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Palaeogeography, Palaeoclimatology, Palaeoecology 172 (2001) 193–205

PALAEO

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Orbital forcing in Pliocene–Pleistocene Mediterranean lacustrine deposits: dominant expression of eccentricity versus precession

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Received 13 March 2000; accepted for publication 20 March 2001

Abstract

Milankovitch forcing of climate is expressed in the sedimentary record as lithological cycles that can have one or more of four typical periods related to precession (21 kyr), obliquity (41 kyr) and eccentricity (100 and 400 kyr). In several Mediterranean continental successions, striking differences in the expression of particularly precession and eccentricity appear. We present the results of an additional lower Pliocene lacustrine succession from Lupoaia (southern Romania), and compare the cyclic expression in this lignite–siliciclastic basin in detail with the time-equivalent lignite–carbonate basin of Ptolemais (northern Greece), the middle Pleistocene lignite–siliciclastic basin of Megalopolis (southern Greece) and the Miocene carbonate–clay basin of Orera (north eastern Spain). It appears that carbonate basins dominantly express precession, while siliciclastic basins dominantly express eccentricity in their lithological cycles. This can be explained by a more linear response to insolation forcing in carbonate basins than in siliciclastic basins. Alternatively, it can be explained by the low amplitude of 100-kyr eccentricity at the times the carbonate sections were deposited. This reduced 100-kyr amplitude was caused by minima in the 2.35 Myr eccentricity cycle, that co-occurred with the deposition in both carbonate basins. Finally, the expression of 100-kyr eccentricity appears to be independent of glacial cyclicity.

Keywords: Orbital forcing; Sedimentary cycles; Magnetostratigraphy; Mediterranean; Lacustrine; Neogene

1. Introduction

Lithological cycles in sediments are now widely accepted as having been caused by astronomical forcing. Precession has a pronounced influence on seasonal contrast and has an opposite effect on each hemisphere. It can change monsoon systems that can in turn affect depositional systems. Obliquity causes fluctuations in the seasonal contrast between summer and winter and its effect increases towards higher latitudes, simultaneously on both hemispheres. Obliquity may enhance the climatic effect of precession on one hemisphere, while it reduces the effect on the other hemisphere. Eccentricity mainly modulates the effect of precession, it has itself very little effect (<0.1%) on the incoming solar radiation. The classic Milankovitch target curve of summer insolation incorporates all these effects and its frequency spectrum is dominated by precession, but obliquity is clearly discernible as well, while eccentricity is virtually absent. Yet,

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0031-0182/01/$ - see front matter
PII: S0031-0182(01)00270-X

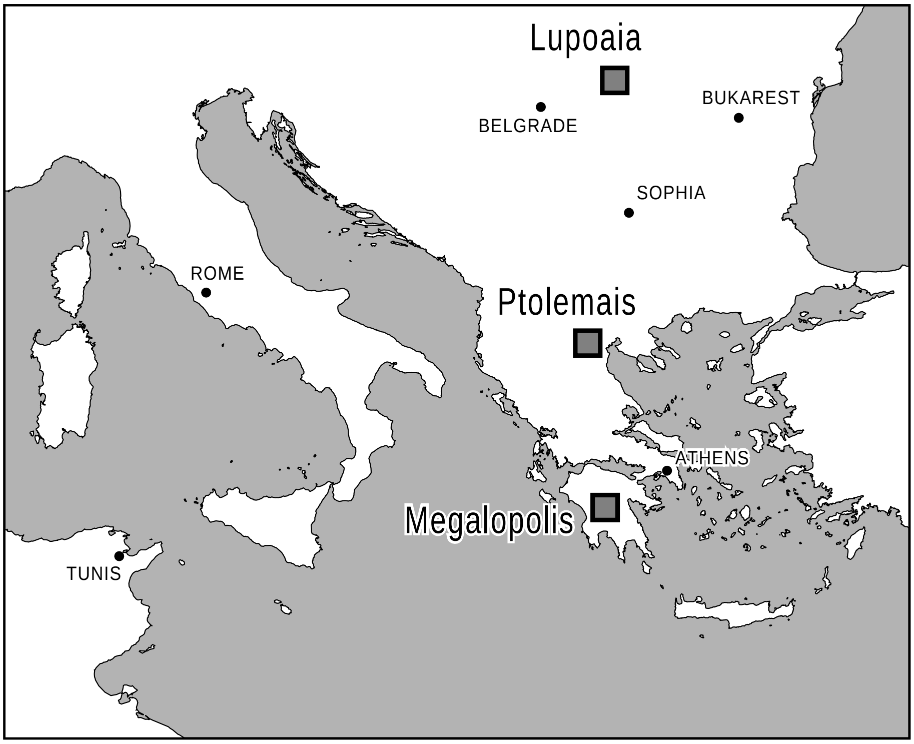

Fig. 1. Map of the northern border of the eastern Mediterranean. Capital cities (dots) and locations of studied sections (squares) are indicated.

the periods of eccentricity (100 and 400 kyr) are clearly expressed in many geological records (e.g. Imbrie et al., 1984; Fischer et al., 1991; Hilgen, 1991a; Olsen and Kent, 1996). This can be explained by non-linear response mechanisms, such as the asymmetric response mechanism of Clemens and Tiedemann (1997) that preferentially introduces variance into the climate system during the warmer portions of the eccentricity cycle. The spectral peaks at the eccentricity-frequencies of their truncated insolation curve are comparable to those in oxygen-isotope records, demonstrating that eccentricity can indeed cause strong 100 and 400-kyr lithological cycles. Another type of non-linear response is used in Paillard's ice-age model with multiple steady states and predefined insolation-related rules (Paillard, 1998). This model can successfully simulate late Pleistocene $\delta^{18}O$ time series, which occurred approximately every 100 kyr. Alternatively, a combination of truncated response and post-depositional effects such as bioturbation may smear the precession cycles and transfer nearly all power from the precession frequencies to eccentricity (Fischer et al., 1991).

Recently, many Neogene Mediterranean records from widely different continental environments have been studied: from alluvial to lacustrine (Krijgsman et al., 1997; van Vugt et al., 1998; Steenbrink et al., 1999; Abdul Aziz et al., 2000; van Vugt et al., 2000). In this paper we present the results from one more continental section from southern Romania. In all these successions, Milankovitch-type cyclicity is expressed in the lithology. The most apparent astronomical periods in these successions are precession and eccentricity, but generally one of them is dominant. We will compare three of these continental sections in detail, all lignite bearing lacustrine successions; two of them are overlapping in time. It will become apparent that the dominant astronomical period expressed in these records is not necessarily related to the geological era and its predominant climate type in which they were deposited. Instead, the sedimentary environment or basin setting seems to

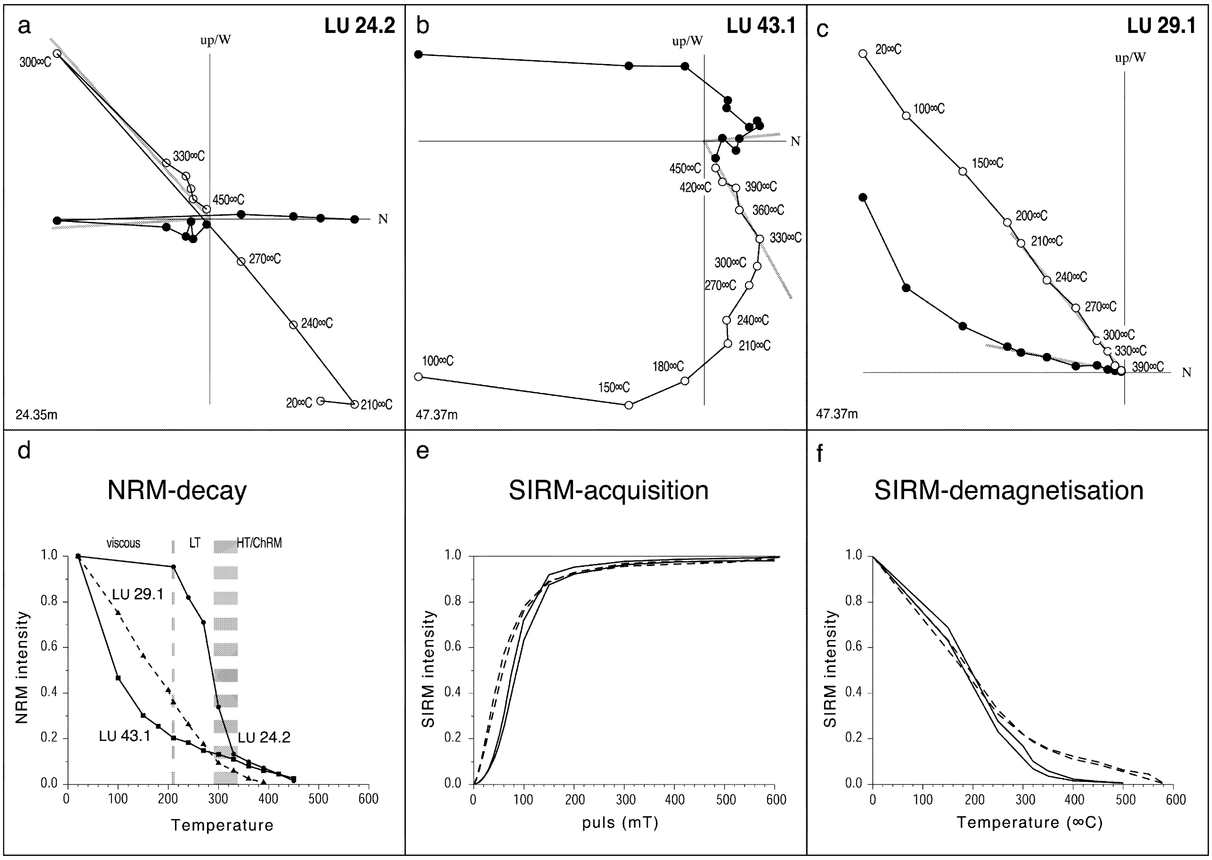

Fig. 2. Upper panel: Thermal demagnetisation diagrams of typical samples; black (white) dots indicate horizontal (vertical) projection. a) LT (up till 300°C) and Ch component (300–420°C) have opposite polarities. b) LT (up till 330°C) and Ch component (330–450°C) are not opposite. c) only Ch component distinguishable. Lower panel: d) normalised intensity plot of NRM during thermal demagnetisation; SIRM acquisition (e) and thermal demagnetisation (f); dashed line: magnetite + iron sulphide, solid line: greigite.

be crucial for whether eccentricity or precession is the dominant astronomical period. Finally, similarities and differences with the other Mediterranean continental records will be discussed.

2. Geological background

The three successions discussed here were all deposited in lacustrine basins and are now exposed in open-pit lignite mines (see Fig. 1 for locations). The first is the lower Pliocene Ptolemais composite section from the elongated intra-montane basin between Kozani and Florina in northern Greece (van Vugt et al., 1998; Steenbrink et al., 1999). The 100 m thick succession consists of a rhythmic alternation of metre-scale lignite and carbonate layers, that can be recognised and correlated across the basin. Intercalated volcanic ash layers serve as isochrons, and prove that the rhythmic lithological changes are synchronous. These sedimentary cycles occur in a regular pattern, except in a 10 m thick interval in the middle of the succession, where the expression of the cycles is less clear. The sediment is almost solely formed by either carbonate or organic material; the siliciclastic fraction is generally less than a few percent.

The second succession is the middle Pleistocene Megalopolis section that was deposited in the half-graben near Megalopolis, southern Greece (van Vugt et al., 2000). This 135 m thick succession contains four 5–30 m thick lignite seams in otherwise

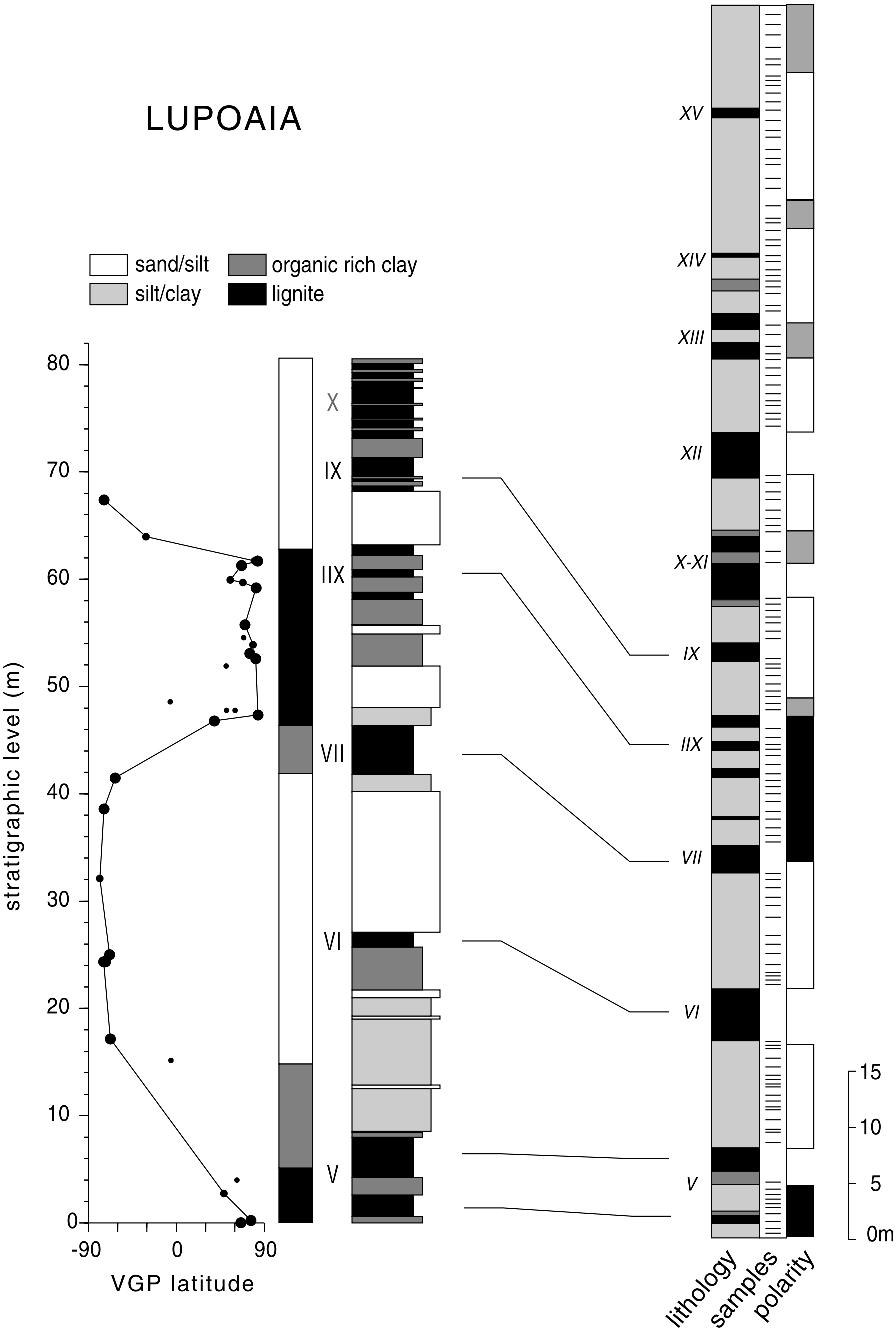

Fig. 3. Lupoaia section with the magnetic polarity pattern. Left hand side: latitude of the virtual geomagnetic pole (larger dots = more reliable data); inferred magnetic polarity (black = normal, white = reversed, grey = uncertain); cycle numbers and lithology from this study. Right hand side: lithology; sample positions and inferred polarity as reported by Radan and Radan (1998).

siliciclastic sediments (clay, silt, sand). The lignite seams can be correlated over a large part of the basin, and a volcanic ash layer confirms that the lithology changes are synchronous. In addition to the large-scale cyclicity, smaller scale cycles were observed within the siliciclastic intervals as 0.5–2 m thick lignite or organic-rich clay layers alternating with clay, silt and/or sand.

The third succession is the lower Pliocene Lupoaia section from the Oltenia basin near the city of Motru, south-west Romania. This section belongs to the Motru coal complex, a member of the Jiu–Motru Formation, that consists of several thick coal seams (~5 m) that are labelled with roman numerals by the mining company. These lignites are separated by ~15 m thick intervals of clay, silt and sand. Most lignite seams occur in this regular alternating pattern, and therefore a lignite and overlying siliciclastic interval are called a sedimentary cycle. In the Lupoaia mine, lignite seams V–XV are exposed, but our study focussed on an interval with a clear cyclic expression: the 80 m long section between lignites V and IX. Subdivision of lignites V and IIX might point to an additional small-scale cyclicity, but lateral continuity of these small-scale cycles should be verified outside the single studied mine before defining these as sedimentary cycles. The magnetostratigraphy for the complete exposed succession was performed by Radan and Radan, 1998. Below we discuss the results of the interval between lignites V and IX.

3. Magnetostratigraphy of Lupoaia

The palaeomagnetic analysis of the Lupoaia section is based on the analysis of 78 magnetostratigraphic sites, cored in the field with an electrical portable drill. The natural remanent magnetisation (NRM) was studied in the laboratory by means of standard stepwise thermal demagnetisation procedures and measured on a 2G Enterprises horizontal DC SQUID magnetometer. A selection of samples was exposed to a pulse field to acquire an IRM and subsequently thermally demagnetised.

The samples generally have a viscous component that is completely removed at 210°C. Several samples have a component that is removed between ~200 and 300–330°C: the low temperature (LT) component (Fig. 2a and b). Most samples have a stable higher-temperature component that generally fully unblocks at 390 or 420°C (Fig. 2a and c); maximum unblocking temperatures higher than 450°C are rarely observed (Fig. 2b). The LT component can be anti-parallel to the HT component or have an intermediate direction (Fig. 2a and b respectively), but mostly, only one of these components could be reliably determined in a single sample (Fig. 2c).

In both the IRM acquisition and demagnetisation diagrams two types of behaviour can be distinguished. The first type shows a steep increase in IRM at low fields, but saturation is not reached until ~600 mT. The IRM strongly decreases on heating up to ~300°C and total unblocking occurs at 580 ~ C. These samples are interpreted to contain magnetite and a ferrimagnetic iron sulphide. The IRM of the second type increases slowly at low fields and saturation is reached at ~600 mT. The maximum unblocking temperature of 400 ~ C points to a ferrimagnetic iron sulphide carrying the IRM, probably greigite, which is very common in fresh-water sediment.

The maximum unblocking temperature of the LT component (300–330°C) indicates that this remanence is probably carried by a ferrimagnetic iron sulphide. Since greigite decomposes upon heating between 270 and 350°C and the Curie temperature for pyrrhotite is 325°C (Torii et al., 1996), they could both be the carrier of this component. These iron sulphides commonly form as an authigenic phase, i.e. they are formed after deposition, and the moment of remanence acquisition is therefore uncertain. Furthermore, the LT component changes the polarity of almost every other sample. Hence, we do not use this component for magnetostratigraphy.

The HT component unblocks at higher temperatures (390–420°C or higher), which indicates that magnetite could be the remanence carrier, but the chemical reaction of iron sulphides upon heating to ~400°C obscures the typical magnetite Curie temperature that was indeed observed in the IRM experiment. Since the directional results of these samples provide a sensible polarity pattern, we take this component as the characteristic remanent magnetisation (ChRM). It is assumed to be of (near) primary origin. The lowermost part of the section (lignite V) and the interval from lignite VII up to IIX have a normal polarity (Fig. 3). The middle and uppermost

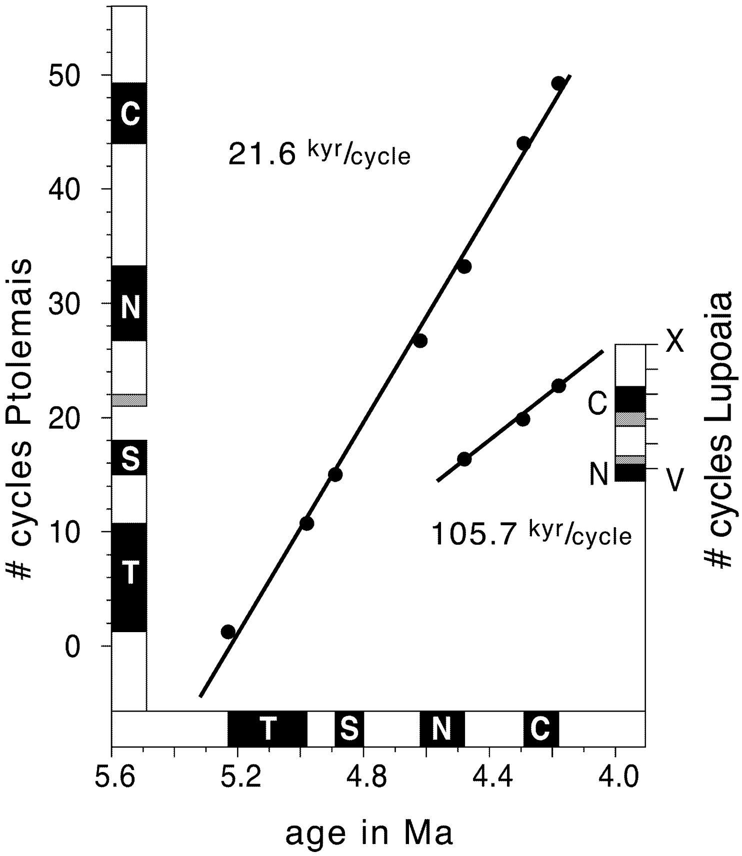

Fig. 4. Polarity column of Ptolemais (left hand side) and Lupoaia (right hand side) in number of cycles versus age (APTS). T = Thvera, S = Sidufjall, N = Nunivak, C = Cochiti subchron. The lines indicate the average duration of a sedimentary cycle: 21.8 kyr for Ptolemais and 105.7 kyr for Lupoaia.

parts are reversed. From previous work in the Lupoaia mine (Radan and Radan, 1998), it is known that the uppermost reversed interval continues at least up to lignite XV (Fig. 3). Assuming an average constant sedimentation rate, this section represents consecutively part of a normal polarity period, two short periods with subsequently reversed and normal polarity, and a reversed interval that lasted at least three times as long as the short periods. Since the Dacian–Romanian stage boundary occurs in this section, it is assigned a Pliocene age (Andreescu, 1981; Alexeeva et al., 1983). Then there are only two possible subchrons to correlate the long reversed interval to: the top of the Gilbert Chron or the base of the Matuyama Chron. The reversed upper Gilbert is preceded by several short normal subchrons (Cochiti, Nunivak, Sidufjall and Thvera subchrons). Since our polarity pattern is not consistent with the base of the Matuyama, we conclude that the polarity pattern in Lupoaia represents the upper part of the reversed Gilbert Chron, and the normal intervals can be correlated to the Nunivak and Cochiti subchrons.

4. Astronomical forcing and tuning of the sedimentary cycles in Lupoaia

Astronomical forcing of sedimentary cycles can be demonstrated by analysing the average duration of the cycles, provided that age calibration points such as polarity reversals are available. When the average period of the cycles in the time domain is constant and identical to one of the known Milankovitch periods, astronomical forcing is a likely cause. The

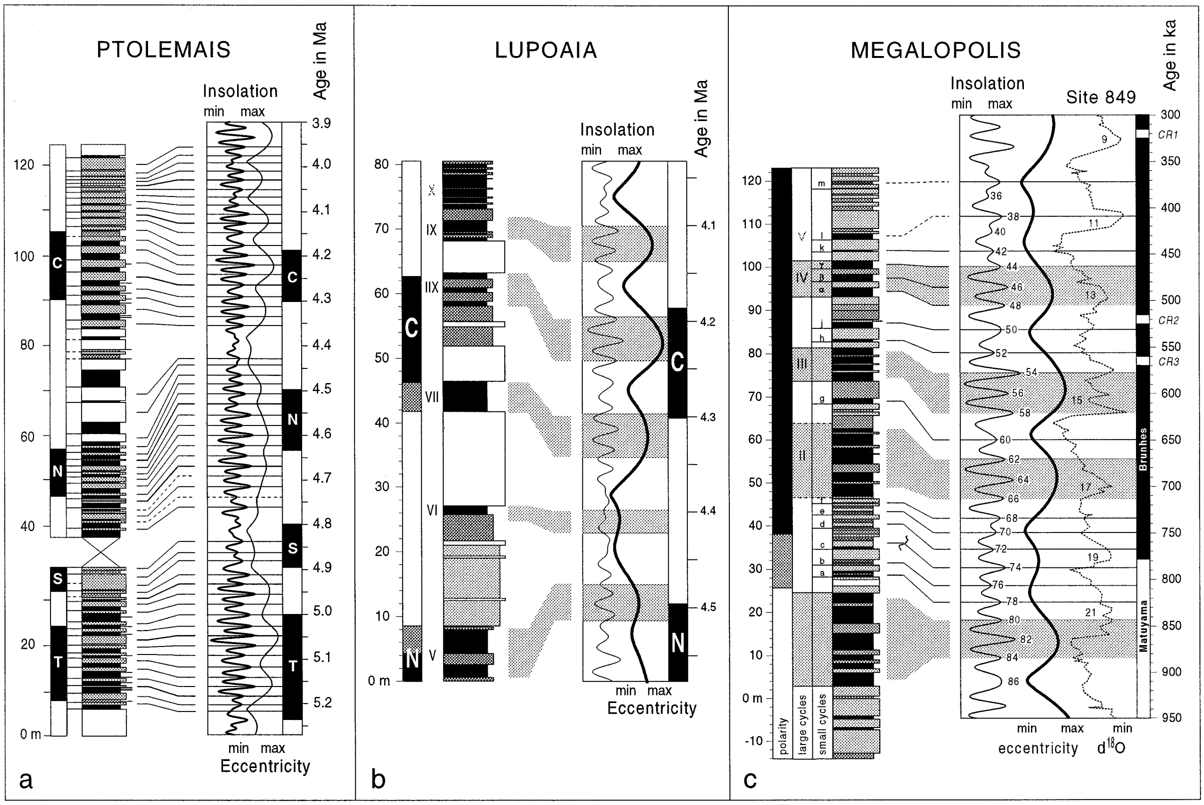

Fig. 5. Astronomical tuning of the discussed lacustrine sections. Left hand panel (a): Ptolemais (van Vugt et al., 1998). Lithology: black (shaded) indented beds = lignite (marly equivalent of lignite); white (shaded) protruding beds = white (grey) carbonate. Carbonate layers are correlated with insolation maxima. Central panel (b): Lupoaia. Lithology: see caption to Fig. 3. Lignite seams are correlated with eccentricity maxima. Right hand panel (c): Megalopolis (van Vugt et al., 2000). Lithology: black (shaded) indented beds = lignite (organic-rich equivalent of lignite); shaded (white) protruding beds = clay or silt (sand) layers. Large-scale cycles are indicated by roman numerals, small-scale cycles by letters. Lignite seams are correlated with eccentricity maxima, small-scale lignites with insolation maxima. The numbers in the $\delta^{18}O$ record indicate oxygen isotope stages (record from Mix et al., 1995).

seven well-defined polarity reversals from Ptolemais (Fig. 4, after van Vugt et al., 1998) were used in this way to show that the sedimentary cycles have the same average duration (21.6 ± 0.5 kyr) as the climatic precession cycle (21.7 kyr, (Berger, 1984)).

Similarly, the three polarity reversals in the Lupoaia section enable examination of the average duration of the sedimentary (lignite) cycles. In Fig. 4, the number of sedimentary cycles and their polarity is plotted versus the astronomical polarity time scale (APTS). The three age calibration points are linearly related, suggesting a constant duration for the sedimentary cycles. The slope of the regression line gives an average duration of 105.7 ± 5.6 kyr for a sedimentary cycle if a lignite — although stratigraphically thinner than a siliciclastic interval — is assumed to represent half a cycle. If a lignite is assumed to represent a lesser amount of time (i.e. less than half a cycle), the slope of the regression line does not significantly decrease. This period is in accordance with the ~100 kyr period of eccentricity, and strongly suggests a causal relation that allows astronomical tuning of the cycles. We can then construct an age model which has sufficient resolution for an accurate correlation with other successions.

The Nunivak and Cochiti reversals are astronomically dated (Lourens et al., 1996) and their positions with respect to eccentricity are thus determined

(Fig. 5b). Correlation of the Lupoaia polarity pattern with the Astronomical Polarity Time Scale (APTS), shows that the lignites correspond to eccentricity maxima, as is the case in the similar Megalopolis basin (van Vugt et al., 2000). This assumes that NRM acquisition is not significantly delayed. Part of the NRM is recorded in authigenic ferrimagnetic sulphides, but this component was not used to determine the direction of the ChRM, and thus to determine the polarity pattern. Indications for systematic delayed acquisition were not observed in either the LT or HT components. Moreover, it is not likely that any delay amounts to more than ~50 kyr in this succession. If the NRM acquisition were untraceably delayed, this would occur much sooner in the organic-rich layers than in the siliciclastic layers, because (partial) oxidation of abundant organic material often causes the magnetic mineralogy to change. Since all three reversals in this section are recorded in a lignite, any untraceable delay of that amount would have to have occurred in the siliciclastic beds.

The phase relationship between lithology and eccentricity is therefore established: the lignites correlate to maxima, the siliciclastic intervals to minima in eccentricity. Tuning of the succession is straightforward (Fig. 5b): lignite V contains the top of the Nunivak and is correlated to the eccentricity maximum around 4.50 Ma and thin lignite VI corresponds to the low-amplitude eccentricity maximum around 4.41 Ma. Lignites VII and IIX, which contain the lower and upper Cochiti reversals, respectively, are correlated to the maxima around 4.32 and 4.22 Ma, respectively, and lignite IX is correlated to the maximum around 4.12 Ma. Correlation of lignites X and higher in the Lupoaia mine is not as straightforward, and we have refrained from doing so.

In summary, we argue that the lower Pliocene cyclic deposits from Lupoaia were forced by eccentricity, with lignite representing the eccentricity maxima. During the Pleistocene, eccentricity maxima corresponded to warm periods (interglacials), while glacial periods occurred during eccentricity minima (Hays et al., 1976). In the early Pliocene, however, there was no eccentricity-related glacial-interglacial climatic regime. The suppressed amplitude of the insolation cycles during eccentricity minima is likely to have resulted in a generally colder climate, but without further data from this succession (e.g. pollen), a palaeoclimatic interpretation must remain tentative.

5. Orbital forcing in continental records

5.1. Lignite-dominated lacustrine basins

The lower Pliocene Ptolemais succession (northern Greece) was deposited during the Gilbert Chron. The upper half of the succession has recorded the Nunivak and Cochiti subchrons (Fig. 5a) and overlaps with the Lupoaia section. The sections are very different, however, in both the lithology and the dominant astronomical period recorded. Although both sections contain lignite, the other lithology consists mainly of carbonate in Ptolemais, as opposed to siliciclastic clay, silt and sand in Lupoaia. Furthermore, the lignite–carbonate cycles from Ptolemais are 2 m thick, whereas the lignite–siliciclastic cycles from Lupoaia are ~20 m thick. As demonstrated in Fig. 4, the sedimentary cycles in Ptolemais are related to precession (21.7 kyr). The cyclic pattern fits with summer insolation when lignite is correlated with insolation minima and carbonate with maxima (van Vugt et al., 1998), but eccentricity (100 kyr) is hardly expressed. In Lupoaia, however, precession is ambiguously recognised, whereas eccentricity is dominantly expressed in the lithology. In marine Mediterranean records of the same age, both precession and eccentricity are clearly expressed in the sedimentary record (e.g. Hilgen, 1991b). Apparently, the response of these continental basins to astronomically forced climatic changes is different for each continental environment and different than in marine environments.

An answer to what determines this response may be found in the Pleistocene Megalopolis basin in southern Greece. It has a similar lithology as Lupoaia: fluvio-lacustrine sands, silts and clays alternating with lignite seams, 7–20 m thick, which were defined as sedimentary cycles (van Vugt et al., 2000). In addition to these prominent cycles, thinner lignite or organic-rich clay layers (up to 2 m thick) could be recognised as small-scale cycles in several intervals (Fig. 5c). A recent palaeontological study indicates a late Early Biharian or Late Biharian age for lignites I and II (van Vugt et al., 2000). This age constraint implies that the polarity reversal at the base of the section must be the Matuyama–Brunhes boundary. The pollen signal showed an alternation of peaks in arboreal pollen in lignites versus non-arboreal pollen in siliciclastic beds (van Vugt et al., 2000). This strongly suggests that the large-scale cycles are climatically induced, similar to glacial–interglacial phases, with the lignite representing the warm and humid phase. We have assumed that the large-scale cycles are related to eccentricity. In addition, the small-scale cycles correlate well with the insolation pattern, see for example how the thick small-scale lignite c is correlated with large-amplitude insolation maximum 74, or the combination of thin lignite h and thick lignite j, which is correlated to short, low-amplitude i-cycle 52 and long, high-amplitude i-cycle 50 (Fig. 5c). The hypothesis of 100-kyr eccentricity forcing was supported by a good fit of the prominent large-scale cyclic pattern with the typical 400-kyr minimum in the 100-kyr eccentricity cycles, and of the small-scale cycles with insolation. Furthermore, the age model provided a realistic and constant sedimentation rate throughout the succession. It appeared that the lignite seams represent eccentricity maxima, the siliciclastic intervals eccentricity minima, while the small-scale lignite or organic-rich clay layers are correlated to precession minima (summer insolation maxima). In summary, the cycles in Megalopolis look very similar to those in Lupoaia and they are dominated by the same astronomical period and moreover have the same phase relationship. Contrary to Lupoaia, which was deposited during a warm (early Pliocene) period, Megalopolis was deposited during the middle Pleistocene ice age regime, when 100 kyr (eccentricity) became the dominant astronomical (quasi-) period controlling glacial cyclicity (Hays et al., 1976; Imbrie et al., 1984).

Although the cyclic pattern in Megalopolis fits closely with the eccentricity curve, it is strikingly distinct from typical open-ocean $\delta^{18}O$ records, which reflect the variation of global ice volume (van Vugt et al., 2000). During low-amplitude 100-kyr eccentricity maxima (due to 400-kyr eccentricity minima), the lignite cycles in Megalopolis are restrained or underdeveloped, whereas every 100-kyr eccentricity cycle is expressed as a glacial–interglacial alternation in the marine $\delta^{18}O$ records, regardless of eccentricity amplitude (the '400 kyr or Stage-11 problem', Imbrie and Imbrie, 1980). The sapropel pattern in Mediterranean Sea cores shows a similar contrast with $\delta^{18}O$ records. The (ghost) sapropels formed at 20-kyr insolation maxima, but generally not during low eccentricity periods (e.g. Langereis et al., 1997; Kroon et al., 1998; Passier et al., 1998). The oxygen isotope stages corresponding to these low 100-kyr eccentricity maxima (OIS 19 and 11) are clearly recognisable, and neither suppressed nor less well developed in the available ^{18}O records from these cores (Langereis et al., 1997; Kroon et al., 1998). Thus, the Mediterranean oxygen isotope records mainly follow changes in global ice volume. Evidently, not the ice ages (glacial–interglacial alternation), but a mechanism more directly related to orbital (eccentricity) forcing of regional climate determined the prominence of the sedimentary cycles in both the Mediterranean Sea and the continental Megalopolis basin (van Vugt et al., 2000).

In conclusion, eccentricity is not expressed in the lignite–carbonate cycles of Ptolemais, which is unlike the time-equivalent marine records. In the overlapping Lupoaia section, only eccentricity is clearly expressed, which is also in contrast to the marine records. The Megalopolis section is dominantly forced by 100-kyr eccentricity, roughly similar to time-equivalent marine records. Strikingly, both Megalopolis and Lupoaia have the same type of sedimentary cycles (lignite–siliciclastic) and are dominantly forced by the same astronomical parameter. The type of sedimentary setting, rather than the global climatic regime, apparently determines by which astronomical parameter the system is dominantly forced. From these three case studies, it would appear that lacustrine carbonate basins are dominantly forced by precession, whereas lacustrine siliciclastic basins are dominantly forced by eccentricity. Maybe carbonate basins are more sensitive to small (threshold) changes, and siliciclastic basins need larger fluctuations to change their sedimentary environment.

5.2. Other Mediterranean continental basins

This observed relation between lithology (i.e. type of sedimentary cycles) and dominant astronomical period has yet to be recognised in continental basins without lignite. Several (fluvio-) lacustrine records from the Mediterranean are described in the literature, but astronomically forced sedimentary cycles are not always recognised and rarely reported. An excellent example of a cyclical succession is the magnetostratigraphically dated Miocene Orera section from the Calatayud Basin in NE Spain. It contains a cyclic alternation between lacustrine carbonate and marl/clay layers, with a precession period of 19–23 kyr (Abdul Aziz et al., 2000). In addition, larger-scale 400-kyr cyclicity could be distinguished and — less clear — a 5-cycle clustering in the lower and upper part of the succession, that is probably related to 100-kyr eccentricity. Both the lithology (carbonate) and the dominant astronomical period (20 kyr) in the Orera section are thus more or less similar to those in Ptolemais.

A second example is the Miocene Armantes section from the Calatayud Basin in NE Spain. This section contains very pronounced asymmetric large-scale (10 m) cycles of reddish silt that gradually changes upward into an indurated bed of whitish caliche with a relatively sharp top. Magnetostratigraphy has shown that the average period of these cycles is 111 kyr, suggesting that it is related to the 100-kyr eccentricity cycle (Krijgsman et al., 1994, 1997). Large-scale cycles contain up to five pink (silty) caliche beds, more closely spaced towards the top of each large-scale cycle, suggesting a precessional origin. Based on palaeoclimatic reasons, the prominent large-scale white limestone beds are correlated to eccentricity maxima, the small-scale pink limestones to precession minima (summer insolation maxima). Although this section contains carbonate, it is mainly formed by precipitation from groundwater, as opposed to the lacustrine carbonate in Ptolemais and Orera. There is a large siliciclastic component (silt), similar as in Megalopolis and Lupoaia, although it is on an average finer grained. The most obvious astronomical period is eccentricity, but precession is locally well expressed. The strong saw-tooth like asymmetry in the carbonate content of the cycles in Armantes is different from the other Mediterranean sections and reminds of the asymmetric Late Pleistocene glacial cycles. They might therefore, like the glacial cycles, be caused by a highly non-linear response mechanism.

The Pliocene fluvio-lacustrine Apolakkia Formation on Rhodes has a very high sedimentation rate (80–140 cm/kyr, based on magnetostratigraphy) and a large siliciclastic input. The section contains some limestone beds of mainly pedogenic origin. van Vugt and Langereis (2000) reported that the thick (~25 m) sedimentary cycles have approximately the same period as precession. So, although the section contains coarse-grained siliciclastic sediment, the dominant period is not eccentricity but precession.

Finally, there are the loess sequences, which are not really Mediterranean, but we mention them because they are important continental successions for palaeoclimate studies. The most famous loess deposits are no doubt from the Chinese loess plateau, but nearer to the Mediterranean, loess is found in central Europe. The magnetic susceptibility records of the late Pleistocene Chinese and European loess are broadly in good agreement with the marine $\delta^{18}O$ record, revealing 100 kyr as the dominant period. The coherence implies a strong causal relation between climatic forcing of northern hemisphere ice sheets and Chinese loess deposition/soil formation (Maher and Thompson, 1999).

5.3. Possible explanations

The dominant expression of eccentricity in the siliciclastic Megalopolis and Lupoaia basins must be explained by some non-linear response to insolation forcing. The mechanism of Fischer et al. (1991), that invokes bioturbation to diminish the expression of precession in favour of eccentricity is not applicable here for two reasons. Firstly, the sedimentation rate is three to four hundred times higher here than in their deep marine core, so bioturbation could hardly mix the sediment as deep as the thickness of a precession cycle. Secondly, precession cycles are typically absent from the lignite seams in Megalopolis, that were deposited in an anoxic lake where burrowing animals could not live and deep-rooting plants such as trees did not grow (Mulder et al., 2000).

The dominance of eccentricity might be explained by a mechanism somewhat similar to Paillard's model (Paillard, 1998), that was designed to explain the late Pleistocene ice ages. The 100-kyr cycles in the middle to late Pleistocene Megalopolis section could — because of their deposition during the global ice age regime — be related to the glacial-interglacial cycles. However, van Vugt et al. (2000) showed that the

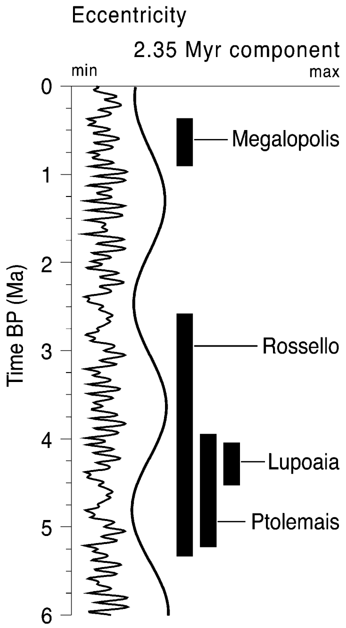

Fig. 6. Eccentricity (Laskar, 1990) and its filtered 2.35 Myr component; the amplitude of the 100 kyr eccentricity cycle is reduced during 2.35 Myr minima. The largest part of the Ptolemais section was deposited during a 2.35-Myr minimum, as opposed to the Lupoaia and Megalopolis sections. The marine Rossello section (Hilgen, 1991b) covers a whole 2.35 Myr cycle; its largest part was deposited during a period with large-amplitude 100-kyr cycles, which are clearly expressed in the lithology. The lower part, which corresponds to a 2.35 Myr minimum, lacks expression of the 100-kyr cycle in the lithology, like the parallel Ptolemais section.

pattern of these cycles did not match ice-volume-related $\delta^{18}O$ records, but was instead similar to the eccentricity curve. This suggests that those cycles were not related to the 100-kyr glacial cycle. The 100-kyr cycles in the Lupoaia section cannot have been influenced by glacial cycles, because the early Pliocene was a warm period during which only minor, obliquity-controlled, glacial cycles intermittently occurred. Nevertheless, Paillard's idea of multiple steady states could be used for a model with two sedimentary-environment states (a lignite-accumulating swamp versus a fluvio-lacustrine basin that deposits siliciclastic sediment), which respond non-linearly to insolation. An additional feature of this model should be that the depositional environment has a memory, which requires the system to remain in one steady state for a certain amount of time before it can pass back to the other state. This amount of time should exceed the duration of half an eccentricity cycle to explain the dominance of eccentricity in our siliciclastic basins. An additional eccentricity effect could be introduced into such a model by using a truncated insolation response (Clemens and Tiedemann, 1997).

A feasible geological explanation for such a mechanism could be that the weathering of source rock to produce abundant siliciclastic sediment during warm and humid periods requires a long time (say 40 kyr). After such a prolonged, densely vegetated period, the local climate became colder and dryer and the weathered material was eroded and deposited in the basin. During cold and dry intervals following short vegetated periods (i.e. during insolation minima in an eccentricity maximum), there might not have been enough siliciclastic material available to bury the swamp vegetation (in the whole basin), and organic material was still preserved in the lignite seams. Occasionally, siliciclastic material was deposited during eccentricity maxima, but only in lenticular sediment bodies or when the basin was nearly filled up (e.g. as observed in cycle IV in Megalopolis).

The lacustrine calcium carbonate systems of Ptolemais and Orera apparently responded more linear to insolation forcing, because precession is so distinctly expressed. However, the lack of a — dominant — expression of the 100-kyr cycle can also be explained otherwise. Both the Ptolemais section and the largest part of the Orera section were deposited during a period that the amplitude of the 100-kyr eccentricity cycle was reduced. Low 100-kyr amplitudes regularly occur because there is — apart from the well-known 100 and 400-kyr eccentricity cycles — also a 2.35-Myr eccentricity cycle that periodically reduces the magnitude of the 100-kyr cycle. Coincidentally, the Ptolemais section and the middle part of the Orera section were deposited during such a 2.35-Myr eccentricity minima (Fig. 6, Orera not shown). The top of the Ptolemais section correlates with an interval with clear 100-kyr cycles, but the fact that the basin was nearly filled up may explain why this period is not clearly expressed in the lithology. This means that there might still be some non-linear response mechanism in lacustrine calcium carbonate basins, but that cannot be checked in these two basins.

Acknowledgements

We gratefully acknowledge the co-operation with Maria and Sorin Rădan. Their extensive palaeomagnetic studies in the Oltenia lignite mines led us to the Lupoaia section in the first place and working with them in the mine was great fun, even despite the horrible weather. Field assistance of Marloes van Hoeve, Joris Steenbrink and Johan Meulenkamp was also greatly appreciated. Discussions with Wout Krijgsman and Hayfaa Abdul Aziz increased our understanding of several Mediterranean successions beyond what publications alone could have provided. The manuscript has benefited from the reviews of Rodolfo Sprovieri and Walther Schwarzacher. Finally, we thank the Romanian mining company and its employees for their friendly permission and service.

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