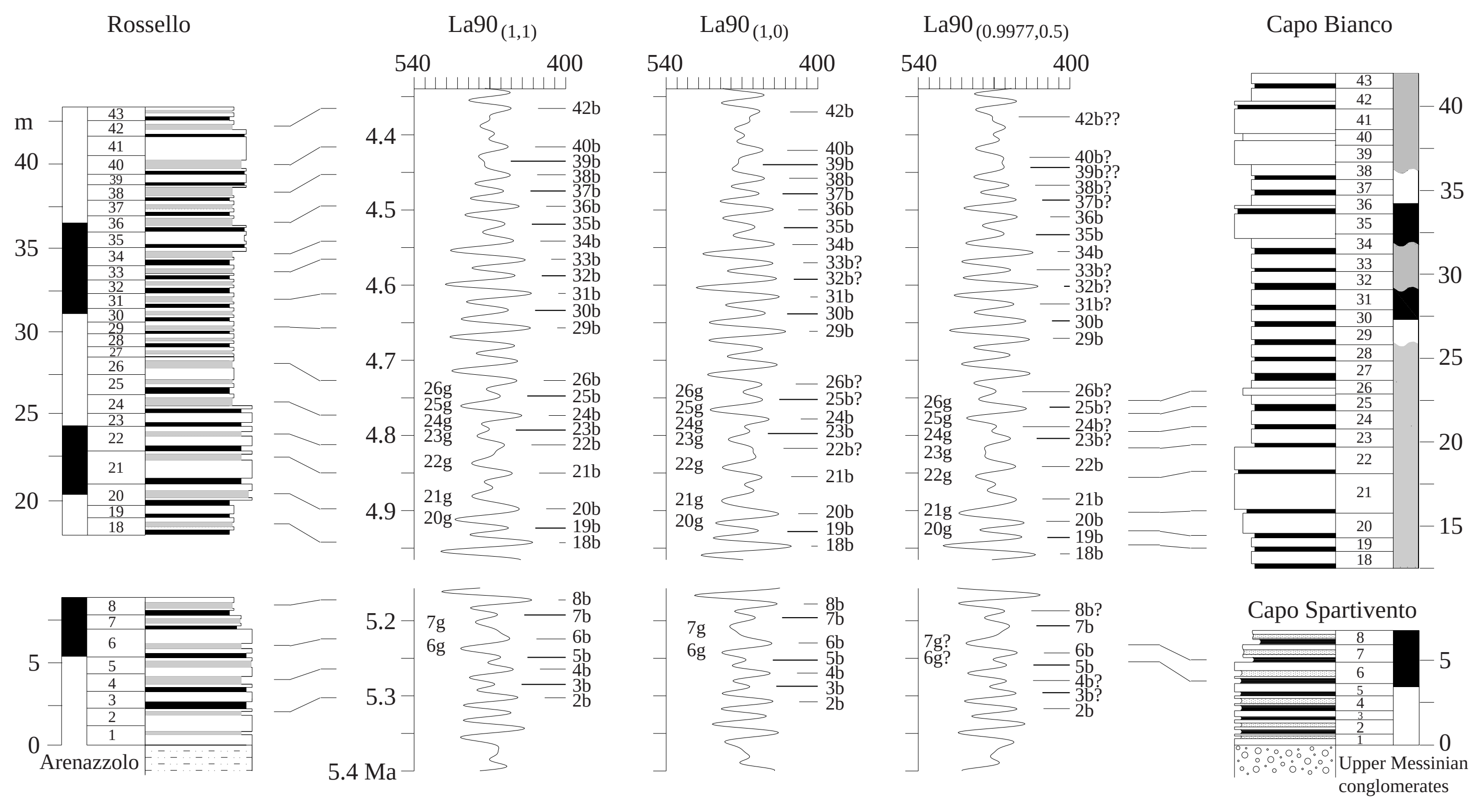

Figure 2. For description see opposite.

dissipation by the Moon. This conclusion was consistent with geophysical modelling studies, which showed that the dynamical ellipticity did not change during glacials to the extent of altering the precessional period significantly from its present-day value (Mitrovica & Forte 1995). The modified ATS served as a standard tool in accurately dating marine cores recovered during ODP Leg 160 from the eastern Mediterranean (Kroon *et al*. 1998; Lourens *et al*. 1998; see also figure 3).

3. Extension of the astronomical time-scale into the Miocene

The obvious next goal was the extension of the A(P)TS into the Miocene. Based on records from ODP Leg 138 in the eastern equatorial Pacific, a preliminary and partial astronomical tuning was established for the interval between 6 and 10 Ma by Shackleton and co-workers (Shackleton *et al*. 1995), while our group obtained an astronomical duration for Late Miocene polarity sequences on Crete (Greece) by multiplying the number of sedimentary cycles with the average period of the precession cycle (Krijgsman *et al*. 1994*a*). As a next step, we studied the sedimentary cycle patterns in the Cretan sections as well as those in partly older sections located on Gavdos and Sicily (figure 1), and calibrated the cycle patterns directly to the astronomical curves (Hilgen *et al*. 1995; figure 4). For this purpose, we used the same phase relations (between sedimentary cycles and astronomical cycles) as employed earlier in the Plio-Pleistocene. Stability of phase relations is suggested by results of high-resolution multi-disciplinary studies of Miocene sapropels (Nijenhuis *et al*. 1996; Schenau *et al*. 1999). The older sapropels reveal the same signals in the proxies analysed as their younger counterparts, suggesting that all sapropels and related cycles are the result of a single mechanism of formation over at least the last 10 Ma (Schenau *et al*. 1999).

One of the results of the Late Miocene A(P)TS is an age of 7.24 Ma for the Tortonian–Messinian boundary. This infers a duration of 1.91 Ma for the Messinian, since the Miocene–Pliocene boundary has an astronomical age of 5.33 Ma. The astronomical ages for the polarity reversals are consistently older than the ages in the most recent geomagnetic polarity time-scale (Cande & Kent 1995). Similar discrepancies are found with astronomically derived ages obtained from the orbital tuning of ODP Leg 138 records. The recently published astronomical time-scale for ODP Leg 154 sediments in combination with calcareous nannofossil biochronology (Shackleton &

Figure 2. Astronomical tuning of selected intervals of carbonate cycles from the cyclically bedded Trubi marl Formation to the 65° N summer insolation target curve according to La90 solutions with different values for the dynamical ellipticity of the Earth and tidal dissipation by the Moon. Intervals were selected in which the quadripartite (grey–white–beige–white) colour cycles reveal distinct interference patterns between precession and obliquity. These interference patterns are particularly evident in the beige layers (b). Distinct beige layers should correspond to high-amplitude summer insolation minima because the grey layers (g) are related to the sapropels and thus correspond to insolation maxima. Beige layers of cycles 2, 4, 6, 24, 34, 36, 38, 40 and 42 are well developed while beige layers of cycles 3, 5, 19, 35, 37, 39 and 41 are far less distinct or not developed at all. The extra-ordinary thick cycles 6, 21 and 22 are double cycles which contain an extra cycle that lacks sedimentary expression. The beige layer of cycle 6 occurs in the lower half of the cycle and thus corresponds to the older of the two correlative insolation cycles. The beige layer in cycle 21 and 22 occurs in the upper half of the cycle and thus corresponds to the younger of the two correlative insolation cycles. Question marks indicate misfits between the sedimentary cycle and insolation patterns. The interference pattern as observed in the colour cycles of the Trubi is in excellent agreement with the insolation curve according to the La90(1,1) solution. (Modified after Lourens *et al*. (1996*a*).)

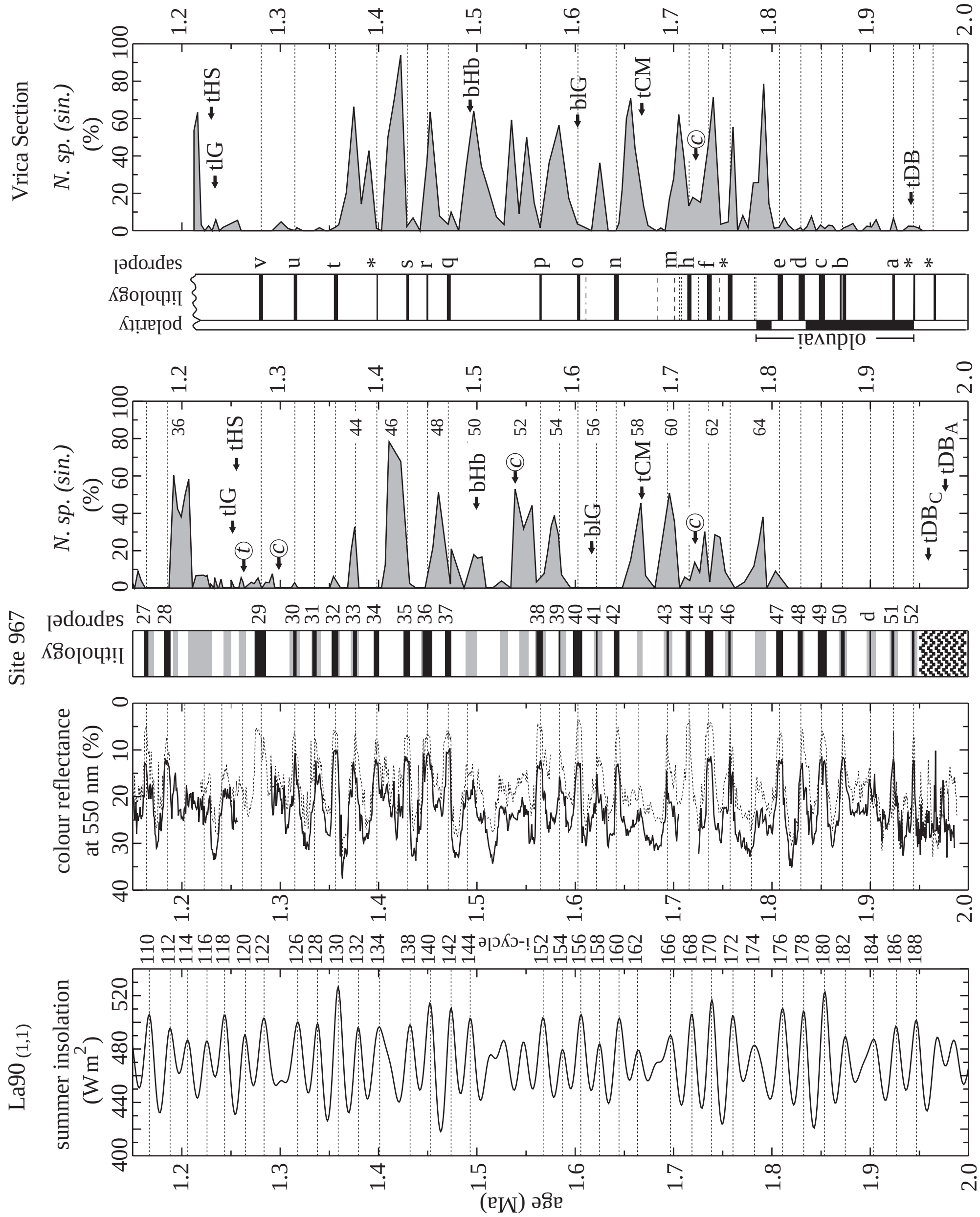

Figure 3. For description see opposite.

Crowhurst 1997; Backman & Raffi 1997), however, confirms that the Late Miocene ages from Leg 138 are too young.

At the end of 1995 (Hilgen *et al*. 1995), the Mediterranean APTS for the Miocene covered the time span from Early Messinian (6.7 Ma) to Middle Tortonian (9.7 Ma), but in the meantime this time-scale has already been extended back to 12.2 Ma (unpublished data). Since the previous time-scale covered the last 5.3 Ma, this results in a 'Messinian Gap' from 5.3 to 6.8 Ma. The main causes of this gap are the presence of sediments deposited during the so-called Messinian 'salinity crisis', which are less favourable to record cyclic climate variability (e.g. diatomites, evaporites), in combination with the notoriously complex depositional history of the Mediterranean during this time-interval.

4. Closing the Messinian gap in the astronomical time-scale

The classical Messinian succession in the Mediterranean starts with an alternation of sapropels and homogeneous marls, passes via diatomites into the Lower Evaporites (evaporitic limestone, gypsum and halite), and ends with the Upper Evaporites and fresh to brackish water sediments of the Lago Mare (e.g. Decima & Wezel 1973). The succession reflects the progressive deterioration of Atlantic–Mediterranean connections in the course of the latest Miocene, eventually leading to the total isolation of the Mediterranean from the open ocean.

The pre-evaporite and evaporite successions display a distinct cyclicity (Dronkert 1976; McKenzie *et al*. 1979; Vai 1997; Sierro *et al*. 1999) which can be employed to close the Messinian gap in the astronomical time-scale and solve many of the still existing and intriguing problems concerning the climatic and tectonic history of the Messinian (Krijgsman *et al*. 1999). As a first step, an integrated cyclostratigraphic, magnetostratigraphic and biostratigraphic framework was established for the pre-evaporitic Messinian by investigating three continuous marine successions located throughout the Mediterranean. All cyclostratigraphic correlations are confirmed in detail by high-resolution planktonic foraminiferal biostratigraphy. Characteristic patterns allow the sedimentary cycles to be calibrated to the astronomical record (Krijgsman *et al*. 1999). Evidence for the correctness of the tuning comes from the excellent match between precession–obliquity interference in the astronomical target and its reflection in the cycle record. The correlations show that the onset of the main evaporite phase is remarkably synchronous throughout the Mediterranean (Krijgsman *et al*. 1999). As a next step, the evaporite cycles of the Lower and Upper Evaporites have been calibrated tentatively to the astronomical record. This calibration in combination with observed relationships between different types of sedimentary cycles (sapropels, diatomites, evaporites) in the field suggests (1) that the two evaporite units are separated by a minor hiatus and (2) that all evaporite cycles are dominantly related to precession controlled variations in regional (circum-)Mediterranean climate. Also the large number of evaporite cycles excludes a dominant control by obliquity-induced glacio-eustatic sea-level variations. Our Messinian

Figure 3. Calibration of Early Pleistocene sapropels in Site 967 and the Vrica Section to the La90(1,1) (Laskar *et al*. 1993) summer insolation curve at 65° N against age (after Lourens *et al*. 1996*b*, 1998). The colour reflectance data of Hole 967A (dashed line) has been shifted to the right with 10% relative to that of Hole 967C. All colour reflectance data are obtained from Sakamoto *et al*. (1998). Cycle codification (i-cycle) is indicated at the right side of the insolation curve after Lourens *et al*. (1996*a*, 1998). The jagged pattern in the lithology column of Site 967 indicates a slumped interval. Solid intervals indicate sapropels, whereas the shaded areas indicate grey layers or less-distinct sapropels. Also shown are biostratigraphic data and events: tDB marks the top of Discoaster Brouweri, tCM the top of Calcidiscus Macintyrei, blG the base of large-sized Gephyrocapsa, tlG the top of large-sized Gephyrocapsa, tHS the top of Helicosphaera Sellii, and bHb the first common occurrence of Hyalinea balthica. C and t indicate influxes of Globorotalia crassaformis and Globorotalia truncatulinoides, respectively. The percentage of left-coiling neogloboquadrinids (N. sp. (sin)) is related to the total of left- and right-coiling neogloboquadrinids. Numbers at the right side of this curve in Site 967 refer to the oxygen isotope stages.

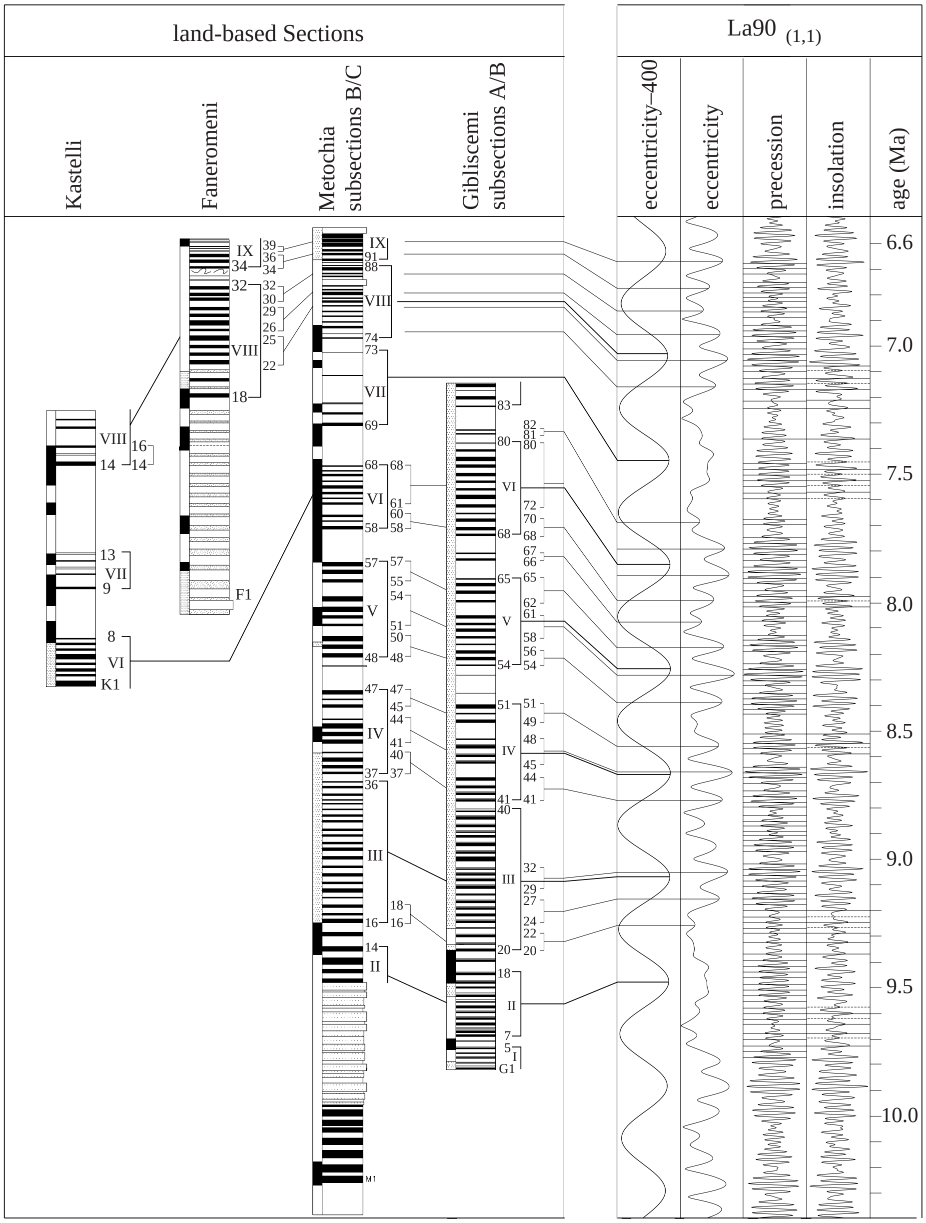

Figure 4. Astronomical calibration of Late Miocene sapropels to astronomical curves of eccentricity, precession and insolation (65° N summer insolation). Larger-scale eccentricity related sapropel clusters were used to establish a first-order astronomical tuning. (Modified after Hilgen *et al.* (1995).)

APTS is consistent with the astronomical time-scale developed by Shackleton & Crowhurst (1997) for ODP Leg 154 sites since markedly similar ages for the reversal boundaries are found if we export the calcareous nannofossil astrochronology from the tropical Atlantic (Backman & Raffi 1997) to the eastern tropical Pacific ODP

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Leg 138 sites having a magnetostratigraphy (see Krijgsman *et al*. 1999). The ages, however, are unexpectedly much older than the ages for the same reversals in CK95 (Cande & Kent 1995).

Other attempts to obtain an astronomical tuning for the same interval yielded different ages for the polarity reversals (Benson *et al*. 1995; Sprovieri *et al*. 1996), but suffer from serious shortcomings. The ATS of Benson and co-workers is hampered by the fact that the number of sedimentary cycles does not match the number of precession cycles in the correlative interval of the orbital time-series. Extraordinarily thick sedimentary cycles may represent double cycles, and thus explain the discrepancy in cycle numbers, but this adjustment will at the same time disrupt the characteristic cycle thickness pattern on which the tuning is based. Sprovieri *et al*. (1996) do not take details of the sedimentary cycle pattern into account and they use high-resolution proxy records from northern Atlantic DSDP Site 552 to span the interval covered by the evaporites in the Mediterranean. This core, however, is less suitable for this purpose because it was recovered before drilling of multiple offset holes became standard practice to overcome discontinuities at core breaks (see Ruddiman *et al*. 1986).

5. Incorporating the continental record

So far, open marine sequences have been used to construct the Late Neogene APTS, but it is evident that the continental record must be included for determining the evolution of continental climate, and its intercalibration with the marine realm. In fact, the terrestrial sedimentary record seems to be the logical place to search for Milankovitch cycles because, in the absence of oceanographic processes with their intrinsic and complicated nonlinear (feedback) mechanisms, a more direct registration of orbitally induced changes in climate may be expected there. Potential and serious drawbacks of using continental successions, however, are the usual lack of a direct and sufficiently accurate time control, and the alleged common occurrence of hiatuses which result from tectonic activity, base-level changes, autocyclic processes and intermittent erosion. Nevertheless, regular subsidence balanced by continuous sedimentation does occur in continental settings as shown by classical studies of Milankovitch cycles in terrestrial successions (see Olsen *et al*. 1996). These examples, however, all date from remote parts in the Earth's history and lack the necessary first-order time control.

Our continental research efforts in the Mediterranean focus on (fluvio)lacustrine cyclicity in Late Miocene and Pliocene basin fills of Greece, and on Middle to Late Miocene red-bed sequences of Spain. First results from Spain suggest that the prominent cyclic bedding of (groundwater) caliches in the red-bed sequences of Section Armantes is related to the 100 ka eccentricity cycle (Krijgsman *et al*. 1994*b*), while less distinct smaller-scale cycles may reflect the influence of precession (Krijgsman *et al*. 1997*a*). Current research in Spain concentrates on a marginal lacustrine to floodplain and distal fan succession exposed around the village of Orera. This succession shows a remarkable and hierarchically arranged cyclicity that reflects the superimposed control exerted by the three orbital parameters, and has the clear potential for extending the APTS further back in time, into the Middle Miocene.

Results of the lacustrine successions of the Ptolemais area in NW Greece indicate that cyclic lignite–marl alternations reflect precession-controlled variations in regional climate (Van Vugt *et al*. 1998; Steenbrink *et al*. 1999). The successions can be correlated in detail to the previously studied marine sequences, thus allowing the reconstruction of the influence of astronomically induced climate changes along terrestrial–marine environmental gradients. Such integrated marine–continental studies will provide important constraints for climate modelling experiments aiming at a better understanding of the astronomical forcing of climate.

An important and crucial aspect for time-scale evaluation and climate reconstructions is that of the phase relations between cycles in the marine and continental record. Preferably, such relations should not be based on interpreting cycles in terms of climate, lake level, etc., but—in the ideal case—on the unambiguous identification of the same volcanic ash layers in both settings. Numerous ash beds are present in the cyclically bedded lacustrine lignite succession of Ptolemais but they have thus far not been identified in the marine record, probably as a consequence of their limited geographical extent. Alternatively, phase relations can be established by tracing the same climatic proxy, for instance the Ti/Al ratio or clay minerals such as kaolinite and palygorskite for African continental aridity, in both settings.

6. Implications for the standard geological time-scale

The success of the orbital tuning approach is clearly demonstrated by the adoption of the astronomical time-scale as a standard for the Pliocene–Pleistocene in most recent time-scales (Cande & Kent 1995; Berggren *et al*. 1995) and it can be anticipated that the Late Miocene A(P)TS will soon be incorporated as well. An important additional advantage of the A(P)TS is that chronostratigraphic boundaries are directly tied to it via first-order calibrations in the Mediterranean. In fact, all Upper Neogene stages presently used in the global chronostratigraphic scale were originally defined in Italy.

Chronostratigraphic boundaries are formally defined by carefully selecting global standard stratotype-section and points (GSSPs) following the procedures and guidelines set by the International Commission on Stratigraphy (ICS; Remane *et al*. 1996). The GSSP for the Pleistocene, which in addition marks the Neogene–Quaternary boundary, is hotly debated but is now definitively defined at the base of the homogeneous claystone unit overlying sapropel e in the Vrica Section (southern Italy; Aguirre & Pasini 1985) dated astronomically at 1.808 Ma. The boundary itself has thus an astronomical age of 1.81 Ma and coincides closely with the Upper Olduvai reversal boundary (Zijderveld *et al*. 1991; Lourens *et al*. 1996*b*). More recently, Pasini & Colalongo (1994) proposed to define the Santernian/Emilian (sub?)stage boundary 6 m above sapropel o at the level that coincides with the first occurrence of the benthic foraminifer Hyalinea balthica in the same section, dated astronomically at 1.57 Ma. The astronomical tuning of this (upper) part of Section Vrica was included in the Lourens *et al*. (1996*a*) paper but serious doubts concerning the stratigraphic continuity were raised soon afterwards, the alternative option being an hiatus of more than 100 ka (see Lourens *et al*. 1996*b*). A detailed comparison of the integrated stratigraphy of Vrica with that of ODP Leg 160 sites confirms, however, that the Vrica Section is continuous and that the initial astronomical tuning of the sapropels is correct (Lourens *et al*. 1998).

The GSSPs for the Piacenzian (Middle Pliocene) and the newly erected Gelasian (Upper Pliocene) Stages are now formally defined in marine sections that have been dated astronomically (Rio *et al*. 1998; Castradori *et al*. 1998). The Gelasian GSSP is placed at the top of a very prominent sapropel in the Monte San Nicola Section (Sicily, Italy), informally labelled the Nicola Bed. This sapropel has been dated astronomically at 2.588 Ma and falls within Stage 103 in terms of the standard oxygen isotope stratigraphy (Lourens *et al*. 1996*a*). The Piacenzian GSSP is pinpointed at the base of the beige marl bed of small-scale carbonate cycle 77 of the Trubi Formation (sensu Hilgen 1991*b*) in the Punta Piccola partial section of the Rossello Composite (Sicily). The boundary, which has been dated astronomically at 3.596 Ma, coincides closely with the Gilbert–Gauss reversal boundary and is located in obliquity-related ^{18}O stage MG8 (Shackleton *et al*. 1995; Tiedemann *et al*. 1994), labelled O-176 by Lourens *et al*. (1996*a*).

GSSPs have further been proposed for the Lower Pliocene Zanclean Stage (and Pliocene Series) and for the Uppermost Miocene Messinian Stage (Van Couvering *et al*. 1998; Hilgen *et al*. 1998). According to these recently advanced proposals the Zanclean GSSP should be placed at the base of the first small-scale carbonate cycle of the Trubi Formation in the Eraclea Minoa Section on Sicily dated astronomically at 5.33 Ma (i.e. at the level that marks the sudden restoration of open marine conditions in the Mediterranean following the Messinian salinity crisis) and the Messinian GSSP at the base of reddish layer no. 15 in the Oued Akrech Section of Atlantic Morocco dated astronomically at 7.24 Ma. Finally, the downward extension of the Gibliscemi Section on Sicily provides us with a potential candidate for defining the Tortonian GSSP as it contains the Serravalian–Tortonian boundary interval in a continuous open marine succession that has been astronomically dated.

Clearly, astronomical dating especially when combined with formal GSSP definitions holds great promise for uniformity and stability in the standard global chronostratigraphic and chronometric scale. But accepting the astronomical time-scale as standard for the Pliocene–Pleistocene also poses a serious problem, namely that the geological time-scale is based on two independent absolute dating techniques, i.e. radioisotopic and astronomical dating.

7. Intercalibration of astronomical and radioisotopic time

Astronomical dating of magnetic reversals in the Pliocene–Pleistocene, i.e. independent from radioisotopic techniques, marked a turning point in the history of the astronomical time-scale. From 1982 onwards (Johnson 1982), the APTS started to deviate significantly from polarity time-scales that were based on K/Ar dating. The new time-scale revealed discrepancies of up to 10%, astronomical ages being consistently older than the K/Ar ages (Shackleton *et al*. 1990; Hilgen 1991*a*, *b*). Since then, the validity of the APTS has been increasingly confirmed by radioisotopic dating using the new ^{40}Ar/^{39}Ar laser fusion technique (e.g. Tauxe *et al*. 1992; Renne *et al*. 1993; Hall & Farrell 1995; Clement *et al*. 1997).

The geological time-scale that existed in the early 1980s was the result of the cumulative work of some 30 years of research in isotope geochronology (Glen 1982). Much of the database was of mixed reliability. This problem was overcome in part by statistical screening of the database for each stage boundary (e.g. Harland *et al*. 1982). The fundamental shortcoming of this approach was that it did not address problems related to the design of the experiment. With the advent of new low blank laser and furnace based techniques using ^{40}Ar/^{39}Ar dating rather than the conventional K/Ar technique, it became evident that problems could arise from, for example, partial alteration of basaltic whole rocks and incomplete degassing from feldspars. Using the $^{40}Ar/^{39}Ar$ methods such problems could be identified either by using an incremental heating technique that allows testing for open–closed system behaviour of the sample that is actually used for dating, or circumvented in the case of undisturbed samples as quantitative recovery of all radiogenic argon is not required to obtain reliable $^{40}Ar/^{39}Ar$ ages.

The factor limiting the accuracy in $^{40}Ar/^{39}Ar$ dating at this moment is the age uncertainty of neutron fluence monitors, or mineral dating standards. All currently used mineral standards can be traced back to a set of primary standards for which the ^{40}K contents and ^{40}Ar contents were measured absolutely by, for example, isotope dilution techniques. Calibration of tracer isotopes used for isotope dilution techniques, and the fact that absolute amounts of ^{40}Ar and ^{40}K need to be measured with conventional K/Ar techniques, resulted in an overall uncertainty of *ca.* 1.0–1.5% in the age of these standards as compared with a typically 0.3% analytical precision of modern $^{40}Ar/^{39}Ar$ techniques. Ages of dating standards have recently been calibrated independently of absolute isotopic abundance measurements by comparing $^{40}Ar/^{39}Ar$ and astronomical ages of geomagnetic polarity reversals over the last 3.5 Ma (Renne *et al*. 1994). An alternative to this indirect approach via interpolated ages of magnetic reversal boundaries is the direct comparison of astronomical and $^{40}Ar/^{39}Ar$ ages of ash layers that are intercalated in astronomically dated sedimentary successions. A first attempt in this direction proved unsuccessful: biotites from Monte del Casino in northern Italy gave a good approximation of the age of the section but were not suitable for high-resolution chronological studies (Krijgsman *et al*. 1997*b*). Biotite, mixed feldspar and sanidine separates from two ash layers intercalated in Late Miocene sections on Crete and Gavdos (Greece) yielded more promising results that are consistent with the work of Renne *et al*. (1994), especially when slightly modified astronomical ages for polarity reversals (Lourens *et al*. 1996*a*) are taken into account (Hilgen *et al*. 1997). All intercalibrated ages were indistinguishable from (at least some of the) then accepted ages of dating standards despite an assumed error of 1–1.5% in the conventional ages. $^{40}Ar/^{39}Ar$ ages on sanidine and biotite separates from ash beds intercalated in the magnetostratigraphically controlled and astronomically tuned Upper Pliocene lacustrine succession of Ptolemais (Greece) revealed that a single lignite–marl alternation represents a time-interval of 21.8 ± 0.7 ka, thus providing support for the proposed precessional origin of the cycles. More importantly, our results for the first time independently confirm the duration of a precessional cycle in the Pliocene.

Ongoing research by the radioisotopic dating community suggests, however, that conventional ages of dating standards may be too young by 1.5–2.0% (Renne *et al*. 1998). In the case of the Ptolemais ash beds we found a constant *ca.* 200 ka (*ca.* 4.5%) discrepancy with the younger astronomical ages for the same beds (Van Vugt *et al*. 1998; Steenbrink *et al*. 1999). Although the origin of this discrepancy is not fully understood at this stage, we feel that it is unlikely to result from an error in the astronomical ages through incorrect tuning, inaccurate magnetostratigraphic data or orbital time-series and/or errors in the A(P)TS (Steenbrink *et al*. 1999). The above results all show that a rigorous intercalibration of astronomic and radioisotopic time is mandatory. Clearly such an intercalibration attempt should run parallel with further improvements in both independent dating methods.

8. Future developments

Astronomical tuning is at present the most accurate absolute dating technique for the youngest part of the Earth's history, the success and validity of the approach being demonstrated by the adoption of the Pliocene–Pleistocene ATS as the standard in the most recent geological time-scale (Berggren *et al*. 1995). Nevertheless, the development and application of pre-Pliocene A(P)TS is still in its infancy despite the progress recently made. Future research will in particular focus on the following topics.

1. Extension of the 'anchored' A(P)TS (sensu Fischer 1995; i.e. an ATS that is tied to the Recent via direct calibration to the astronomical record) to older (pre-)Neogene intervals of the geological record. This extension will provide more insight in the potential link between long-term orbital cycles with periods in the 1–3 Ma range and third-order sequences in sequence stratigraphic charts (e.g. Lourens & Hilgen 1997). On the other hand the use of long-period orbital cycles may provide an excellent opportunity to establish a direct astronomical calibration for much older parts of the geological record.

2. Further evaluation of the ATS is mandatory because astronomical solutions start to include realistic viscoelastic Earth models and ^{18}O records as a measure for ice volume (Mitrovica & Forte 1997; Forte & Mitrovica 1997). Like the previous one (Lourens *et al*. 1996*a*), this evaluation will concentrate in particular on precession–obliquity interference patterns because such patterns are extremely sensitive to small changes in the astronomical solution. Such an evaluation is critical to palaeoclimate studies directed at establishing phase relations between orbital forcing and climate response as recorded in sedimentary archives of the Miocene, but may also provide constraints on for instance lower mantle viscosity values.

3. Integration of sedimentary cycles in the marine and continental records into a single astronomically tuned cyclostratigraphic framework, using an integrated stratigraphic approach. Much attention should be paid in this respect to geographically extend the study area to areas supposedly affected by the same climate oscillations and to incorporate sedimentary cycles which accumulated in different depositional environments. Prime examples are the sedimentary cycles of the marine Bou Regreg succession of Atlantic Morocco and different types of cycles encountered in the continental basins of Spain (e.g. cyclically bedded alluvial fan deposits).

4. To arrive at a synthetic model for sedimentary cycle formation in the Mediterranean (Late) Neogene within the framework of a single astronomically induced oscillatory climate forcing mechanism. Validation of the target curve applied in astronomical time-scale work in the Mediterranean Neogene—the 65° N summer insolation—is required because its selection is based on a visual comparison of the contribution of obliquity relative to that of precession on cycle patterns rather than on understanding the causal mechanisms themselves. In addition the direct link to climate modelling experiments is mandatory.

5. A rigorous intercalibration of radioisotopic and astronomical time is needed in view of the ongoing uncertainty in the age of dating standards and the value

of decay constants in combination with the fact that the standard geological time-scale is based on two independent absolute dating methods of which the intercalibration is not yet firmly established.

Project MIOMAR (MIOcene Marine Archives Reading) received financial support from the EU Human Capital and Mobility programme. Programme CoMCoM (Continental Marine Correlations in the Mediterranean) and continental research in Spain is supported by The Netherlands Geosciences Foundation (GOA) with financial aid from The Netherlands Organization of Scientific Research (NWO).

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