Chapter 4

Refinement of the Messinian APTS from sedimentary cycle patterns in the lacustrine Lava section (Servia Basin, NW Greece)

Abstract

A high-resolution cyclostratigraphy and magnetostratigraphy is presented for the Messinian lacustrine Lava section from the Servia Basin in NW Greece, constraining more precisely the absolute ages of magnetic polarity subchrons C3An.1n and C3An.2n. The section contains fifteen distinct sedimentary cycles of alternating dark and light-coloured marks, while the gamma-ray attenuation record reveals an additional five to six cycles. The cycles in the lower half of the section are on average 5.3 m thick, as opposed to the cycles in the upper part, which have an average thickness of 3.1 m. Palynological results define the lithological alternations in both the lower and upper cycles in terms of periodic changes in humidity, where the light marks represent the humid periods and the dark marks the relatively dry periods. Changes in cycle thickness and shifts in average gamma-ray values suggest a rather abrupt decrease in sedimentation rate at ~60 m in the section. This is confirmed by the magnetostratigraphy, which recorded four reversals, which – given the bioturbinic constraints from the Lava locality – could be correlated unambiguously to subchrons C3An.1n and C3An.2n of the geomagnetic polarity time scale. With this magnetostratigraphic time control, the average duration of the cycles can be calculated to be constant in the entire section, and similar to precession. The astronomical origin of the cycles is confirmed by the results of spectral analyses of gamma-ray and susceptibility time series. The sedimentary cycles in the upper part of the Lava section are unambiguously tuned to insolation using the typical clustering of the cycles that follows the eccentricity cycle. The filtered gamma-ray record centred at 41 kyr confirms the tuning in the upper part and allows tuning of the lower part. The tuning results in accurate ages for the sedimentary cycles and polarity reversals that confirm the astronomical tuning of Krijgsman et al. (1999a), but define more precisely the astronomical polarity time scale.

Introduction

The astronomical theory of climate change, according to which climatic oscillations are linked to perturbations in the Earth’s orbit (Milankovitch, 1941), is at present widely accepted. During the last decades, deep-sea oxygen isotope records have convincingly demonstrated that Pleistocene glacial cycles are driven by orbitally controlled variations in solar radiation (Emiliani, 1955; Shackleton and Opdyke, 1973; Hays et al., 1976; Imbrie et al., 1984). More recently, the recognition of Milankovitch cycles in sedimentary records of especially marine deposits has enabled the development of very accurate time scales for the entire Neogene marine record. In combination with magnetostratigraphy this has resulted in the development of an Astronomically Polarity Time Scale (APTS, Lourens et al., 1996a; Hilgen et al., 1997a; Shackleton and Crown, 1997; Shackleton et al., 1999). For the Messianian, the first attempts for the constructing of an APTS using astronomical tuning was in the Bou Regreg Section in Morocco (Benson et al., 1995). Currently, the APTS is based on the integrated stratigraphy of several marine sections in the Mediterranean (Krijgsman et al., 1999a). The astronomical tuning of these sections is confirmed by open-ocean calcareous nanofossil biochronology from ODP Sites 855 and 926 and by their implications for sea-floor spreading rates (see Krijgsman et al., 1999a, Table 1). The magnetostratigraphic data were derived from the Spanish Sorbas Basin (Krijgsman et al., 1999a) and the Cretan Paneromeni section (Krijgsman et al., 1994). Because of the moderate quality of the paleomagnetic signal in these sections, the astronomical ages of the polarity reversals in the APTS are not well constrained (uncertainties of 20 to 60 kyr).

<table>
<thead>
<tr>
<th>Reversal</th>
<th>Position</th>
<th>The study APTS age</th>
<th>KAMBS SR age</th>
<th>KAMBS APTS age</th>
<th>CA95 GPTS age</th>
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<tr>
<td>C3An/In</td>
<td>19.1 ± 0.8</td>
<td>6.73 ± 0.005</td>
<td>6.28</td>
<td>6.26 ± 0.02</td>
<td>6.137</td>
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<td>C3An/2n</td>
<td>9.6 ± 0.1</td>
<td>6.63 ± 0.007</td>
<td>6.34</td>
<td>6.44 ± 0.01</td>
<td>6.265</td>
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<tr>
<td>C3An/3n</td>
<td>44.2 ± 1.9</td>
<td>6.619 ± 0.005</td>
<td>6.73</td>
<td>6.71 ± 0.03</td>
<td>6.567</td>
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Table 1: age models, sedimentation rates and cycle periods for the Lava section

<table>
<thead>
<tr>
<th>Polarity Interval</th>
<th>Length</th>
<th>Cycle thickness</th>
<th>Duration</th>
<th>Sed rate</th>
<th>Period</th>
<th>Sd rate</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3An/In</td>
<td>23.6 ± 0.3</td>
<td>3.1 ± 0.8</td>
<td>150</td>
<td>0.1 ± 0.01</td>
<td>1.9 ± 0.02</td>
<td>3.8 ± 0.04</td>
<td>1.3 ± 0.01</td>
</tr>
<tr>
<td>C3An/2n</td>
<td>51.3 ± 1.9</td>
<td>4.3 ± 1.0</td>
<td>300</td>
<td>0.7 ± 0.01</td>
<td>2.7 ± 0.02</td>
<td>2.7 ± 0.02</td>
<td>2.7 ± 0.02</td>
</tr>
</tbody>
</table>

Table 1. Upper panel: Paleomagnetic age models for the Lava section. Position (m) of reversal horizons in the Lava section and ages (Ma) of the corresponding reversals based on spreading rates (SR) and astronomical tuning (APTS) (Krijgsman et al., 1999a), and sea-floor anomalies (GPTS) (Cande and Kent, 1995). The error estimates in the astronomical reversal ages refer to the uncertainty in the stratigraphic position of the reversal with respect to the astronomically dated cycles only, not taking into account errors arising from tuning. Asterisks correspond to the two astronomical ages for C3An.2n(o), related to the two correlation options (Figure 6). Middle panel: Length (m) of the polarity intervals and average cycle thickness (m) within these intervals. Duration (kyr) and average sedimentation rate (m/kyr) in these intervals according to the different time scales. Note the difference in sedimentation rate between the two polarity intervals for both the SR and APTS time scales. Lower panel: As middle panel, with the sedimentation rate from subchron C3An.1r extrapolated down to 60 m. Note the similarity of the average cycle periods and the period of precession for the SR age model, and divergent periods for the other age models.
Evidently, orbital forcing influences not only marine, but also continental sediments. The best
known example of orbital forced sedimentary cyclicity is the Triassic lacustrine succession of the
Newark Basin (Olsen and Kent, 1996; Kent and Olsen, 1999). Long and continuous cyclically-
bedded continental successions are also present in the Mediterranean area. Recent studies
demonstrated a strong orbital control on sedimentation for Late Miocene marginal lacustrine-
floodplain sequences in the Calatauqui Basin in Spain (Abdul Aziz et al., 2000), for Lower
Pliocene lignite-marl alternations in the Ptolemais Basin in northern Greece (see this thesis,
Chapters 1 and 2), and for middle Pleistocene lignite seams in the Megalopolis basin (Van Vugt,
2000).

In this paper, we present the results of an integrated study on the cyclically bedded Messinian
lacustrine Lava section from the Servia basin, NW Greece. Astronomical tuning of the
sedimentary cycle pattern combined with a reliable magnetostratigraphy offers a unique
opportunity to confirm and define more precisely the APTS ages in the Messinian.

Geological setting

The intramontane lignite-bearing Servia basin is located approximately 100 km south-west of
Thessaloniki and is part of an elongated NNW-SSE trending graben system that extends over a
distance of 120 km from Bitola in the Former Yugoslav Republic of Macedonia (F.Y.R.O.M.) to
Servia in northern Greece (Figure 1). The graben system developed in the Pelagonian Zone, the
westernmost zone of the Internal Hellenides (Brunn, 1956), in response to Late Miocene NE-SW
extension (Pavides and Mountrakis, 1987). A Pleistocene episode of NW-SE extension resulted
in the development of several basins including the basins of Florina, Ptolemais and Servia
(Pavides and Mountrakis, 1987). The basins are flanked by mountain ranges that are primarily
composed of Mesozoic limestones, Upper Carboniferous granites and Paleozoic schists (Figure 1).

The basin fill comprises a ~600 m thick Late Miocene to late Pleistocene succession of
predominantly lacustrine sediments with intercalated lignite seams and fluvial deposits, which can
be divided into a number of basin-wide lithostratigraphic units (Ehlers, 1960; Anagnostopoulos and
Koukouzas, 1972, Figure 1).

In this study, we focus on a part of the lower Komnina Formation, which was dated as Late
Miocene (Turolian, lower part of mammal zone MN 13) on the basis of small mammals
(Apodemus sp., de Brujin et al., 1999), plant remains (Velitzelos and Gregor, 1990) and
chiropterys (Antoniadis and Rieber, 1997). The Komnina Formation is ~300 m thick; it
unconformably overlies the pre-Neogene basement and is predominantly composed of fluvial
sands and conglomerates, lacustrine (diatomaceous) marls and clays, with some intercalated
lignite seams. This information is mainly derived from drillings and from outcrops in open-pit
lignite mines in the Florina (Athlada and Vevi mines), Ptolemais (Vegeora mine) and Servia Basins
(Lava and Prosilio mines) (Figure 1).

Studied section and sampling

The Lava section is exposed in a private open-pit lignite mine, situated a few kilometres south
of Servia and close to the deserted village of Lava (Figure 1) in the footwall block of a major fault
system that runs ENE-WSW and forms the southern margin of the Servia basin. We selected the
Lava mine for this study for a number of reasons. It has the most complete succession of the
Komnina Formation. The sediments that crop out in the Lava mine display a distinct sedimentary

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cyclicity and, in contrast to some of the other mines, are all fine-grained, which is preferred for our paleomagnetic study. Moreover, a biostratigraphic age constraint to calibrate these paleomagnetic data is provided by a fossiliferous level with small mammal remains (de Bruijn et al., 1999).

Figure 1. Geological map of the Florina, Ptolemais and Servia basins. F.Y.R.O.M. is the Former Yugoslav Republic of Macedonia. The inset shows the location of the Lava mine. Sketched stratigraphic column of the basin fill after IGME (1997).

The Lava section has a thickness of 130 m (Figure 2). The basal ~20 m of the section contain two (sylite-type) lignite seams, which are separated by homogeneous clays and laminated marls with abundant charophyte oogonia and freshwater gastropods. The upper ~110 m consist mainly of lacustrine marls and clays with abundant leaves (among which the characteristic Late Miocene *Glyptostrobus europeus*, Velitzelos and Gregor, 1986), freshwater diatoms and ostracods, and show a distinct cyclicity. Rather abrupt changes towards more clayey and organic-rich sediments occur twice in the lithology, namely between 60 and 67 m and between 85 and 88 m in the section. At 41.6 m, a 5 cm thick bed full of gastropods is found (key-bed I) and at 73.2 m, a 5 cm thick clay inter-bed yielded abundant fish teeth and vertebrae (key-bed II). These two key-beds have a constant thickness over the entire mining area and were also recognised in the five km westerly situated Prosilio mine, which supports their potential use as marker-beds.

Detailed logging and sampling of the Lava section was done in two campaigns. In 1994 the section was logged and sampled from the base up to 115 m, an upward extension was done in 1997. We took oriented paleomagnetic samples, cored with a portable drill at 194 levels over a stratigraphic interval of 130 meters, which corresponds to an average spacing of 67 cm. Additional
non-oriented samples were taken at the same levels for chemical and pollen analyses. During the 1994 sampling campaign, the gamma-ray signal was measured seven-fold at each sampling level with a UG135 differential gamma spectrometer. Data were measured in the TC2-mode, detecting all energies above 400 keV. The low-field bulk magnetic susceptibility of the samples was measured in the laboratory on a KLY-2 susceptibility bridge. The natural remanent magnetisation (NRM) was studied in the laboratory by means of standard stepwise thermal demagnetisation procedures and measured on a 2G DC SQUID magnetometer.

Cyclostratigraphy of the Lava section

The lacustrine succession that constitutes the upper ~110 m of the Lava section is composed of alternating light- and dark-coloured marls on various scales. The dark-coloured marl beds are faintly laminated and enriched in organic matter and/or clay. The light-coloured marl beds are homogeneous and enriched in carbonate. The most prominent colour variations occur on a scale of 3 to 5 metres. A basic sedimentary cycle is defined as one such 3 to 5 metres thick dark-light marl couplet. The distinct dark marl beds, which we defined as the base of a sedimentary cycle, are numbered in ascending order from the base of the Lava section upward. Faintly developed (or very thin) dark-coloured marl beds are also present in various parts of the section (see below), but these were not numbered.

The Lava section contains 15 distinct sedimentary cycles. These cycles are not present throughout the entire section, but are found in two intervals. The first interval forms the lower part of the marl succession, it starts from ~20 m in the section, just above the second lignite, and continues up to ~60 m in the section. It contains seven regular cycles (cycles 1 to 7) of alternating dark- and light-coloured marl beds, which have an average thickness of $5.1 \pm 0.7$ metres. The dark-coloured marl bed of cycle 5 is the most prominent one in this interval. Within the light-coloured marl beds of cycle 6, which is very carbonate-rich and distinctly yellowish-coloured, two additional thin dark-coloured marl beds are present. The dark-coloured marl bed of cycle 7 is composed of one thin, and two thicker dark-coloured marl beds (Figure 2).

The second interval is found in the upper part of the section, between roughly 90 and 120 m and contains eight cycles that are arranged in two clusters. The lower cluster comprises four well-developed cycles (cycles 8 to 11), with an average thickness of $3.3 \pm 0.6$ metres. Especially the dark marl beds of cycles 10 and 11 are very distinct and clay-rich. The upper cluster contains four sedimentary cycles (cycles 12-15), of which the three lower cycles (cycles 12-14) are very regular, both in thickness (~3.3 m) and appearance, and have prominent dark-coloured clay beds. Cycle 15 is relatively thin (2.3 m); its dark marl bed is strongly lignitic and the light marl segment of this cycle contains abundant freshwater gastropods and is composed almost exclusively of carbonate. In between the two clusters of the second interval lies a more homogeneous interval in which a few cm-thick dark-coloured clay beds are intercalated: four at around 105 m and one at around 108 m, suggesting that two more cycles might be present in this interval (Figure 2).

The two intervals with well-developed sedimentary cycles are separated by an interval, which runs from ~60 to 90 m and lacks an obvious lithological cyclicity. This interval is not homogeneous, but the difference between the dark and light coloured marl beds is less pronounced. This makes subdivision into sedimentary cycles arbitrary. There are a few prominent dark-coloured marl beds, but these are very thin (<10 cm) and not regularly spaced (Figure 2).
Figure 2. Top: Schematic lithological column of Lava with sedimentary cycle numbers: black indented = lignite, white = carbonate, light shaded = marl, intermediate (dark) shaded = dark (terr) marl, black = clay. I and II denote key beds; mouse denotes level with small-mammal fauna (de Bruin et al., 1999) and vertical lines indicate the position of the two palynological records. Dashed lines indicate thin dark marl beds. Gamma-ray and magnetic susceptibility records with their filtered components (dashed lines) in the depth domain. Bottom: Maximum entropy variance spectra of the GR (187 data points, length of filter is 16.6 % of the series) and k records (215 data points, length of filter is 14.9 % of the series), computed with the Atrianalysis program (Paillard et al., 1996), investigated in the frequency range 0.1 to 0.5 cycle/meter. The Blackman-Tuckey and Multi Taper Method yielded comparable results (not shown). The cycle length (m) is indicated; the shaded bands indicate the bandwidths of the 5.4 and 3.1 m filters.
Gamma-ray and susceptibility

The gamma-ray intensity and low-field magnetic susceptibility records of the Lava section were measured to quantify the subtle light-dark colour variations that we observed in the field. Moreover, spectral analysis of these records in either the depth or time domain enables an objective estimate of periodic characteristics. The gamma-ray (GR) intensity is mainly a function of the Uranium-content (Ten Veen and Postma, 1990); Uranium tends to be more abundant in both detrital minerals and organic-rich sediments. The low-field susceptibility (κ) is positively influenced by the concentration of ferri-magnetic and paramagnetic (clay) minerals and negatively by diamagnetic material (carbonate). Both gamma-ray and susceptibility are thus good parameters to describe the alternation of organic-rich clay layers and carbonate-rich mud layers.

The GR and κ records are marked by a high variability showing a close correlation with the lithological variation (Figure 2). More precisely, they reveal relatively high values in the dark-coloured clay-rich beds and low values in the light-coloured carbonate-rich beds. The GR record reflects all sedimentary cycles as recognised in the field. In addition, the GR recorded another five or six minima and maxima in the interval between −60 and −90 m, where no distinct sedimentary cyclicity was observed. These maxima correspond to thin darker (clay) layers, which suggests that cyclicity is present in this interval as well, but less distinct than in the rest of the section. Sedimentary cycles 2-7 and 9-16 can be recognised as peaks in the κ record, but κ does not show any regular minima and maxima in the non-cyclic interval. The GR record shows a much smoother curve than the κ record, because κ is measured on discrete samples, while the gamma spectrometer measures the GR intensity at the outcrop averaged over a 25 cm diameter. Two sharp increases in the mean GR value between 60 and 67 m and between 85 and 88 m co-occur with two earlier described lithological changes towards more clayey and organic-rich sediments. The κ record, on the other hand, does not show any pronounced change in its mean value.

The variance spectra of the GR and κ records in the depth domain show that power is concentrated in two broad bands (Figure 2, bottom). One is centred at −5.4 metres and the other at −3.1 metres. These two values are indistinguishable from the average cycle thickness in the lower and upper part of the section, which was calculated as 5.1 ± 0.7 and 3.3 ± 0.6 metres, respectively. Further confirmation of cyclicity in both the GR and κ records with periods close to those of the sedimentary cyclicity is given by applying a Gaussian bandpass filter to the GR and κ records (centred at 5.4 and 3.1 m). The filtered records centred at 5.4 m follow the GR and κ records - and thus the lithological cyclicity - best in the lower half of the section, while the filtered records centred at 3.1 m reproduce the cyclicity best in the upper part of the section (Figure 2). The shift from a dominantly 5.4 m-scale cyclicity towards a 3.1 m-scale cyclicity is especially obvious from the filtered GR record and occurs between 60 and 67 m, coinciding with the first increase of the mean GR values.

Palynology of sedimentary cycles

We conducted a palynological study on 26 samples covering cycles 4 and 5, and cycles 13 and 14 from the lower part and upper part of the section, respectively (Figure 2). Such a study enables us to interpret the lithological cyclicity in terms of changes in vegetation, from which changes in precipitation and/or temperature can be inferred.

During the four cycles investigated (Figure 3), mixed deciduous/coniferous forests appear to have been widespread in the mid-altitude uplands surrounding the intramontane sedimentary
basin. Montane forests with *Pinus, Cedrus, Abies* and *Fagus* dominated at higher elevations. Lowland elements, characteristic for fringing swamp vegetation around the lake, are mainly represented by *Taxodium*.

The palynological evidence points to continuously wet and warm-temperate climatic conditions. This is notably apparent from the records of conifer pollen. *Cathaya* presently occurs in mid-altitude forests in China where annual precipitation is in excess of 2000 mm (Farjon, 1990). *Tsuga* is nowadays restricted to mountainous regions in Asia and North America where similarly high precipitation occurs throughout the growing season (Farjon, 1990). An annual precipitation between 1000-1500 mm at higher altitudes can be inferred from the occurrence of *Cedrus* (Farjon, 1990). *Cedrus* forests nowadays occur only in high mountains around the eastern Mediterranean basin. Humid warm-temperate conditions were also inferred from studies on macro-flora of the Lava mine (Veltezelos and Gregor, 1986). Additional evidence that conditions may have been generally moister than at present is provided by the conspicuous absence of dry-tolerant sclerophyllous evergreen species of *Quercus*, characteristic of modern Mediterranean vegetation. The subordinate presence of *Juniperus* may have been controlled more by substrate than by (low) precipitation.

![Pollen diagram](image-url)

**Figure 3.** Pollen diagram of cycles 4, 5, 13 and 14 from Lava. The results are presented as percentages of a pollen sum including all pollen and spores, excluding fungi and algae. The grey bands indicate dark mark. Herbs are a sum of mainly Poaceae, Asteraceae and Chenopodiaceae; lowland consists of *Taxodium* and some *Salix* and *Alnus*, Aquatics are a sum of Cyperaceae, *Nuphar* and *Ceratophyllum*, Ferns are a sum of Polyodiaceae and *Osmunda*. *Quercus robur* type consists only of deciduous species of *Quercus*.  

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Superimposed on these generally wet conditions, palynological data for cycles 13 and 14 indicate periods of relatively increased precipitation that more or less coincide with the deposition of the light-coloured marks. Analogous to Holocene vegetation development in the eastern Mediterranean region (van Zeist and Bottema, 1982), a marked spread of *Pinus* at the expense of *Cedrus* can be interpreted as an increase in precipitation at higher elevations, resulting in downward expansion of *Pinus* into the mid-altitude deciduous forests. Similarly, increased montane humidity may also be responsible for an expansion of *Fagus* at the cost of *Abies*. The pollen spectra of cycles 4 and 5 have generally higher amounts of *Fagus* and *Quercus* relative to the upper cycles. This may be due to higher (winter) temperatures in the lower cycles. Cyclic changes in precipitation are less obvious in the pollen records of these lower cycles than in cycles 13 and 14, which is in agreement with the less-pronounced lithological changes in these lower cycles. Apparently, climate was more equitable during deposition of these lower cycles. Yet, careful inspection of the pollen curves suggests similar patterns for the relation between *Pinus* and *Cedrus*, as well as for *Fagus* and *Abies*. Palynological data of both the lower and upper cycles thus indicate that climate was generally humid and warm-temperate, but cyclic changes in precipitation seem to have occurred. Periods with increased precipitation occurred during deposition of the light marks, in the lower, as well as in the upper cycles.

**Paleomagnetic analysis**

We used magnetostratigraphy in combination with small mammal biostratigraphy (de Bruijn et al., 1999) to construct a high-resolution chronology for the Lava section. Thermal demagnetisation reveals a two-component NRM (Figure 4a–b). The low-temperature (up to 200°C) component generally has a random direction, but it may be approximately parallel to the present-day field in the slightly weathered uppermost part of the section. The characteristic remanent magnetisation (ChRM) is isolated above 200°C and shows both normal and reversed polarities. These normal and reversed ChRM directions are almost antipodal (Figure 4c). Above ~400°C, both direction and intensity of the remanence change in many samples, indicating the presence of iron-sulphides (pyrite). To find the maximum unblocking temperatures, some samples were given an IRM that was thermally demagnetised. The samples have a maximum unblocking temperature of 500°C or higher, indicating magnetite (Figure 4d).

The declinations and inclinations of the ChRM compose a well-defined magnetic polarity pattern in the Lava section, with two reversed and two normal intervals (Figure 4e). Given the constraint that the mammal assemblage from Lava belongs to the lower part of MN13 (de Bruijn et al., 1999), we find a unique correlation with the geomagnetic polarity time scale, in which the lower normal polarity interval represents C3An.2n, and the upper normal interval C3An.1n (Figure 4e).

**Astronomical forcing of the sedimentary cycles**

Recently, two new time scales have been proposed for the Messinian (Krige et al., 1999a), one based on astronomical tuning of sedimentary cycles and one based on sea-floor spreading rates. Although the spreading-rate (SR) ages are statistically indistinguishable from the astronomically-tuned ages (APTS), there is a notable difference in the duration of the polarity intervals (Table 1). Based on the SR and APTS age models calculations were made for sedimentation rates and cycle periods (Table 1).
The APTS and SR ages are significantly older than those from previous time scales, which were based on marine magnetic anomaly spacings in the South Atlantic and on ~10 Myr spaced age calibration points (Cande and Kent, 1992, 1995). These earlier time scales, for example CK95 (Cande and Kent, 1995), were presented pending further refinements such as the results of higher-precision radiometric and astronomical dating methods, as stated by the authors. Since these refinements are now presented by Krijgsman et al. (1999a), we will not use the CK95 ages in this discussion, though for comparison, calculations based on these ages are listed in Table 1.

With the magnetostratigraphic time control, the average sedimentation rates in the two complete polarity zones in Lava can be calculated. As expected from other observations, the sedimentation rate in the lower interval is higher than in the upper interval. There is no reason to assume that the change in sedimentation rate co-occurs with a polarity reversal; in fact, it is probably located between 60 and 67 m, where the change in both the thickness of the cycles and the average GR attenuation occurs (Figure 2). We assume that the shift is located at 60 m, because higher positions resulted in less consistent average cycle periods. The sedimentation rate
for the reversed polarity zone was extrapolated downwards to 60 m. This yields a new, virtual age control point, with which the average sedimentation rate for the lower part of the normal polarity zone is determined. The average sedimentation rate based on the SR age model arrives at 0.23 m/kyr (Table 1). Extrapolation of the sedimentation rate using the APTS age model leaves a negative amount of time for the lowermost part of the normal zone C3An.2n, and, therefore, an impossible sedimentation rate of -2.2 m/kyr (Table 1). Hence, only the calculations based on the SR age model will be used in the further discussion.

Combining the sedimentation rates from the SR age model with the average length of the sedimentary cycles in each interval results in an average duration for the cycles of 19.9 ± 5.4 to 23.0 ± 3.1 kyr for the thin sedimentary cycles, and 22.8 ± 4.0 kyr for the thick cycles (Table 1). The similarity of the periods of the thin and thick cycles suggests that the cycles are related to the same forcing mechanism. The average duration strongly suggests that the cycles were forced by precession.

The palynological data point to comparable changes in precipitation between the upper and lower cycles, and thus underline the hypothesis that the cycles are related to a single forcing mechanism. Palynological research on the Pliocene Potala Formation suggested similar changes in precipitation for secondite–marl cycles (Van Hoeve et al., 1998), which were proven to be related to precession-controlled variations in regional climate (see this thesis, Chapters 1 and 2). This analogy between the palynological results from the Potala and Lava cycles confirms our interpretation that sedimentary cycles in Lava were controlled by precession.

Spectral analysis of proxy records provides an objective estimate of periodic properties in time series of data. To be useful in testing the orbital hypothesis, the data must be transformed into a geological time series. We constructed GR and K time series by linear interpolation between and extrapolation beyond the control points, provided by – in our case – the SR ages of the paleomagnetic reversals (Krigman et al., 1999a) and the extra age control point that we calculated for the 60-m level in the section (Table 1).

The variance spectra of the GR and K records vs. age are given in Figure 5 (bottom). Both spectra reveal peaks in two frequency bands. The first frequency band includes periodicities close to the obliquity period of 41 kyr and is located at 36.6 kyr in the GR and 43.2 kyr in the K record. The second frequency band includes periodicities close to the precession periods of 23 and 19 kyr. A 19.9-kyr periodicity is present in the GR record and the K spectrum reveals a prominent peak at a period of 24.0 kyr. Further confirmation of cyclicity close to the mean of precession is given by applying a Gaussian bandpass filter to the GR and K records centered at 21.7 kyr (Figure 5, top). These results indicate that both the GR and K records, and thus the sedimentary cyclicity, have a strong orbital control that is dominated by precession and to a lesser extent by obliquity.

Astronomical tuning of the sedimentary cycles

In the preceding paragraph, we have shown that the sedimentary cycles are linked to dominantly precession-controlled variations in climate. Moreover, the pollen study has shown that the dark-coloured marl beds correspond to relatively dry periods, while the light-coloured marl beds correspond to more humid periods. In the Mediterranean area, relatively humid (and warm) climate occurred during summer insolation maxima, while the opposite regime occurred during insolation minima (Rohling and Hilgen, 1991). The dark-coloured marls can thus be correlated to insolation minima and the light coloured marls to insolation maxima.
Figure 5. (Top) GR and χ time series with their filtered components. The time series are generated from the SR ages for the reversals and our virtual age control point (see text) and re-sampled with 2.5-kyr intervals. Cycles that were not expressed in the lithology, but were clearly present in the GR or χ record, are indicated with an asterisk. For an explanation of the lithological column, see Figure 2. (Bottom) Maximum entropy variance spectra of the GR (207 data points, length of filter is 12.8% of the series) and χ (243 data points, length of filter is 11.2% of the series) time series, computed with the AnalySeries program (Paillard et al., 1996) and investigated in the frequency range $10^{-4}$ to $10^{-1}$ cycle/kyr. The shaded areas indicate the width of the obliquity and precession frequency bands, as used for the filtered precession components of the GR and χ records. Numbers indicate cycle periods (kyr).
Typical clusters of 3-4 cycles are observed in the upper part of the section (cycles 8-11 and 12-14) (Figure 6). Considering that the individual sedimentary cycles are related to precession, those clusters represent maxima in 100-kyr eccentricity cycle. With the upper two magnetic polarity reversals as approximate tie-points we can now tune these clusters to groups of high-amplitude insolation cycles related to the eccentricity maxima at ~6.4 and ~6.3 Ma (Figure 6).

Next, individual sedimentary cycles can be tuned to insolation. Cycle 11 has the most prominent organic-rich layer, and the underlying dark marl beds are alternatingly reduced and enhanced in GR and, to a lesser extent, K. Therefore, cycle 11 is correlated to the high-amplitude minimum at 6.4 Ma, and the underlying cycles to consecutively older minima. The dark marls of cycles 12 to 14 are very prominent; they are therefore correlated to the cluster of three high-amplitude insolation minima around 6.3 Ma.

In the middle of the section, no cycles were recognized in the lithology or in the K record. The GR record, however, showed several distinct maxima in this interval (Figures 2 and 5), indicated by an asterisk in the stratigraphic column of Figure 5. These cycles are correlated to a series of relatively high-amplitude insolation minima between 6.55 and 6.60 Ma, with the most prominent dark clay bed (key bed II) corresponding to the highest amplitude insolation minimum. The GR peak immediately below cycle 8 is very wide, and likely covers two cycles (see also filtered record, Figures 2 and 3).

The cycles in the lower part of the section (1-7) show no typical clustering, and they can thus not be tuned using the eccentricity modulation of insolation. We can only use the position of the magnetic polarity transition as an approximate tie-point. Therefore, there are two likely correlations for cycles 1 to 7 (Figure 6). The first option uses the pronounced lithological expression of sedimentary cycles 5-7 as starting point for the tuning. Cycles 5-7 are correlated to three consecutive insolation minima with slightly higher amplitudes than the minimum below (~6.71 Ma). Cycles 1 to 4 are correlated to consecutive insolation minima. The second option correlates cycles 2-7 to one insolation cycle older, the prominent light-coloured carbonate bed of cycle 6 is correlated to the high-amplitude insolation maximum at ~6.68 and the carbonate-rich lithology of cycle 1 and below is correlated to the high-amplitude insolation maximum at ~6.79 and 6.85 Ma.

The quality of the correlation can be tested by applying a Gaussian bandpass filter centred at 41 kyr to the GR and K records. Since the Lava record was tuned to the dominantly precession-related peaks of insolation, and thus independent of obliquity, a good fit between the filtered records and obliquity would suggest that the tuning is correct. The GR and K records were filtered for both tuning options (Figure 6). The filtered components of both GR and K are almost identical in the uppermost part of the records, where the age models are identical, and they are in phase with obliquity, indicating that the tuning in this interval is correct. The lowermost parts of the two filtered records are clearly distinct; the first option (left-hand side in Figure 6) results in negligible amplitude for the 41 kyr component in this interval, so the phase cannot be compared; the second option (right-hand side in Figure 6) results in a higher amplitude, and the cycles are almost in phase with obliquity. Therefore, we have a strong preference for the second correlation option.

We can now assign astronomical ages to the polarity reversals of the Lava section (Table 1). The positions of all the reversals are well-defined (Figure 6 and Table 1), and the unambiguous astronomical tuning of cycles 8-15 results in high-precision ages for the C3An.2n(y) and C3An.1n(o) reversals (Figure 6). The two correlation options for cycles 1-7 result in two possible astronomical ages for reversal C3An.2n(o) (Figure 6), the older of which is preferred. Comparison
with the APTS ages shows that all our reversals are within the error limits of the APTS ages, but have a higher precision (Table 1). The SR ages of the upper two reversals cannot be distinguished from our astronomical ages; the SR age of the lower reversal is within the error limits of our preferred tuned age.

![Figure 6](image_url)

Figure 6. Tuning of the sedimentary cycles in Lava to L90(1,1) 65°N summer (average of June and July) insolation (Laskar, 1990). For the correlation of the lower cluster (cycles 1-7), two options are indicated. Filtered GR and k records with a Gaussian band-pass filter centred around 41 kyr are plotted on top of obliquity (Laskar, 1990). Two different age models were applied, according to the two correlation options of cycles 1-7 in the Lava section. The filtered components are almost identical and in phase with obliquity in the upper part of the records. The first option results in negligible amplitude in the lowermost parts; the second option shows higher amplitudes, which are almost in phase with obliquity, and is thus preferred. The polarity pattern in the time domain is derived from our tuning and compared with the APTS and SR time scales (Krijgsman et al., 1999a).
Conclusions

A reliable magnetostratigraphy is established for the Messinian Lava section, which results in an age of ∼6.9 Ma for the base and ∼6.2 Ma for the top of the section. The cycles in the Lava section, as expressed in the lithology, gamma-ray attenuation and susceptibility records have the same duration and are forced by precession. Palynological data indicate that dark marks were deposited during summer insolation minima (drier periods with cooler summers), and light marks in maxima (more humid periods with warmer summers). Astronomical tuning of the cycles yields absolute ages for the polarity reversals that confirm and define more precisely the APTS ages of Krijgsman et al. (1999a).

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Late Miocene to Early Pliocene depositional history of the intramontane Florina-Ptolemais-Servia Basin, NW Greece: interplay between orbital forcing and tectonics

Abstract

Upper Miocene and Lower Pliocene shallow lacustrine deposits from the Florina-Ptolemais-Servia Basin in northwestern Greece show a distinct m-scale sedimentary cyclicity of alternating marls and lignites or clays, which were shown to be primarily related to precession-induced climate variations (see this thesis, Chapters 1, 2 and 4). Three additional sections and three drill cores from the same basin are studied using a combination of cyclostratigraphy, magnetostratigraphy and \(^{40}Ar/^{39}Ar\) dating. Together with the earlier studied sections, they provide a continuous succession that documents the depositional history of the intramontane Neogene basin fill. Sedimentation in the basin started at around 8 Ma ago with deposition of coarse-grained terrigenous clastics in an alluvial environment (Komnina Fm, Servia member). From −7.1 to −6.1 Ma ago, (diatomaceous) marls were deposited in a lacustrine environment, frequently interrupted by deposition of clays and local xylite-type lignite seams (Komnina Fm, Lava member). Hereafter, deposition of alternating coarse- and fine-grained terrigenous-clastic alluvial sediments took place (Komnina Fm, Prosiko member), followed by a gradual shift towards lacustrine sedimentation at around 5.5 Ma. Deposition of alternating fine-grained clastics (silts and clays) and biochemical sediments (carbonates, marls and thin lignites), with episodic periods of sub-aerial exposure (Komnina Fm, Toma Eks member) continued until −5.23 Ma. From then onwards up to −3.9 Ma, regular alternating lignites and marls are formed in a shallow lacustrine environment (Ptolemais Fm). Precession-induced fluctuations of regional climate primarily defined the m-scale variations in lithology as observed in all members of succession, whereas the 100 and 400-kyr eccentricity cycle had a clear impact on larger-scale lithological alternations (in at least parts) of the succession. A marked similarity in the ages of fundamental changes in depositional environments between the Florina-Ptolemais-Servia Basin and the marine basins in the Mediterranean is observed, suggesting (but not necessarily implying) that they have a common, possibly tectonic origin.

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Introduction

Paleoclimate and environment reconstructions provide a key to understanding modern climate changes, and geological deposits contain a natural archive of past climate. The astronomical theory of climate change, according to which climatic oscillations are linked to perturbations in the Earth's orbit (Milankovitch, 1941), is at present widely accepted. The recognition of orbital or Milankovitch cycles in the geological record has enabled the development of a very accurate time scale for the entire Neogene (Lourens et al., 1996a; Hilgen et al., 1997a; Shackleton and Croughurst, 1997; Shackleton et al., 1999). Such a time scale provides the basis for climate modelling experiments aiming at a better understanding of the astronomical forcing of climate.

Evidently, orbital forcing influences not only marine, but also continental, environments. Lacustrine sediments in particular can give valuable information on the palaeoclimate and environment (e.g., Oleson and Kent, 1996). This was also recently illustrated for parts of the Upper Miocene to Lower Pliocene sequences of the Florina-Ptolemais-Servia (FPS) Basin in NW Greece. In this intramontane basin, cyclically bedded lacustrine deposits are continuously exposed in a series of open-pit lignite quarries (Figure 1). Both 

\[ ^{40}Ar/^{39}Ar \] dating of intercalated volcanic ash beds and high-resolution magnetostratigraphy of several parallel sections demonstrated that the sedimentary cyclicity is primarily related to precessional variations in the Earth's orbit (see this thesis, Chapters 1, 2 and 4). Orbital tuning of sedimentary cycle patterns to astronomical time series showed that the lacustrine successions from the Ptolemais lignite open-pit complex and the Lava lignite quarry cover the time-interval between 5.3 and 3.9 Ma and between 6.9 and 6.2 Ma, respectively. These age assignments indicate that our previous studies didn't cover the time interval from about 6.2 to 5.3 Ma.

In this study, we present the results of an integrated stratigraphic study on additional sections and drill cores from the FPS Basin. Together they are thought to provide a continuous succession of the Messinian and Early Pliocene and allow us to reconstruct the tectonic and/or climate processes, which controlled the filling of the basin. Moreover, correlation of the sedimentary cycle patterns inferred from the composite record of the basin with those of the Mediterranean marine record offers a unique opportunity to gain more insights in the interplay between tectonic processes and climate variations, in particular prior to, during and following the Messinian salinity crisis.

Geological background and earlier studies

The studied sections consist of a series of open-pit lignite quarries, natural exposures and drill cores. They are located in the NNW-SSE trending intramontane FPS Basin, which extends over a distance of 120 km from Bitola in the Former Yugoslav Republic of Macedonia (FYROM) to Servia in northwestern Greece (Figure 1). The basin developed in the Pelagonian Zone, the westernmost zone of the Internal Hellenides (Brunn, 1956) in the Late Miocene, in response to NE-SW extension (Pavlidis and Mountrakis, 1987). A subsequent Pleistocene episode of NW-SE extension resulted in the fragmentation of the basin into several sub-basins, i.e., the sub-basins of Florina, Ptolemais and Servia (Pavlidis and Mountrakis, 1987). These sub-basins are presently located between 300 and 700 m above sea level and are flanked by mountain ranges up to ~2000 m, which are primarily composed of Mesozoic limestones, Upper Carboniferous granites and Paleozoic schists (Brunn, 1956, Figure 1). Continuous sedimentation resulted in the accumulation
of a ~600 m thick succession of Late Miocene to Early Pleistocene lake sediments with intercalated lignites and alluvial deposits, which are divided into four lithostratigraphic units (Ehlers 1960, Figure 1). Of main interest to this study are the basal Komnina and overlying Polemais Formation.

The Komnina Fm. is ~300 m thick, unconformably overlies the pre-Neogene basement and is predominantly composed of alluvial sands and conglomerates, lacustrine (diatomaceous) marls and paleosol clays, with some intercalated (sylite-type) lignite seams. Recent studies in the Lava open-pit lignite quarry dated the middle part of the Komnina Fm., as Late Miocene (Turolian, lower part of mammal zone MN13) on the basis of small mammals (Apoeum sp.3, de Brujin et al. 1999) and using a combination of magneto- and cyclostratigraphy (see this thesis, Chapter 4). The overlying Polemais Fm., has a thickness of ~110 m and consists of a rhythmic alternation of m-scale lignite and lacustrine mud beds, with intercalated fluvial sands and silts and some 20 volcanic ash beds. The Polemais Fm. was dated as Early Pliocene (early Ruskovian, MN Zones 14 and 15) on the basis of paleontologic data from small mammals (Van de Weerd, 1979) and, more recently, using a combination of magneto- and cyclostratigraphy and 40Ar/39Ar dating (see this thesis, Chapters 1 and 2). The resulting high-resolution age model for the Polemais and the middle part of the Komnina Fm. showed that the sedimentary cyclicity in both successions is primarily related to precessional variations in the Earth’s orbit.

Figure 1. Geological map of the Florina-Polemais-Serbia Basin (after IGME, 1997) with the locations of the studied sections and the stratigraphic column of the basin fill (after Ehlers, 1960). F.Y.R.O.M. is the Former Yugoslav Republic of Macedonia.
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The palynological record of these sedimentary cycles reveals a significant response of mountainside vegetation, i.e., regional climate to orbital forcing (Kloosterboer-van Hoeve, 2000, this thesis, Chapter 4). Cyclic trends in the relative abundance of colline and montane components are considered to express periodic variations in soil-moisture availability, resulting from changes in orographic winter-time precipitation.

Lithostratigraphy and magnetostratigraphy

Methods

Three sections (Prosilio, Vegora and Tomea Eks) and three drill cores (Lava, Tomea Eks and Komina), which together cover the top half of the basin Komina Fm, and the first few metres of the Ptolemais Fm., are subject of the present study. These sections and drill cores were logged in detail, with emphasis on the sedimentary cyclicity, and sampled for paleomagnetic studies. A portable electric drill and a generator as power supply was used to take oriented 2.5 cm-diameter cores in the field, which were later cut into 2.2 cm-long specimens in the laboratory. From the Prosilio section 150 levels were sampled, from the Vegora section 79 levels, from the Tomea Eks core and section together 117 levels, and from the Lava core 66 levels. The average sampling spacing was ~1 m. In the Prosilio C sub-section and Lava core sampling spacing was considerably larger (~3.5 m) due to the lack of suitable sampling lithologies. In the Tomea Eks section, no samples were analysed from the interval 50-70 m below the base of the Ptolemais Fm. Fine-grained lithologies (marls, clays and silts) were preferably sampled, because these were expected to give best paleomagnetic results. As routine procedure, we removed the weathered surface in order to drill in sediments as fresh as possible. Note, that sediments in the top ~15 m of the Prosilio D sub-section remained weathered even after digging a ditch of ~1 m.

Bulk magnetic susceptibility was measured on a KLY-2 Kappa bridge. The natural remanent magnetisation (NRM) was thermally demagnetised in a laboratory-built shielded furnace and measured on a 2G Enterprises DC SQUID cryogenic magnetometer. Thermal demagnetisation was performed by step-wise temperature increments of 30-50°C, from room temperature up to a maximum of 500°C. The temperature steps above 410°C principally showed viscous and random oriented components. Demagnetisation diagrams (Zijderveld, 1967) through selected data points were used to determine the NRM components. The samples from the vertical Tomea Eks drill core could only be oriented in the vertical sense (up/down), and hence only the inclination of the analysed samples is reported.

Vegora section

The Vegora section is exposed in a private open-pit lignite quarry along the road from Amnestycon to Vegora near the northern rim of the Ptolemais Basin (Figure 1). The section has a length of 128 m and consists primarily of lacustrine and alluvial sediments (marls, clays, silts, sands and xylite-type lignites) from the middle part of the Komina Fm. (Figures 2 and 3). The basal part of the section (unit 1) consists of 11 m of strongly xylitic lignite with some thin silty intercalations. The lignite seam is conformably overlain by 63 m of faintly laminated marls (unit 2), with an upward increasing amount of silt and some local, slightly erosive conglomerate intercalations. The marls are rich in leaves (Velitzelos and Gregor, 1990), diatoms (Gerasoulis and Velitzelos, 1978) and ostracods and show subtle colour variations, with six regularly spaced dark-coloured clay-rich intervals. Four cm-thick biotite-rich tephra layers are found at ~60 m in the
section. Between 74 and 82 m from the base, a fine-grained, dark-coloured interval is found, which is composed of grey-brown lignitic clay at its base, followed by multi-coloured (orange, red, grey), mottled clays, silts and fine sands (unit 3). The transition from the second, marly unit towards the dark-coloured clay-rich unit takes place over an interval of about 25 cm. Probably, the fairly abrupt but conformable change in sedimentation conditions was at least in part related to tectonics, as evidenced by syn-sedimentary faults (mostly trending NE-SW), which cut the marls and the lower part of the overlying succession. The following part of the section, between 82 and 100 m, consists of three 5-10 m thick lining-upward sequences, with slightly erosive, cross-bedded conglomerates and coarse sands at their base, which are overlayed by multicoloured (orange, red, grey) mottled clays, silts and fine sands, with abundant calcareous nodules. The top of the section, from 100 m upward, is formed by some 30 m of dark-red mottled sands, silts and clays.

The NRM and bulk susceptibility values show little variation with depth and fluctuate at around ~0.5 mA/m and ~200×10⁻⁶ SI units, respectively (Figure 2). Demagnetisation diagrams generally have a two-component NRM. The first component is generally removed between 100 and 230°C (Figure 4a, b); it has a present-day orientation before bedding tilt correction and is therefore considered to be of secondary origin. The second component decays towards the origin at higher temperatures (230-410°C) and shows both normal and reversed directions (Figure 4a, b). Some demagnetisation diagrams of samples with low initial NRM intensities show only a cluster in the temperature range from 230 to 410°C, but the normal or reversed polarity is in most cases unambiguous. We interpret this 230-410°C component as the characteristic component. Five out of the seven samples between 22 and 40 m in the section and some samples from the multicoloured mottled part, between 82 and 100 m, are characterised by a more complex demagnetisation behaviour (Figure 4c, d). Besides a low-temperature component, there is an intermediate-temperature component that shows only reversed directions and a third, high-temperature component that has mainly normal directions, although few intermediate directions occur. The intermediate-temperature component has the same unblocking spectrum as the characteristic component from the lower part of the succession, but they are not exactly parallel or antipodal. This might be caused by the partially overlapping demagnetisation spectra of the intermediate- and high-temperature components. We interpret the intermediate-temperature component as the characteristic remanent magnetisation. The magnetic directions derived from the demagnetisation diagrams reveal two normal and two reversed polarity intervals in the Vegora section (Figure 2). The middle polarity transition at ~40 m in the section is best constraint, while the other two reversals, at ~15 m and 70 m, respectively, are less well defined.

Figure 2 (next page). Paleomagnetic results, polarity zones, lithology, NRM intensity and magnetic susceptibility (ø) of the Vegora section. Six regular spaced clay-rich intervals are labelled (a to f) next to the lithology column and V64 refers to the ^40Ar/^39Ar dated volcanic ash bed. Closed (open) circles samples with reliable (less reliable) paleomagnetic directions that linearly decay towards the origin (form a cluster in the normal or reversed quadrant). Open squares: samples with less reliable paleomagnetic directions whose intermediate temperature component is interpreted as the characteristic remanent magnetisation. In the polarity column, black (white) denotes normal (reversed) polarity, while shaded indicates undetermined polarity.
Figure 3. Vegora section from the private open-pit lignite quarry along the road from Amytheon to Vegora (for location, see Figure 1). Indicated levels in metres refer to position in the Vegora section (see Figure 2).
Figure 4. Thermal demagnetisation diagrams of representative samples from the Vegora (a-d) and Tomea Eksi section (e-f). The closed (open) circles represent the projection of the vector end-points on the horizontal (vertical) plane. a-b) Secondary LT (up till 200°C) and HT (230-410°C) characteristic component. c) Secondary LT (up till 290°C), intermediate (320-380°C) characteristic and HT (above 380°C) viscous component. d) Secondary LT (up till 200°C), intermediate (200-320°C) characteristic and HT (above 320°C) viscous component. e-f) Secondary LT (up till 150°C) and HT (200-350/410°C) characteristic component.

**Tomea Eksi and Komanos sections**

The Tomea Eksi and Komanos sections are from the similar named open-pit lignite quarries, which are located some 15 km SE of Ptolemais (Figure 1) and form part of the complex of open-pits exploited by the Public Power Corporation (P.P.C.). The sections are downward extensions of earlier studied sections (see this thesis, Chapters 1 and 2), which comprised the entire Lower Pliocene Ptolemais Fm, and the first few metres of the underlying Kommina Fm. In the Tomea Eksi quarry, the top 60 m of the Kommina Fm, was exposed and sampled; a 10 cm thick drill core, taken by a private drilling company, provided a downward extension up to 140 m below the base of the Ptolemais Fm. At this point, further drilling was impossible due to the fact that the drill reached an aquifer, which produced an enormous water blow-out. In the Komanos quarry, a similar core was taken up to a depth of 58 m from the base of the quarry, i.e., the base of the Ptolemais Fm.

The top 10 m of the Tomea Eksi section are composed of five lignite-grey marl alternations, sedimentary cycles K1-5 of the Ptolemais Fm, (Figure 5). Downwards, the section can roughly be subdivided into three ~50 m thick intervals. From the top of the Kommina Fm, (level 0) to a
depth of 50 m, the section consists of nine regular alternations, labelled A to I, of beige carbonate-rich marls, brown lignites and lignitic marls, and green and pink clays (Figures 5 and 6). The beige marls form the larger part of each cycle and contain freshwater ostracods (Bopyris, Canidona, Dantasula and Metacypria), fish teeth and vertebrates (Ehlers, 1960). The uppermost metre of the beige marls often contains indurated concretions, showing evidence of dissolution. The contact with the overlying lignite and/or lignitic marl is irregular and sharp. These organic-rich sediments contain abundant reed fragments, freshwater and land snails, and mammal remains. The next lower ~50 m of the section are composed of identical beige marls as higher up in the section, more or less irregularly intercalated with some dm-thick darker-coloured clay-rich marls. The basal ~40 m of the section, which was only poorly recovered by the drill, are composed of two 10-15 m thick green chlorite sand bodies, separated by clay-rich marls and clays.

Figure 5. Paleomagnetic results, polarity zones, sub-sections, lithology and NRM intensity of the Tomea Eksi section and lithology and magnetic polarity of the Komanos section. Large (small) closed circles: samples that linearly decay towards the origin and are fully demagnetised at 410°C (350°C). Lignitic levels have been numbered [A-I] from the top of the Komnina formation in both sections. Kfm is Komnina Fm. and Pfm is Ptolemai Fm. Paleomagnetic data from the Komanos section and the top 10 m from the Tomea Eksi section are from this thesis, Chapter 2. For lithological legend see caption to Figure 2.
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Figure 6. Part of the Torna Eksi section, from the similar named open-pit lignite quarry (for location see Figure 1). Numbered are the dark-coloured lignitic levels of sedimentary cycles E to I from the Torna Eksi member of the Komnina Fm.

In the Komninos section, the first 10 m of the Ptolemais Fm. show six lignite–grey marl alternations, sedimentary cycles K1–6 of the Ptolemais Fm. (Figure 5). Downwards, the first 25 m of the core are composed of alternating beige marls, brown lignitic marls and lignites, and green-blue clays, silts and sands. They form six sedimentary cycles, labelled A to F, which correlate with the same cycles from the Torna Eksi section. The remainder of the section, from -25 m down to -58 m is composed of green chlorite sands, with some minor silt and clay interbeds.

The NRM-intensity of the Komnina Fm. in the Torna Eksi section varies between 90 and 17,000 mA/m with an average of -1000 mA/m. Relatively low intensities correspond to lignitic and clay-rich lithologies and relatively high values to carbonate-rich beige marl lithologies (Figure 5). Bulk magnetic susceptibility ranges between 2.6 and 172-10^-6 SI units, with an average of 56.10^-6 SI units. Thermal demagnetisation generally shows a small viscous and randomly oriented, which is removed at 150°C (Figure 4e-f). Upon further heating the NRM decays linearly towards the origin and is fully demagnetised after heating until 410°C (Figure 4e). Thermal demagnetisation of samples from the lignitic marls and/or clays generally starts to deviate already at lower temperatures. The Komnina Fm. in the Torna Eksi section is entirely of reversed polarity (apart from two samples from the drill core with apparent normal directions) and a change from reversed to normal polarity is detected in the lignite of cycle K2 in the overlying Ptolemais Fm. (Figure 5).
*Prosilio section*

The Prosilio composite section is located in a small subsidiary depression of the Servia sub-basin, some 10 km SW of Servia (Figure 1). The composite section displays almost 200 m of lacustrine, palustrine and alluvial sediments (marls, lignites, clays, sand and conglomerates), exposed in four partly overlapping sub-sections, labelled A-D (Figures 7 and 8a). The lowermost sub-section, Prosilio A, is taken from a private open-pit lignite quarry a few hundred metres W of Prosilio along the N-S side of the road from Prosilio to Trnovátko. The sediments exposed in the lignite quarry are intersected by a N-S trending normal fault, but marker beds allow an unambiguous correlation between the parts of the Prosilio A sub-section at either side of the fault (Figure 8a). The other three sub-sections (Prosilio B-D) are natural exposures along the S-side of the same road (Figure 8a). Correlation between the sub-sections was established by tracing specific marker beds in the field and by matching characteristics in the sedimentation patterns.

The basal five metres of sub-section Prosilio A consist of xylitic lignite, which is topped by 2 m of laminated, beige-coloured lacustrine carbonate with abundant charophyte oogonia and (opercula of) freshwater gastropods (Figure 7). Above this, 57 m of faintly laminated, blue-coloured marls are found, with abundant leaf, fish remains and freshwater ostracods. This part of the sub-section displays a subtle colour banding on various scales of alternating darker-coloured clay-rich marls and lighter-coloured carbonate-rich marls. On m-scale, these dark-light alternations are especially evident between 10 and 27 m and from 35-42 m in the section (Figures 7 and 8b). Hereafter, from 42-67 m, dominantly siliciclastic sediments are found, arranged in five to seven m-thick fining-upward successions. They have slight erosive conglomerates at their base, primarily composed of purple-coloured ophiolite pebbles, and are followed by (finer) sands and silts, showing various types of lamination (cross-, parallel- and wavy-lamination). The top of each succession is formed by massive clayey marl, which occasionally contains wood fragments, opercula, charophyte oogonia and ostracods. The top 9 m of sub-section Prosilio A overlap with sub-section B and consist of four distinct m-scale cycles of dark-coloured clay and light-coloured carbonate-rich marl beds, both containing leaves, fish remains and ostracods.

After an ill-exposed interval of ~6 m, sub-section B continues with a 3 m thick fining-upward sequence of sand, silt and clay (Figure 7). Hereafter, 7 m of thinly bedded, light-coloured carbonate-rich marls are recorded (Figure 8c), with abundant oogonia of charophytes and ostracods and thin lentic and sandy interbeds. The top of sub-section B contains two fining-upward sequences. The first has an abrupt basal contact and is composed of alternating silts, clays and marls with some pebbly strings at its base, while the second contains a prominent erosive reddish-coloured conglomerate at its base subsequently followed by finer grained sediments (Figure 8c).

The distinct light-coloured carbonate-rich marl bed, which forms the basal few metres of sub-section C and the next higher fining-upward sequence, composed of alternating silts, clays and marls with some pebbly strings at its base, correlates with sub-section B (Figure 7). Next, just like in sub-section B, a prominent erosive reddish-coloured conglomerate is found. This conglomerate bed marks the start of a dominantly siliciclastic interval, which continues up till ~145 m in the composite section (Figure 8d). It contains 11-16 alternations of red- and yellow-coloured conglomerates and/or coarse sand beds and green- and blue-coloured, mottled pebbly silts and clays (Figures 7). The contacts between the coarse and fine-grained sediments are generally sharp; the conglomerate and sandy intervals are erosive at their base and often contain calcareous nodules at their top. From ~145 m, the siliciclastic sediments become progressively finer-grained and the predominantly clayey sediments become enriched in organic matter. Moreover, within the top 15 m of this sub-section, five more or less regularly spaced light-coloured, indurated carbonate beds
were recorded, with abundant freshwater ostracods and (opercula of) gastropods. The topmost of these has a thickness of 25 cm and was used to correlate the C and D sub-sections.

Sub-section D can be separated in two parts (Figures 7 and 8f). The lower half, up to 172 m in the composite section, is composed of alternating light-coloured (carbonaceous) marls, dark-coloured clays and lignites, arranged in six or seven ~2 m-thick sedimentary cycles. The light-coloured marls contain abundant lacustrine ostracods and gastropods, whereas the dark-coloured clays often contain calcareous nodules and frequently have a mottled appearance. The top half of sub-section D consists of massive (diatomaceous) carbonate-rich marls that show a subtle colour variation, resulting from varying contributions of clay and carbonate. Darker levels are generally enriched in clay, whereas lighter levels have higher proportions of carbonate. On m-scale, six, regularly spaced dark levels are found. The sub-section ends with ~2.5 m of strongly weathered lignite.

The initial NRM of the Prosliao section shows widely varying intensities ranging from 0.1 to 90 mA/m, while bulk susceptibility varies between 0.1 and 6400×10^-6 SI units (Figure 7). In general, highest NRM intensities and susceptibility values are recorded in the samples from the fresh sub-sections A and B, whereas lower values are found in the more weathered C and D sub-sections. In contrast, relatively low NRM intensities are found at ~40 m and ~70 m in the Prosliao composite section, while susceptibility values remain high at these levels (Figure 7). Demagnetisation diagrams of the samples from the Prosliao section are generally composed of two components (Figure 9a-c). The first component is generally removed between 100 and 200°C. It has a present-day orientation before bedding tilt correction and is therefore considered to be of secondary origin. The second component decays towards the origin at higher temperatures (200-410°C) and shows both normal and reversed directions. This component is interpreted as the characteristic remanent magnetisation (ChRM) component. The demagnetisation diagrams of samples with low initial NRM intensities often show a cluster in the temperature range from 230 to 410°C (Figure 9c). Demagnetisation diagrams of samples in the upper ~10 m of the sub-section A reveal a more complex behaviour (Figure 9b). They show a normal component at low temperatures (100-200°C), a reversed component at intermediate temperatures (230-290°C) and a third, high-temperature normal but viscous component. The intermediate-temperature component has the same unblocking spectrum as the characteristic component from the samples that show a two-component NRM. Therefore, we interpret the reversed intermediate-temperature component as the characteristic remanent magnetisation. Samples from the middle, siliciclastic part of the Prosliao A sub-section have meaningless directions; Declinations tend to be south, but inclinations have a random direction (Figure 9b).

The magnetic directions derived from the demagnetisation diagrams, show that the Prosliao section contains three normal and three reversed polarity intervals (Figure 7). None of the polarity reversals, however, is well defined. The lower reversed polarity interval is represented by just one sample with low NRM intensity and ambiguous direction (Figure 7 and 9c). The samples around the second reversal at ~40 m all have low NRM intensities, inhibiting an unequivocal estimation of the ChRM. Moreover, this reversal is located at around the change towards siliciclastic lithologies, which didn't provide any sensible paleomagnetic directions (Figure 7 and 9b). The third reversal at ~80 m is not well constrained either, due to an ill-exposed interval within the Prosliao sub-section B. The next reversal at ~100 m is also poorly constrained, due to the absence of suitable, fine-grained lithologies. The uppermost reversal is represented by only four samples; two have indistinct directions and two are less ambiguous (Figure 7 and 9c).
Figure 7. Paleomagnetic results, polarity zones, sub-sections, lithology, NRM intensity and magnetic susceptibility of the Prosilio composite section. Closed (open) circles: reliable (less reliable) paleomagnetic samples that linearly decay towards the origin (form a cluster in the normal or reversed quadrant). Open squares: samples with a normal LT component (100-200°C), a reversed component at intermediate temperatures (230-290°C) and a HT normal, but viscous component. Stars: samples with meaningless directions; declinations tend to be south, but inclinations have a random direction. At 15 m from the base of the section, a 5-cm thick green clay bed (key-bed, kb) is found yielding abundant fish teeth and vertebrae. This characteristic marker-bed was also recognised (and named key-bed II) in the five km easterly situated Lava quarry (see this thesis, Chapter 4). Stars next to the lithology column at ~150 m denote indurated carbonate beds, that were used as marker-beds between the sub-sections C and D. Approximate number of m-scale sedimentary cycles have been indicated right from the lithology. For lithological legend see caption to Figure 2.
Chapter 5

Figure 8. a) Sampling trajectories of the Prosilio sub-sections A to D, located in a small subsidiary depression of the Servia sub-basin, some 10 km SW of Servia (for location see Figure 1). Photo is facing south. Note trucks bottom left for scale.

**Lava drilling**

A drill core with a diameter of 10 cm (core Z-10), taken by I.G.M.E, approximately 1 km N of the Lava lignite open-pit quarry provided a downward extension of some 150 m of the Lava section. The Lava drilling and the Lava quarry section did not overlap; we estimate that a gap of some ~30 m exists between the two. The top 20 m of the core consists of light-coloured (beige-grey) lacustrine marl, with freshwater ostracods and diatoms. Below this, some 5 m of alternating (mottled) clays, lignitic clays and thin lignite beds are found. The remainder of the core, to a depth of some 145 m consists of conglomerates, gravels and (arenitic) sands, arranged in 35-40 fining-upward sequences. From ~100 m depth, some large (several cm diameter) limestone clasts are found, floating in a sandy/clayey matrix and at ~125 m an obvious colour change is observed from grey to yellow. The basal five metres of the core is composed of multi-coloured (yellow, red and black) gravels and sands. Unfortunately, the 66 samples from the Lava drill did not yield any sensible palaeomagnetic results, either due to (possible) orientation errors of the samples or due to unsuitability of the lithology of the samples.

Figure 8. (next two pages) b) Prosilio open pit, sub-section A. The sediments exposed in the quarry are intersected by a north-south trending normal fault, but marker beds allow an unambiguous correlation between the parts of the sub-section at either side of the fault. c-e) Prosilio sub-sections B-D. Levels in meters refer to position in the Prosilio composite section (see Figure 7).
Figure 8 (continued)
Figure 9. Thermal demagnetisation diagrams of representative samples from the Prosilio section. The closed (open) circles represent the projection of the vector end-points on the horizontal (vertical) plane. a-c) Secondary LT (up till 200°C) and characteristic HT (above 230°C) component. d) Secondary LT (up till 200°C), intermediate (200-290°C) characteristic and viscous HT (above 290°C) component. e) Secondary LT (up till 150°C) and characteristic HT (200-410°C) component that forms a cluster in the reversed quadrant. f) Sample from the middle, siliciclastic part of the Prosilio A sub-section with a meaningless direction.

40Ar/39Ar geochronology of the Vegora ash

Methods

Field reconnaissance in the Vegora section led to the identification of four cm-thick volcanic ash beds, which were interpreted as primary ash-fall tephra, as noted by sharply delineated bases, lateral continuity and uniform thickness over the entire open-pit, and by distinct mineralogy. Isotopic dating focused on biotite and sanidine separates of the uppermost, thickest and coarsest tephra, ash bed VG4 (Figure 2). Biotite crystals of VG4 were analysed via the incremental heating approach, while single step, total-fusion and incremental heating measurements were performed on the sanidine.

40Ar/39Ar analyses were performed on the argon laser-probe facility (VULKAAN) at the Vrije Universiteit in Amsterdam using facilities, sampling preparation and analytical procedures similar to those described in (Wijbrans et al., 1995, this thesis, Chapter 1). The VG4 ash was sampled twice; the first sample was collected in 1995 and analysed in irradiation runs VU16 and VU21,
while the second sample was collected in 1997 and analysed in irradiation run VU32. Mineral separates of sanidine and biotite were concentrated using standard heavy liquid and magnetic separation techniques, and finally by hand-picking the clear (fresh) phenocrysts under a binocular microscope. Irradiation with fast neutron was done at the TRIGA reactor at Oregon State University, for 2h (irradiation run VU16) and 7h (irradiation runs VU21 and VU32). The monitor minerals used were Taylor Creek Rhyolite sanidine 27.92 Ma (Dalrymple and Duffield, 1988) and Drachenfels sanidine 24.99 Ma (Wijbrans et al., 1995). Plateau and isochron ages were calculated from the corrected $^{39}$Ar, $^{40}$Ar and $^{40}$Ar intensities using the ArArCALC v1.6 software (Koppers, 1998). Individual isotope intensities were corrected for system blanks, interfering nucleogenec isotope reactions involving isotopes of Ca and K, for isotopic decay of $^{39}$Ar and $^{40}$Ar during the period between irradiation and analysis, and, for the plateau calculation, the $^{40}$Ar intensity was corrected for atmosphere derived $^{39}$Ar. The uncertainty for the $^{40}$Ar/$^{39}$Ar ages ($\pm 2\sigma$) includes the analytical uncertainties in the J value, procedure blanks, regression of peak intensities, the correction factors for interfering isotopes and the mass discrimination factor. Plateau gas fractions were selected from age spectra following the criteria as described in (Koppers, 1998).

Results

The results of argon dating experiments on the VG4 tephra are summarised in Table 1. The age spectra, isochrons and total fusion results are given in Figure 10.

Fourteen heating steps with increasing laser beam intensity were conducted on the biotite separate from irradiation batch VU16. The resulting age spectrum is characterised by high apparent ages in the low temperature (LT) increments that exponentially decrease into a plateau (Figure 10a). Five consecutive steps, from step 10 to fusion, yielded 44% of the $^{40}$Ar released and produced a weighted mean age of 6.05 ± 0.14 Ma. Using the concordant increments an inverse isochron age of 5.85 ± 0.53 Ma and $^{40}$Ar/$^{39}$Ar intercept of 398 ± 298 was calculated (Figure 10b).

For the VU21 biotite separate, the incremental heating experiment included sixteen heating steps. The resulting age spectrum is again characterised by high apparent ages in the LT increments that exponentially decrease into a plateau (Figure 10c). Only two consecutive steps, steps 6 and 7, yielding 56.3% of the $^{40}$Ar were concordant and gave a weighted mean age of 6.36 ± 0.09 Ma and when regressed in terms of $^{40}$Ar/$^{39}$Ar vs. $^{40}$Ar/$^{40}$Ar, a $^{40}$Ar/$^{39}$Ar intercept of 332 ± 16 (Figure 10d).

Nine heating steps were conducted on the VU32 biotite separate and again, the spectrum shows high apparent ages in the LT increments that decrease exponentially into a plateau (Figure 10e). Four consecutive steps, steps 5 to 8, yielded 61% of the $^{40}$Ar released and defined a plateau age of 6.09 ± 0.07 Ma. The inverse isochron age of 6.05 ± 0.13 Ma is in agreement with the plateau age, and the $^{40}$Ar/$^{39}$Ar intercept of 314 ± 38 is indistinguishable from the atmospheric ratio of 295.5 (Figure 10f).

The step-heating experiment on the sanidine separate from irradiation run VU16 consisted of twelve steps. The $^{40}$Ar release patterns showed a disturbed age spectrum, with high apparent ages for the first two increments, concordant ages (yielding 32% of the $^{40}$Ar released) for steps 3 to 7, and high variable ages for the high-temperature increments (Figure 10g). High radiogenic yields of individual gas fractions (>95%) precluded regression in isochrons.

The sanidine separate was also analysed via single step total fusion. The total fusion ages from five replicates of the sanidine crystals of the VU16 irradiation batch showed considerable scatter; all individual replicate analyses are different at the 95% confidence limit (Figure 10h), suggesting

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Depositional history of Florina-Ptolemais-Serbia Basin

the presence of xenocrystal contamination and/or variable amounts of excess argon (Koppers, 1996). Therefore, the youngest age obtained from one of the replicates, \(5.98 \pm 0.04\) Ma, provided a maximum age for VG4. The nine total-fusion ages of the VU32 irradiation batch gave better results; six of the replicate analyses were within 2\(\sigma\), and the three remaining analyses gave significantly older apparent ages (Figure 10b). The weighted mean average of the six concordant total fusion ages gave an apparent age of \(5.97 \pm 0.07\) Ma, which is within error limits of the youngest total fusion age of the sandine separate of VU16.

To summarise, the VU32 \(^{40}\)Ar/\(^{39}\)Ar dating experiments for both the biotite and sandine separate gave best results. The VU16 and VU21 dating experiments yielded plateau gas fractions below 50\%, only two concordant heating steps or discordant total fusion ages for all experiments (Table 1). The VU32 biotite incremental heating experiment yielded plateau and inverse isochron ages for the VG4 tephra of \(6.09 \pm 0.07\) and \(6.05 \pm 0.13\) Ma, respectively; The total fusion sandine experiment yielded a weighted mean average age of \(5.97 \pm 0.07\) Ma. These biotite and sandine \(^{40}\)Ar/\(^{39}\)Ar ages are consistent and provide the best estimate for the age of deposition of the volcanic ash bed VG4 tephra.

Correlation to the astronomical polarity time scale

The magnetic polarity column of the Vegora section reveals four magnetozones, with two normal and two reversed intervals (Figures 2 and 11). The middle two polarity complete intervals are of approximately equal length. The \(^{40}\)Ar/\(^{39}\)Ar age of \(~6.05\) Ma of the VG4 volcanic ash provide an independent age constraint for correlation with the Upper Miocene astronomical polarity time scale (APTS) and suggests that the lower normal polarity interval represents the C3An.2n and the upper normal interval the C3An.1n (Figure 11). This magnetostratigraphic correlation is in agreement with paleobotanical evidence from the same section, which indicates an Upper Miocene (Messinian) age (Veltzél and Gregor, 1990).

An earlier paleomagnetic study included the top few metres of the Kómmina Fm, and the overlying Ptolemais Fm, of the Tommix Eski section (see this thesis, Chapter 2). This study showed that the normal polarity interval just above the base of the Ptolemais represent the Théva, the lowest Subchron of the Gilbert Chron (Figure 11). The Kómmina Fm, of the Tommix Eski section is entirely of reversed polarity, apart from two samples from the drill core with apparent normal directions (Figures 5 and 11). This long reversed interval correspond to the long reversed interval below the Théva Subchron (Figure 11), whereas the two single normal samples either represent brief normal excursions, or result from an orientation error or secondary overprint. Additional age constraints for the long reversed polarity interval are provided by small mammal remains from the lignite marl levels D and E from the top of the Kómmina Fm, and from the first two lignite beds of the Ptolemais Fm, (de Bruijn, 2000, pers. comm., Figure 11). The murid genera \(M\)an\(i\)s, \(A\)p\(o\)lem\(u\)s and \(O\)ch\(a\)n\(o\)m\(y\)s make up about 70% of the associations in all four levels. Other genera, however, show a clear break in the composition of the fauna. The genera \(A\)rt\(h\)ain\(i\)s and \(P\)seud\(o\)m\(e\)n\(o\)m\(i\)s in levels D and E are replaced by \(R\)ha\(g\)o\(p\)o\(l\)e\(m\)us and \(P\)rom\(o\)m\(o\)m\(y\)s in the Ptolemais Fm. samples. Simultaneously there is a sharp decrease in the Ochotonidae and the Soricidae, and an increase in \(A\)nth\(a\)n\(o\)m\(a\). The fauna associations of levels D and E are assigned a Late Turolian age (top MN13), whereas the Ptolemais Fm. samples are dated as Earliest Ruskician (base MN14, de Bruijn, 2000, pers. comm.). The Turolian-Ruskician (MN13/14) boundary is generally believed to be coincident with the Miocene-Pliocene boundary (de Guíll, 1989; Marabini and Vai, 1989), which has been astronomically dated at 5.33 Ma (Lourens et al., 1996a).
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Table 1: Compilation of 40Ar/39Ar step heating and total fusion ages data from Vegora ash VG4. Ages were calculated using \( t = 1/λ \ln (1 + (1 - λ)Ar/39Ar)) \), where \( λ = 5.547 \times 10^{-11} \text{ yr}^{-1} \); the irradiation parameter \( λ \) is a measure of the integrated fast neutron flux as found from the monitor data; \( Ar = \text{radiogenic } Ar; Ar = \text{Ar from the irradiation induced nuclear reaction } Kn(p,p)Ar \). Mass discrimination during this study was monitored by aliquots of air from an on-line air pipette system was 1.0029 per mass unit for VU16 and 1.0066 for VU32. Blank intensities, measured every 3-5 sample runs were in the range 1.1-6.0 \( 10^{-5} \text{ moles for m}=40, 0.4-4.3 \ 10^{-6} \text{ moles for m}=39, 1.1-5.3 \ 10^{-7} \text{ moles for m}=38, 1.7-2.5 \ 10^{-7} \text{ moles for m}=37 \) and 3.3-7.9 \ 10^{-7} \text{ moles for m}=36. Ages in bold provide the best estimate for the age of deposition of the volcanic ash bed VG4 tephra (see text and Figure 10).
Figure 10. VG 4 volcanic ash bed from the Vegora section: $^{40}$Ar/$^{39}$Ar incremental heating spectra, $^{40}$Ar/$^{39}$Ar vs. $^{40}$Ar/$^{39}$Ar isochrons and single fusion ages. a-f) incremental heating results of biotite separate; g) incremental heating results of sanidine separate; h) single fusion results of sanidine separate. In the regression diagrams the solid squares indicate analyses included in the isochron and plateau calculations. Dashed lines indicate regression between selected points (solid squares), and the atmospheric $^{40}$Ar/$^{39}$Ar ratio. For location of the ash bed see Figure 2. All errors shown are listed at the 2σ level, internal precision.

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The base of the Ptolemais Fm. has been astronomically dated at 5.25 Ma (see this thesis, Chapter 2). So an age of 5.33 for the MN13/14 boundary, which is located within four cycles below the base of the Ptolemais Fm., fits well in this age model. Note, that this age is ~400 kyr older than the age as suggested by Opdyke et al., (1997), who correlated the Turonian–Ruscian boundary near the base of the Sidujall Subchron, at 4.9 Ma, based on combined mammal stratigraphy and magnetostratigraphy of the Spanish Gabriel section. However, the latter calibrations should be taken with some caution because the mammal localities are spaced far apart in the stratigraphy (Sen, 1997) and also the correlation of the magnetic polarity sequence of the section to the APTS is not unambiguous.

The magnetic directions derived from the demagnetisation diagrams, show that the Prosilio section contains three normal and three reversed polarity intervals (Figures 7 and 11). The uppermost reversed interval is considerably longer than the others. No firm age constraints have been published for sediments from the Prosilio section. Knobloch and Velizelos (1986) reports the finding of several large mammal fragments (e.g. Mastodon angustidens f. subcapitata, Hipopotam and Rhinoceros) that points to an upper Miocene to lower Pliocene age and a similar age for the Prosilio section is suggested from a palynological study (Van de Weerd, 1983). The clay-rich bed at ~168 m in the Prosilio composite section (Figure 11) yielded a small mammal fauna association that showed a close resemblance to the associations from the lignitic mud levels D and E from the Tomea Eksi section, which were dated as latest Turonian (top MN13, see above). An indirect age assessment for the Prosilio sections relies on correlation of a characteristic 5-cm thick green clay bed with abundant fish teeth and vertebrae at ~20 m in the section. This characteristic bed was also recognised in the five km easterly situated Lava quarry and astronomically dated at ~6.57 Ma (Figure 11). These age constraints enable us to correlate the polarity sequence in the Prosilio section with the geomagnetic polarity time scale. The lower normal polarity interval correlates with Subchron C3An.2n, the middle normal interval with C3An.1n and the upper short normal interval with the Thvera (Figure 11).

Stratigraphic and environmental framework

The combined time-stratigraphic data inferred from the Vegora, Prosilio and downward extended Tomea Eksi quarry sections, the Tomea Eski, Komanos and Lava drillings, and those of the Kominna Fm. in the Lava open-pit quarry (see this thesis, Chapter 4) and of the Ptolemais Fm. in the Ptolemais lignite open-pit complex (see this thesis, Chapters 1, 2) indicate the presence of a continuous Late Miocene to Late Pliocene succession in the FPS Basin (Figures 11 and 12). Although roughly time-equivalent parts of the sequence differ from one another in various aspects, they also show high degrees of similarity (Figure 11). Moreover, it appears that the major changes in the depositional environment are roughly synchronous between the different sections. Below, we will discuss in some more detail the characteristics of the depositional systems and elaborate the timing and effects of time-successive events. This will be done for successively the Kominna and the Ptolemais Formations. For the former formation, informal members will be proposed, which are, from bottom to top, the Servia, Lava, Prosilio and Tomea Eksi members. For the Ptolemais Fm., the depositional characteristics for the successive Kyrios, Theodorus and Notio members will be summarised after Spoonbrink et al. (see this thesis, Chapter 1).
Figure 11. Correlation of the palaeomagnetic data of the Vegora, Komanos, Torma Eksi, Prosilio and Lava sections to the astronomical polarity time scale and comparison to the precession and eccentricity curves (Laskar et al., 1993). The age of the lower Thera is after Lourens et al. (1996a); the top of Subchron C3An.1n follows Krijgsman et al. (1999a) and the other three polarity reversals are after this thesis, Chapter 4. Eccentricity maxima in the astronomical curve are numbered I to XXI and their supposedly corresponding expression in parts of the stratigraphic columns of the Komina Fm. are equally numbered. MN13/14 refers to the position of samples that yielded and MN13/14 fauna. For explanation of the lithological columns, see Figures 2-4. The Lava section lithology and magnetostratigraphy are after this thesis, Chapter 4.

**Servia member**

This lowermost member of the Komina Fm. is thought to record the onset of intramontane sedimentation in the basin system (Figure 12). Our data on this member are confined to the Lava drilling. Additional information from surface outcrops around Servia and Lava (Desprairies and Faugères, 1971) facilitates to characterise the outlines of depositional environments during accumulation of the Servia member. The Lava drilling consists of 150 m of conglomerates, arenitic sands, clayey sands and clays, arranged in an overall fining-upward sequence. The detailed sedimentological analyses of surface outcrops (Desprairies and Faugères, 1971) corroborate the conclusion that the Servia sediments accumulated in alluvial depositional environments (alluvial fans, channel-fills, floodplains and levees), with a general change towards lacustrine and palustrine conditions towards the top of the member.

No sound first-order age assignments could be obtained from the Servia member, which impedes to accurately date the onset of sedimentation. Downward extrapolation of average sedimentation rates (0.18 m/kyr) from the Lava lignite quarry section gives an estimate of about 8 Ma ago for the onset of sedimentation in (at least this part of) the basin (Figure 12). An age in the
same order of magnitude is obtained if the 30-40 fining-upward sequences in the Lava drilling are regarded to be precession-controlled.

**Lava member**

The transition between the Servia and overlying Lava member is characterised by the gradual change from coarse-grained, predominately fluviatile, sands to fine-grained, lacustrine (lignitic) marls and palustrine clays (Figure 12). This transitional interval is recorded in the upper ~50 m of the Lava drilling (and possibly continues upwards in the non-exposed interval between the Lava drilling and Lava quarry section). Downward extrapolation of average sedimentation rates (0.18 m/kyr) from the Lava quarry section gives an age of ~7.3 Ma for the base, and ~6.9 Ma for the top of this interval.

The most complete record of the Lava member is exposed in the Lava lignite quarry, parts of the member are also exposed in the Vegora and Prosilio sections (Figure 11). It has a thickness of ~150 m and consists predominantly of light-coloured marls. The marls are rich in leaf imprints, fish remains, diatoms and ostracods (see also Desprairies and Faugères, 1971; Velizelos and Gregor, 1990; Antoniadis and Riefer, 1997). The diatoms indicate that the marls were deposited in a freshwater lake in less than 15 m depth (Desprairies and Faugères, 1971). The up to 20 m thick lignite seams encountered in the lower half of the member are classified as autochthonous floodplain or back-river forest swamp coals; they reflect the effects of continuously migrating open ponds and forested areas in a highly unstable fluviatile hydrological regime (Riegel et al., 1998). This conclusion is corroborated by the results of our magnetostratigraphic datings, which indicate different ages for the main phase of lignite accumulation: 6.85 Ma in the Lava open-pit, 6.73 Ma in the Prosilio quarry and 6.47 Ma in the Vegora section (Figure 12).

Thin, generally subordinate dark-coloured lignite and clay-rich interbeds are found in the predominantly light-coloured carbonate-rich marl succession, particularly so in the middle and uppermost parts of the succession (Figures 11 and 12). A detailed palynological study indicated that these beds mirror episodes of somewhat reduced humidity (probably coupled with lower lake-levels) in an overall wet climate (see this thesis, Chapter 4). A prominent, coarse-grained terrigenous-clastic interval of sands, gravels and conglomerates found in the middle part of the Lava member in the Prosilio section (Figure 11) is taken to document an ephemeral, local change from lacustrine to alluvial conditions.

**Prosilio member**

The predominantly fine-grained lacustrine marl of the Lava member pass upwards fairly abruptly into coarse-grained, terrigenous-clastic sediments of the Prosilio member (Figure 12). The boundary between the two members is recorded in the Vegora and Prosilio sections at 74 and 92 m, respectively. It corresponds approximately with the top of Subchron C3An.1n both sections (Figure 11) and may thus be considered to have occurred roughly at the same time (~6.05 Ma). In the Vegora section, where the magnetic polarity change is best determined, the age can be further constrained through extrapolation of average sedimentation rates, which, also taking into account uncertainties in the position of the reversals, results in an age of 6.02 ± 0.02 Ma. We find an average age of 6.07 ± 0.07 Ma if we apply the same calculations on both the Vegora and Prosilio records.

The Prosilio section records the most complete sequence of the Prosilio member (Figure 11). Here it reaches a thickness of some 65 m. The member is also exposed in the top part of the Vegora section and its sediments were encountered in the Torska Eks and Komanos drill cores as
well (Figure 11). Invariably, the Prosilio member displays multi-coloured (red, brown and yellow) conglomerates and arenitic sands, alternating with generally motled green- and blue-coloured pebbly siltstones and clays. Locally, calcite and pedosol-type sediments were observed. As a rule, the conglomerates and sands are erosive at their base and often contain calcareous nodules at the top. Their overall characteristics suggest that the clastics were predominantly derived from nearby-located sources. Although no detailed sedimentological analyses were performed on the sediments of the member, the available data suggest that they were deposited in alluvial and fluvial environments. Pedogenic features point to repeated episodes of non-deposition. The amounts and composition of the terrigenous clastics supplied to the basin system rather strongly varied from one area to another. This may, at least in part, be attributed to local and areal variations in sediment supply and to the composition of basement rocks in the provenance areas of the clastics.

Tomea Eksi member

The sediments of the uppermost, Tomea Eksi member of the Komina Fm, portray the return towards predominantly fine-grained (carbonate, clay and lignite) sedimentation. A gradual decrease of terrigenous clastics and an increasing number of lacustrine mud intercalations mark the transition from the Prosilio into the Tomea Eksi member (Figures 11 and 12). It occurs at different levels below the base of the next-higher Ptolemais Fm. In the Prosilio section, it is found between 50 and 25 below the base of the Ptolemais Fm, in the Tomea Eksi drill core, at ~107 m and in the Komanois drilling at ~55 m (Figure 11). This suggests that the Prosilio to Tomea Eksi transition was not synchronous in the various sub-basins. Extrapolation of sedimentation rates makes it likely that this change took place between about 5.6 and 5.4 Ma ago (Figure 12). Above the transitional interval, the amount of clastic supply drastically decreased and sedimentation became defined by the accumulation of irregular alternations of (motled) lacustrine clays and lacustrine marls, followed by deposition of regular alternations of lacustrine marls, lacustrine clays and thin lignites (Figures 11 and 12). The sediments of the upper part of the member in the Tomea Eksi and Komanois sections are arranged in up to nine sedimentary cycles (Figure 11). The pollen record from the uppermost six cycles (A to F) from the Tomea Eksi section reveals significant changes in vegetation that are primarily caused by fluctuations in precipitation (Kloosterboer-van Hoeve, 2000). The organic-rich facies correspond to relatively dry climatic conditions at times of lake-level lowstand, whereas the clay- and carbonate-rich marls reflect periods of raised lake-levels.

Ptolemais Formation

The transition from the Komina to the Ptolemais Fm, is marked by the onset of the main (Pliocene) lignite deposition phase in the FPS Basin (see this thesis, Chapters 1 and 2). The results of magnetostratigraphic analyses and the correlation of the uppermost Komina and lowermost Ptolemais deposits to the APTS indicate that the transition from predominantly marl towards lignite accumulation was about coeval in the Ptolemais and Servia sub-basins (Figure 11). In fact, the transition corresponds approximately to the base of the Thivera sub-chron, i.e., it can be dated at 5.23 Ma (Figures 11 and 12). Possibly, the onset of lignite formation started slightly later (60 kyr, i.e., three precession cycles) in Prosilio than in Tomea Eksi and Komanois (Figure 11). It should be emphasised that the onset of sedimentation of the Ptolemais Fm, post-dates the Miocene-Pliocene transition, dated at 5.33 Ma ago (Lourens et al., 1996a). The end of sedimentation of the Ptolemais Fm, cannot be ascertained, since a pronounced unconformity,
suggested uplift and erosion marks the contact with the overlying Proastio Fm. (Figure 1). The youngest Ptolemais sediments are dated at 3.94 Ma (Figure 12).

Presently, the distribution of the Ptolemais Fm. is mainly confined to the Ptolemais sub-basin proper, although the lowermost part is present in the Servia sub-basin (section Prosilio, Figure 11). This suggests that the Pliocene lignites may have had a much larger distribution. It may thus be argued that the Ptolemais Fm. sediments have been eroded from the presently more elevated Servia sub-basin, in response to post-Early Pliocene displacements along WSW-ENE trending faults subdividing the once comprehensive basin system into a number of sub-basins (Pavlides and Mountrakis, 1986). However, it is equally possible that the “break-up” of the Late Miocene basin system already started earlier and that sedimentation of the Ptolemais Fm. in the Servia sub-basin already came to a close shortly after the inception of lignite formation in the Pliocene.

The overall sedimentation characteristics of the Ptolemais Fm. portray the accumulation of shallow lacustrine, carbonate-rich marls and humodetrinite-rich lignites (see this thesis, Chapter 1, Mulder et al., 2000). The formation has been subdivided into the (from bottom to top) Kyrio (5.23–4.48 Ma), Theodoxus (4.48–3.6 Ma) and Notio (4.36–3.94 Ma) members, characterised by the predominance of lignite, carbonate and alternating marl–lignite sedimentation, respectively (Figure 12). Smaller-scale marl–lignite cycles were demonstrated to be precession-controlled (22 kyr cycles), in a way that marl deposition would reflect periods of lake-level highstand, whereas lignite formation would represent episodes of lake-level lowstand (see this thesis, Chapters 1 and 2). This conclusion was corroborated by the results of palynological analyses (Kloosterboer-van Hoeve, 2000). Similarly, it may be argued that also the larger-scale predominantly lignite – predominantly marl alternations may portray the effects of larger-scale lake-level fluctuations.

Florina–Ptolemais–Servia composite sequence

In summary, we conclude that the Late Miocene to late Early Pliocene sedimentary history of the FPS Basin includes five major intervals, which can be characterised as follows (Figure 12):

1) Late Miocene, 8.0 – 7.1 ± 0.2 Ma. Deposition of terrigenous–clastic, fining-upwards sequences in predominantly alluvial and fluvialic environments, following the inception of intramontane basin formation (Kommina Fm., Servia member).

2) Late Miocene, 7.1 ± 0.2 – 6.07 ± 0.07 Ma. Deposition of predominantly (diatomaceous) marls in an open lacustrine environment, which alternate with palustrine clays and autochthonous floodplain or back-river forest swamp (xylite-type) lignites (Kommina Fm., Lava member).

3) Late Miocene, 6.07 ± 0.07 – 5.6 / 5.4 Ma. Deposition of terrigenous–clastic sequences in alluvial and fluvialic environments with episodic non-deposition; decrease of coarse–clastic supply in the course of time, followed by a gradual shift towards lacustrine and palustrine conditions (Kommina Fm., Prosiliko member).

4) Late Miocene – earliest Pliocene, 5.6 / 5.4 – 5.23 ± 0.04 Ma. Deposition of alternating marls, thin lignite beds and fine-grained clastics (clays and slts) in lacustrine-palustrine environments with episodic periods of sub-aerial exposure (Kommina Fm., Toma Eksi member).

5) Early Pliocene, 5.23 ± 0.04 – 3.94 Ma. Deposition of lignites and marls in shallow lacustrine environments with larger-scale and smaller-scale lake-level fluctuations (Ptolemais Fm., Kyrio, Theodoxus and Notio members).
Figure 12. Florina-Ptolemais-Servia (FPS) composite section compared to the 400-kyr component of eccentricity (Laskar et al., 1993) and the schematised marine Mediterranean record. Ages of the Ptolemais fm. member boundaries are after this thesis, Chapter 2. Age of the Licafa-Tripoli boundary after Hilgen et al. (1995), the Tripoli-Lower Evaporites and Lower-Upper Evaporites boundary after Krijgsman et al. (1999a) and the Upper Evaporites-Trubi boundary after Lourens et al. (1996a). Note the bundling of dark-coloured clay- or organic-rich marls in the Lava member in the FPS composite and in the Licafa and Trubi fm. in the marine record at times of maxima in the 400-kyr eccentricity. Ages of the reversals in the APTS are after Lourens et al. (1996a, Thvera, Sidufjall, Nunivak, Cochiti), Krijgsman et al. (1999a, top of Subchron C3An.1n), this thesis, Chapter 4 (other three C3An reversals), Hilgen et al. (1995, C3B and C4 reversals). For explanation of the lithology see Figure 2.
Discussion

The sediment successions of each of the major intervals allow us to reconstruct environmental change on different time scales. The events underlying the major changes outlined above and those controlling the shorter-term environmental fluctuations will be discussed and elaborated in terms of tectonics and the response to climatic change associated with orbital forcing in various frequency bands. In addition, we will explore the interrelationships between our data and interpretations pertaining to the evolution of the intramontane FPS Basin and those inferred from the time-equivalent marine record of the Mediterranean.

Small-scale cycles

All members of the Kommina Formation exhibit regular, m-scale lithological variations, expressed as mud–clay alternations in the Lava and Torna Eksı members and as relatively coarse-grained–fine-grained alternations in the Servia and Prosilio members, respectively. Similarly, the successions of the Ptolemais Formation display m-scale rhythmic alternations of lignites and marls.

For the sequences of the Ptolemais Mf, and the sediments of the Lava member of the Kommina Fm, exposed in the Lava lignite quarry, it was demonstrated that these rhythmic alternations reflect the impact of precession-induced fluctuations in regional climate (see this thesis, Chapters 1, 2 and 4). Precession minima were shown to correspond to episodes of increased precipitation, rise of lake-level and deposition of marls, whereas precession maxima were coupled with decreased precipitation, lake-level fall and deposition of lignites (Ptolemais Mf.) or clays (Kommina Mf.). Detailed palynological records of some selected intervals of the Kommina and Ptolemais Mf suggest that higher lake-levels during precession minima were primarily caused by increased winter precipitation, in response to an increased influence of the North Atlantic Circulation on regional Mediterranean climate (Kloosterboer-van Hoeve, 2000).

The close correspondence in nature and thickness between light–dark alternations in the Lava member of the Prosilio section and those in the Lava quarry section make it likely that the former are precession-controlled as well. This conclusion is consistent with the age model for the Prosilio section, based on its magnetostratigraphic calibration with the APTS (Figure 11). The estimated number of rhythmic alternations in the succession covering the Prosilio and Torna Eksı members in the Prosilio section (28-37, see Figure 7) is in fairly good agreement with the number of precession peaks (38) for the corresponding time interval (Figure 11). Therefore, it can be anticipated that these regular m-scale light–dark alternations also reflect precession-induced climate fluctuations. For the Servia member, the presumed impact of orbital forcing is inferred from the correspondence between the thickness of the m-scale alternations (~4 m) and the (extrapolated) sedimentation rate (0.18 m/kyr). Precession-induced sedimentary cyclicity of coarser- and fine-grained clastics in the Servia and Prosilio members can be explained in terms of the effects of cyclic fluctuations in clastic supply in response to climate-induced fluctuations in intensity of (local) run-off towards the basin.

We conclude that precession-induced fluctuations in (wintertime) precipitation primarily defined the m-scale variations in lithology observed in all members of the Late Miocene to Early Pliocene sequence of the intramontane FPS Basin. Such a scenario is in accordance with the dominant role of precession-induced humidity changes on the formation of time-equivalent sedimentary cycles in the marine realm (Rossignol-Strick, 1983; Hilgen, 1987; Ralhing and Hilgen, 1991; Schrenau et al., 1997; Wehausen and Brumsack, 1999; Foucault and Mélières, 2000).
Larger-scale cycles

Eccentricity (100 and 400-kyr cycles) modulates the amplitude of precession and, because of the dominant role of precession with respect to the origin of the m-scale variations discussed above, it may be anticipated that eccentricity-induced climate fluctuations defined the larger-scale lithological alternations observed in the (various members of the) Kommina and Ptolemais Fm.

The influence of precession on the lithology is evident in the Ptolemais Fm., but the expression of the 100-kyr eccentricity not readily apparent, perhaps only in the upper part of the Notio member (see this thesis, Chapter 2). This can be attributed to the weak expression of the 100-kyr eccentricity cycle in the astronomical time series calculated for the interval between 5.3 and 4.4 Ma ago relative to their expression before and after. This expression appears in particular reduced between 4.8 and 4.4 Ma, because this interval marks the eccentricity minimum related to the long-term 2.35 Myr cycle: such minima are characterised by relatively low and constant amplitude variations in precession, and, consequently, by a weak expression of the 100-kyr cycle.

In order to explore a possible 100-kyr eccentricity-induced control on lithological variations in the Kommina Fm., the eccentricity curve is included in Figure 11. Eccentricity maxima in the astronomical curve for the interval between 7.0 and 5.0 Ma ago were numbered I to XXI and their supposedly corresponding expression in [parts of] the stratigraphic columns of the Kommina Fm. were equally numbered. Prominent 100-kyr eccentricity maxima between 7.0 and 6.0 Ma ago are clearly expressed in the Lava section as bundles of darker-coloured clay layers (IV, VII and VIII, Figure 11). The occurrence of similar type of bundles in the Vegora and Proslio sections suggests a similar relation between variations in lithology and the 100-kyr-eccentricity cycle. This holds in particular for the Vegora section, where, given the good magnetic polarity constraints, six successive bundles of darker coloured beds can be correlated with the eccentricity curve. The more prominent bundles VIII and IX correlate well with strong 100-kyr eccentricity maxima, whereas the less prominent bundles VI, VII, X and XI can be linked with weak(er) maxima, which suggests that the influence of the 400-kyr eccentricity cycle is recorded as well (see below). A similar good match is observed between the lower bundles (IV and V) in the Proslio section and the two high-amplitude eccentricity maxima at ~6.6 Ma ago. The darker, clay-rich interval at around 6 m can either be correlated to the eccentricity maximum at 6.3 Ma (IX) or to the maximum at 6.2 (VIII); a conclusive correlation is impeded by the lack of tight time-control for this part of the Proslio section.

The occurrence of 100-kyr cycles in the Proslio and Toma Eksi members of the Kommina Fm. is less apparent, if present at all. Only some questionable matches between eccentricity maxima and lithology have been included in the Proslio section. Perhaps this near-absence of discrete 100-kyr eccentricity-induced variations in lithology in the Proslio member is due to the depositional environment involved, which were possibly less suitable to register more subtle variations in astronomical forcing. The first sight surprising absence of a 100-kyr cyclicity in the upper part of the Toma Eksi member (formed in basically the same type of depositional environment as the Lava member, where 100-kyr cycles are well-developed) can be attributed to the less prominent character of the eccentricity time series in this interval, related to the 400-kyr minimum around 5.3 Ma (Figure 11).

Above we already suggested that prominent bundles of dark-coloured clay-rich beds in the Lava member correspond to extreme 100-kyr maxima, thus reflecting the influence of the 400-kyr eccentricity maximum at 6.66 and 6.25 Ma (Figures 11 and 12). On the other hand, the carbonate-rich intervals in the Ptolemais Fm. around 4.8 and 4.4 Ma (middle part of the Kyrio member and Theodoxus member), correlate with 400-kyr eccentricity minima, whereas intervals
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showing a distinct cyclicity correlate with 400-kyr eccentricity maxima (Figure 12). This scenario also fits with the carbonate-rich interval in the upper part of the Tomia Eksi member, which corresponds to the 400-kyr eccentricity minimum at ~5.25 Ma.

No long, detailed palynological records straddling the 100 and 400-kyr sedimentary cycles in the various members of the Komina and Poolemais Formations are available. This impedes us to interpret these cycles in terms of climate control. However, it may be argued that the climatic effects of eccentricity may have been similar to those related to the precession-induced fluctuations, because eccentricity modulates the precession amplitude. If true, the larger-scale eccentricity related cycles in the Poolemais Fm, and the Lavam member of the Komina Fm, would reflect longer-term fluctuations in lake-level, superimposed upon short-term precession-induced lake-level fluctuations, expressed by the small-scale cycles.

Comparison between the lacustrine Poolemais record and the deep marine Mediterranean record reveals similar sedimentary cycle patterns related to eccentricity. In the Poolemais record, 100 and 400-kyr eccentricity maxima correspond to episodes of well-developed (bundles of) precession-induced lignite–marl cycles (Poolemais Fm, base and top of Kyrio member, and base of the Notio member) or clay–marl cycles (Komina Fm, Lavam member, around 6.65 and 6.25 Ma). Similarly, the Mediterranean marine record also shows prominent (bundles of) precession-induced sedimentary cycles at times of 100 and 400-kyr eccentricity maxima (Hilgen, 1991b; Hilgen et al., 1995; Hilgen and Krijgsman, 1999; Krijgsman et al., 1999a), which are especially apparent in the Liscata and Trubi Formations (Figure 12). Evidently, both the 100 and 400-kyr eccentricity cycle had a pronounced and coeval impact on the development of major lithological features during (at least parts) of the Late Miocene to Early Pliocene evolution of the lacustrine Poolemais and deep marine Mediterranean environments.

**Major non-cyclic changes**

The above scenario of climate-controlled lake-level fluctuations in response to orbital forcing in various frequency bands satisfactorily explains the small- and larger-scale lithological variations within the successive units of (at least parts of) the Komina and Poolemais Formations. However, orbital forcing alone cannot explain the major lithological transitions between most of the members, which portray fundamental (non-cyclic) changes in the depositional environment. Here, we will mainly concentrate on transitions both within as well as at the base and top of the Komina Fm. The intra-Poolemais Fm, member boundaries have already been discussed elsewhere (see this thesis, Chapter 2) and in the previous paragraph on the orbital signature of the 400-kyr eccentricity cycle in the Poolemais Fm.

**Base Servia member, late Tortonian**

The inception of coarse-grained terrigenous clastic sedimentation at the base of the Servia member is dated at around 8 Ma (Figure 12). These sediments are found directly above the pre-Neogene basement and mark the opening of the FPS Basin. The size and nature of these basal sediments testify that tectonic movements were responsible for the opening of the depression (Desprairies and Faugères, 1971). Basin-defining NW–SE directed normal faults provide additional evidence that the opening of the basin was controlled by extensional tectonics (Pavlidis and Mountrakis, 1986, 1987).

The timing of the opening of the FPS Basin coincides with a major paleogeographic reorganisation all along the African–Eurasian convergent plate boundary, from Iberia and Morocco in the west towards the Caucasus and the Arabian platform in the east (Meulenkamp et
al., 2000a, b). In the Aegean, a pronounced episode of accelerated arc migration took place at the same time, resulting in, for instance, the opening of the Southern Aegean back-arc basin and the inception of a discrete phase of E-W extension on Crete (Ten Veen and Postma, 1999a, b; Zacharias, 2001, pers. comm.). As a consequence, the FPS Basin might have originated through NE-SW extension at the rear end of the south-westward migrating fold and thrust belt of the Hellenides. Concomitant phases of tectonic activity included the onset of sedimentation at the Atlantic side (Hodell et al., 1994; Barbieri and Ori, 2000) and within the Riftian Corridor (Krijgsman et al., 1999b), the inception or acceleration of foredeep-deepocenter migration in the Southern Apennines (Van der Meulen et al., 1999), and the opening of the Tyrrhenian back-arc basin (Kastens et al., 1987; Duermeijer et al., 1998).

Servia-Lava member transition, early Messinian

The transition between the Servia and Lava members is characterised by the gradual change from coarse-grained, alluvial clastics to fine-grained, lacustrine marls and palustrine clays and lignites (Figure 12). Downward extrapolation of average sedimentation rates from the Lava quarry section yielded an age of ~7.3 Ma for the base, and ~6.9 Ma for the top of this transitional interval. Three processes might be responsible for the increase of fine-grained sediments at the expense of the coarse-grained clastics: a rise in lake-level, a flattening of reliefs and a more dense forest cover (Desprairies and Faugères, 1971). At present, it is not possible to determine which of these processes was (were) responsible. If we interpret the lithological change to reflect a deepening of the basin, it might again be related to a tectonically controlled increase of subsidence. Although direct tectonic evidence is lacking, this assumption seems to be corroborated by lateral facies and thickness changes observed in the area of the Lava quarry. The latter observation would indicate increased subsidence rates of more centrally located parts of the basin relative to the margins around the transitional interval.

In the marine realm, an abrupt and probably tectonically controlled shallowing of the Riftian Corridor occurred at 7.16 Ma (Krijgsman et al., 1999b), while geochemical and benthic foraminiferal data from the Mediterranean reveal a first major step in isolation of the basin at the same time (Kouwenhoven et al., 1999). Slightly later, an abrupt transition from marls to limestones occurred on central Crete, reflecting a phase of onlap and basin deepening, possibly related to extensional tectonics in the Hellenic arc (Zacharias, 2001, pers. comm.). Such an interpretation is corroborated by a series of volcanic ash beds, the first of which is intercalated directly above this transition. The transition further markedly coincides with the change from a predominantly marly succession with sapropels to diatomites on Sicily dated at 7.0 Ma (base Tripoli Fm., Figure 12). The onset of diatomite formation south of Crete is 200-300 kyr younger and coincides with the transition from Lower to Upper Abad marls in southeast Spain (Krijgsman et al., 1999a) and from marls and sapropels to limestones on Crete (Hilgen et al., 1997b). The latter transition is associated with a marked reduction in sedimentation rate and has been termed the "Early Messinian Starvation Event" based on the inferred decrease in the terrigenous supply (Santarelli et al., 1998).

These observations suggest that both the intramontane domain in northwestern Greece and the marine domain in the Mediterranean were affected by a decrease of terrigenous-clastic supply, possibly in response to a rise of the base-level of erosion, at approximately the same time, around ~7.0 Ma. In the intramontane basin in northwest Greece, the decrease may correspond to a tectonically controlled inception of increased subsidence rates, whereas tectonics may also have played a role at the transition from marls to limestones or diatomites in the marine domain.
Lava-Prosilio member transition, late Messinian

The next higher major facies change took place at ~6.07 Ma and corresponds to the transition from the lacustrine Lava into the alluvial fan/fluvialite Prosilio member (Figure 12). The supply of large amounts of relatively coarse terrigenous-clastic sediments, which marks the onset of the Prosilio member, reflects a pronounced lowering of the base level of erosion. Observations of syn-sedimentary tectonic activity in the Vegora lignite quarry suggest that the increase in differential relief has primarily been controlled by tectonics.

At approximately the same time, the Mediterranean witnessed the onset of evaporite sedimentation in the marine realm (Lower Evaporites, onset of the Messinian salinity crisis proper, Krijgsman et al., 1999a). Tectonics may have (indirectly) contributed to the onset of evaporite deposition by controlling the (final) closure of the Rifian Corridor at that time (Barbieri and Ori, 2000), which led to an increase in the residence time of marine waters in the Mediterranean, thus creating conditions favourable for evaporite formation.

Prosilio-Tomea Eksı member transition, latest Messinian

A gradual change from alluvial coarse-clastics towards shallow lacustrine, fine-grained sediments marks the transition from the Prosilio into the Tomea Eksı member (Figure 12). This facies change occurred between about 5.6 and 5.4 Ma and is similar in nature to the transition from the Servia to the Lava member. Similarly, the Prosilio-Tomea Eksı transition may reflect a rise in lake-level (or basin deepening), a flattening of relief or a more dense vegetation cover. Palynological data from the Kommina Fm. do not provide evidence for the latter, although data from the Prosilio member are lacking (Kloosterboer-van Hoeve, 2000). Although flattening of relief can certainly not be excluded, the transition may reflect a deepening of the basin, either through a tectonically controlled increase in subsidence rate that is not balanced by sedimentation or by a humidity increase.

The transition coincides approximately with the boundary between the Lower and Upper Evaporites in the Caltanissetta basin on Sicily and their correlative lithostratigraphic counterparts in northern Italy (Figure 12). The contact between the two evaporite units is often marked by an angular unconformity which is attributed to tectonics (the so-called intra-Messinian event, Decima and Wezel, 1973; Marabini and Vai, 1989). In addition, the contact shows clear signs of erosion for which the main phase of evaporitic draw-down is held responsible. In northern Italy, the Colombacci Fm., i.e. the equivalent of the Upper Evaporites from Sicily, marks a major palaeoclimate change towards cooler and definitely more humid conditions, which occurred almost concurrent with, but apparently independent from the intra-Messinian compressional tectonic phase (Vai, 1997).

The magnetostratigraphic calibration of the Prosilio composite section to the APTS in combination with the admittedly rough estimate of the number of cycles in the various members (Figures 7 and 11) suggest that the lower half of the Tomea Eksı member corresponds to the Upper Evaporites in the “marine” realm. However, lateral changes and the apparently diachronous nature of the Prosilio-Tomea Eksı transition do not allow to unambiguously recognise the same sequence of events in the parallel sections (Figure 11). Such observations raise considerable doubts about a possible link between changes in the Prosilio composite and concomitant changes in the “marine” record.

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Kommnina-Ptolemais Fm. boundary, latest Messinian-earliest Pliocene

The onset of extensive Pliocene lignite accumulation marks the boundary between the uppermost Tomaia Eks member of the Kommnina Fm. and the basal Kyrio member of the Ptolemais Formation (Figure 12). It corresponds approximately to the base of the Thivera subchron and is dated at ~5.23 Ma. The boundary coincides with a marked climatic change from prominent precession-controlled variations in precipitation and relatively low winter temperatures (top part of the Tomaia Eks member) towards more subtle precession-related variations in humidity and increased winter temperatures (Kyrio member, Kloosterboer-van Hoeve, 2000). Although the transition itself seems to reflect an overall lake-level lowering, periodic climate-controlled desiccations of the lake as recorded in the top part of the Tomaia Eks member are not manifested in the Ptolemais Fm. Deformational features observed in the top part of the Kommnina Fm. might plead in favour of a tectonic control of the Tomaia Eks-Kyrio transition, but unambiguous evidence to corroborate this hypothesis is lacking.

The Miocene/Pliocene boundary as defined in the marine realm marks the Pliocene flooding of the Mediterranean following the Messinian salinity crisis, dated at 5.33 Ma (Lourems et al., 1996a). The abrupt transition marks the renewed accumulation of pelagic deposits in the marine basins probably in response to the opening of the Straits of Gibraltar; the pelagic sediments conformably overlie non-marine fresh to brackish sediments of Lago Mare facies. Remarkably enough, this drastic environmental change has no clear counterpart in the intramontane sequence of northwest Greece with the possible exception of the transition from the lower to the upper part of the Tomaia Eks member in the Prothio composite (see earlier discussion).

The fundamental change in environmental conditions between the Kommnina and Ptolemais Fm. took place around 5.23 Ma ago, thus post-dating the major environmental change at the Miocene/Pliocene boundary in the marine realm with approximately 100 kyr. The transition at 5.23, however, corresponds well in time with the formation of the so-called “marl breccias” on Crete. These marls flow mirror the effect of tectonic instability during the earliest part of the Pliocene (Meulenkamp et al., 1994). The event further coincides with another drastic environmental change in the marine realm, dated at 5.22 Ma; this event is interpreted to reflect a marked change in Mediterranean circulation probably in response to gateway changes at the Mediterranean–Atlantic connection (McKenzie et al., 1990; Spizzaferrì et al., 1998). All of these findings may suggest that the re-establishment of a marine connection at the base of the Pliocene, whatever important impact it had on marine depositional environments in the Mediterranean, was a relatively minor feature with respect to major tectonic and, possibly, climate events before (5.6–5.4 Ma) and after (5.23 Ma) the earliest Pliocene flooding.

Top Ptolemais Fm., middle Pliocene

Greenish clays, sands and conglomerates overlying the Ptolemais Fm. in the Ptolemais lignite open-pit complex portray the effects of the inception of a renewed episode of increased terrigenous-clastic supply (Proastio Fm., Figure 1). Findings of smaller mammal associations from the basal part of these terrigenous clastics, indicative of the uppermost part of MN15 zone (de Brujin, 2000, pers. comm.) allow us to constrain this major change in depositional environment. The dating of the uppermost beds of the Ptolemais Fm. at 3.94 Ma and the correlation of the top of MN15 to about the Early–Middle Pliocene transition at 3.58 Ma (Fejfar et al., 1998) indicate that this major change took place in the late Early Pliocene. Concomitantly, lignite formation came to a close. Numerous large-scale NW-SE and NE-SW striking normal faults cut the Late Miocene to Early Pliocene sediments, thus providing evidence that this change was (at least
Concluding remarks

Summarising, there is a marked similarity in the ages of fundamental changes in depositional environments between the intramontane basin of NW Greece and the marine basins in the Mediterranean. This is especially the case for the late Miocene at times of the Messinian salinity crisis in the marine basins. It should be realised, however, that a coincidence in time does not necessarily imply a causal connection between apparently (and roughly) synchronous transitions in lithology in the continental and marine realm. The apparently stepwise development leading to — and including — the salinity crisis in the marine realm might well be attributed to a complex interplay of the 400-kyr eccentricity cycle, which occurs superimposed on a possibly more gradual tectonically controlled trend (Krijgsman et al., 1999a). It can be questioned however whether a similar scenario is also responsible for the approximately time-equivalent transitions in lithology and, thus, depositional environment in the intramontane FPS Basin. Clearly, more research is necessary before this problem can be solved. The present study, however, shows that continental basins such as the FPS Basin may provide essentially continuous sedimentary records and a high-resolution age model that are a prerequisite to address such fundamental questions.

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Conclusions and perspectives

The data and interpretations presented in this thesis are the outcome of research carried out as part of the multi-disciplinary CoMCoM programme (Continental-marine correlations in the Mediterranean). This programme aims in particular at the reconstruction of the concurrent influence of – astronomically induced – cyclic changes of sedimentation in Neogene terrestrial and marine depositional environments. The primary objective of the thesis was to construct a detailed cyclostratigraphic framework for the lacustrine sequences exposed in the intramontane Florina-Ptolemais-Servia basin in northwestern Greece. This framework should then serve as the basis for correlation with previously studied marine sections and with time series of orbital change. An additional objective was to establish depositional models for the various (cyclic) sedimentary sequences and to correlate major facies changes with those inferred from coeval marine successions. Two parallel Utrecht University studies in the CoMCoM programme focused on magnetostratigraphic and palynological analyses, respectively, which were partly based on the same sections (Ph.D. theses Van Vugt and Kloosterboer-van Hoeve).

The results of our studies demonstrate that the basin fill of the Florina-Ptolemais-Servia basin indeed offers unique possibilities for a detailed cyclostratigraphic study. Integrated stratigraphic analyses of the continuous succession covering the interval from 8 to 4 Ma ago unambiguously demonstrate the uninterrupted influence of dominantly precession-induced variations in regional climate on sedimentation in lacustrine depositional environments. Such variations are expressed throughout the succession as cyclic changes in lithology, most obviously so as lignite–marl and clay–marl alternations. Our integrated stratigraphic study has allowed to establish an astronomically calibrated (polarity) time scale (A(P)TS) for the Late Miocene to Early Pliocene terrestrial sedimentary record, and thus to correlate the lacustrine sedimentary cycles on a “bed-to-bed” scale to previously studied cycles in the marine realm (see also Ph.D. thesis Van Vugt). A “perfect” match was not obtained for all parts of the lacustrine succession. This may illustrate that the signal to noise ratio in lacustrine records is generally lower than in (deep) marine settings because of the influence of local variations in sedimentary regimes that tend to obscure or even obliterate the externally forced variations.

The lacustrine sedimentary cycles can be attributed to precession-controlled lake-level fluctuations in such a way that organic-rich (lignite) and clayey sediments were deposited at times of precession maxima, relatively dry climate conditions and lake-level lowstands, whereas marls were deposited during precession minima, relatively humid climate conditions and lake-level highstands. Opposite phase relationships between the organic-rich cycle component and precession are inferred for marl-clay and clay-sapropel cycles in deep marine settings in the Mediterranean, thus portraying the coeval, albeit different impact of precession-induced, climate-controlled forcing on lacustrine and deep-marine sedimentation.

Our results allow to conclude that the shallow lacustrine successions in the Florina-Ptolemais-Servia basin record astronomically induced variations in (regional) climate. The results of palynological studies (Ph.D. thesis Kloosterboer-van Hoeve) allowed to interpret the sedimentary cycles in terms of changes in orographic winter precipitation. Reduced (winter) precipitation corresponds to the clay or lignite phase of the cycles and, thus, to lake level lowstands. A quantification of the climate fluctuations in terms of the precipitation/evaporation balance and (possible) variations in temperature would be a logical next step. Quantitative paleoclimate data can in principle be obtained via transfer functions, which have already been successfully applied to
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Pleistocene pollen records. Potential other methods to extract more quantitative information include (bulk or compound specific) stable isotope analysis of carbonate or organic matter. Another interesting and partly related topic for future studies is the possible connection between the cyclic climate oscillations as recorded in the FIS basin and variations in the North Atlantic Oscillation (NAO; Ph.D. thesis Kloosterboer-van Hoeve). This question can also be formulated as to how precession-induced climate forcing will affect mode and intensity of NAO.

Clearly, higher frequency variations in lithology occur superimposed on the dominantly precession-controlled sedimentary cycles in Early Pliocene successions of the Florina-Peloponnes-Servia basin. Our findings on the presence of such climate-controlled variations in lithology in the sub-Milankovitch frequency band of the spectrum demonstrate that millennial-scale climate variability played already a prominent role prior to the onset of major Northern Hemisphere glaciation. Comparable millennial-scale climate variations are well-known from the late Pleistocene and are at times attributed to the effects of internal ice-sheet dynamics. However, such a mechanism does not satisfactorily explain the millennial-scale cycles in the Lower Pliocene of northwestern Greece. Consequently, we speculate that the same may be true for the Pleistocene cycles, although an unambiguous alternative explanation is still lacking. The concentration of spectral peaks in preferred frequency bands similar to those of harmonics of precession (and obliquity) may argue for an external forcing related to the primary orbital cycles. Clearly, such a preference should be checked both in other intervals of the succession as well as in time-equivalent marine records from the Mediterranean, while extra-Mediterranean regions should be studied to demonstrate the potentially global significance. *In situ* measurements should be carried out to test the alternative scenario that these sub-Milankovitch variations are related to solar (output) forcing.

Late Miocene to Early Pliocene lacustrine sedimentation in northwestern Greece was also influenced by long-term climate fluctuations probably related to the 100 and 400 kyr eccentricity cycles and, to a lesser extent, to the 40 kyr obliquity cycle. For instance, the observed larger-scale changes in the overall composition of the sediment successions, such as those pertaining to the shifts from predominantly marly to predominantly lignite sedimentation (and vice-versa), may, at least in part, have been controlled by the 400 kyr eccentricity cycle.

Correlation with the marine record of the Mediterranean shows that the major changes in lithology in the intramontane basin of northwestern Greece were approximately coeval with the sequence of fundamental changes in depositional environments described from the Upper Miocene to Lower Pliocene of Sicily, including those related to the Messinian salinity crisis. This suggests a common cause of such changes, contemporaneously affecting lacustrine and deep marine environments. It was beyond the scope of this thesis to unravel the complex interrelationships between the impact of tectonics, climate and sea level for the time-span considered. However, our high-resolution data and correlations provide an excellent starting point for future, integrated studies on the detailed reconstruction of the coeval evolution of terrestrial and marine environments prior to, during and after the Messinian crisis.

The age model we established has been corroborated by evidence provided by *40Ar/39Ar* datings of intercalated volcanic ash beds. The radiometric datings provided independent evidence for the orbital, precession-induced forcing of marl-lignite cycles. Surprisingly, however, they also revealed a consistent discrepancy of about 200 kyr between the astronomical and *40Ar/39Ar* dating results. This discrepancy cannot be explained satisfactorily as yet but ongoing research directed at the intercalibration of radiometric and astronomical time suggests that it is
partly related to hitherto existing uncertainties in accurately determining parameters critical for calculating radiometric ages (Ph.D thesis K. Kuiper).

Finally, numerous mammal-bearing fossil sites have been detected and studied in the cyclically bedded and astronomically dated succession of the basin. Our high-resolution age model allows to accurately date the entrance of Promimowys (5.25 Ma) and the replacement of Promimowys by Minowys (4.90 Ma), with a much higher precision than was previously possible. Such an accurate dating is crucial for studies of migration patterns of mammals and of the (evolutionary) mammal community response to climate change.
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References


Arisele, 350 BC. Meteorologica, Book 1.


References


References


Fisher, D.A., 1982. Carbon-14 production compared to oxygen isotope records from Camp Century, Greenland and Devon Island, Canada. Climate change 4, 419-426.


References


Krijgsman, W. et al., 1999b. Late Neogene evolution of the Taza-Guercif Basin (Rifian Corridor, Morocco) and implications for the Messinian salinity crisis. Marine Geology 153, 147-160.
References


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Meulenkamp, J.E., Sissingh, W. and others, a., 2000b. Late Tortonian (map 22). In: J. Dercourt, M. Gacani and c. al. (Eds.), *Atlas Peri-Tethys, Palaeogeographical maps. CCGM/CGMW.* Paris.


References


Pestiaux, P., Mersch, I.v.d., Berger, A. and Duplessy, J.C., 1988. Paleoclimatic variability at frequencies ranging from 1 cycle per 10,000 years to 1 cycle per 1000 years: evidence for nonlinear behaviour of the climate system. Climate change 12, 9-37.


Prell, W.L. et al., 1986. Graphical correlation of oxygen isotope stratigraphy application to the late Quaternary. Palaeoceanography 1, 137-162.


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Sinds mensenheugenis realiseert men zich dat regelmatige afwisselingen in sedimentaire milieus op aarde samen kunnen hangen met variaties in het klimaat, en dat deze klimaatsvariaties weer beïnvloed worden door veranderingen in de hoeveelheid inkomende zonnestraling. Aristoteles suggereerde in het boek *Meterologika* reeds dat sedimentatieve patronen, zoals het ontstaan van delta’s en overstromingen van land een soort cycliteit lieten zien. Hij meende dat deze cycli niet ontstonden door processen gestuurd vanuit het aardse systeem maar door toename en afname van de hoeveelheid zonnestraling die de aarde bereikt. Aristoteles ging er nog vanuit dat de zon rondom de aarde draait en bij koppelde de variaties in de hoeveelheid zonnestraling aan variaties van de baan van de zon rondom de aarde. Het werk van koning Ptolemaeus, later uitgebreid door onder andere Kepler en Newton, stelde onomstotelijk vast dat de aarde rondom de zon draait en niet andersom en dat deze beweging een zeer regelmatig terugkerend patroon laat zien. Meer dan een eeuw geleden relateerde Gilbert deze regelmatige bewegingen aan het voorkomen van kalk-mergel cycli in het late Krijt. Uitgaande van deze vooronderstelling berekende hij de duur van een deel van het late Krijt, welke later in goede overeenstemming bleek te zijn met moderne tijdsschalen. Weer dertig jaar later behandelde Bradley de invloed van de baan van de aarde rondom de zon op het voorkomen van sedimentaire cycli in menge-dolomitie afzettingen. Deze wetenschappers waren hun tijd ver vooruit. De Joegoslavische geofysisicus en astronoom Milutin Milankovitch zorgde rond 1940 met zijn ideeën over de mogelijke relatie tussen de astronomische parameters en het klimaat op aarde voor een doorbraak. Na jarenlange rekenwerk publiceerde hij een curve die de hoeveelheid zonnestraling op een bepaalde breedtegraad door de tijd heen liet zien. Deze curve bleek verraadend goed overeen te komen met het optreden van ijstijden gedurende ruwweg de laatste miljoen jaar.

De Milankovitch of astronomische theorie van klimaatsveranderingen geeft een verklaring voor het optreden van de seizoenen. De beweging van de aarde rondom de zon en rondom zijn als worden beïnvloed door de aantrekkingskracht van de maan, de zon, en de andere planeten. Deze bewegingen zijn niet constant maar variëren met de tijd. Drie perioden zijn hierbij van betekenis. Ten eerste kan de baan van de aarde meer ellipsvormig worden en dan terugkeren tot hij bijna cirkelvormig is. Een volledige cyclus van dit verschijnsel duurt ongeveer 100,000 jaar. Zowel de duur als de mate van de uitbreiding variëren. Bij dit laatste verschijnsel hoort een cyclus van 400,000 jaar. In extreme gevallen kan het zonlicht dat de aarde bereikt in de loop kan een jaar variëren met 30%. Op het ogenblik wijk de baan niet sterk af en is deze bijna cirkelvormig. Ten tweede varieert het moment in het jaar waarop de afstand tussen de aarde en de zon minimaal is. Hoewel het nu op het zuidelijk halfrond zomer is als de aarde het dichtst bij de zon is, was dit 10,000 jaar geleden op het noordelijk halfrond het geval en zal dat over 10,000 jaar weer zo zijn. De oorzaak is, dat de aarde de beweging maakt van een tol die bijna uitgedraaid is. Terwijl de tol nog een behoorlijke draaiwijdte heeft, maakt de as een trage beweging, waarbij de top langs een cirkel beweegt, terwijl de punt op zijn plaats blijft. De rotatie-as van de aarde maakt deze beweging ook, waarbij het middelpunt van de aarde stilstaat en de twee polen in ongeveer 21,000 jaar een cirkel beschrijven. Astronomen noemen dit gedrag de precesie. Ten derde schommelt de aarde als een schip heen en weer, waarbij de aardas helt onder een hoek die varieert tussen de 22 (meer rechtop) en 25 (meer hellend) graden. Dit is de variatie in de helling van de aardas (obliquiteit) ten opzichte van de ecliptica. Een volledige beweging tussen beide extremen neemt 41,000 jaar in beslag. Hoe groter de helling, hoe sterker het verschil tussen...
winter en zomer. Gedurende de laatste tienduizend jaar bevond de aarde zich in een opwaartse beweging, wat betekent (als dit de enige factor zou zijn) dat de zomers steeds minder mooi worden, met andere woorden korter.

Astronomisch gecoreerde klimaatsveranderingen worden vastgelegd in sedimentaire gesteenten als variatie in samenstelling, chemische karakteristieken en fossiel inhoud. Aardwetenschappers kunnen deze variaties in de sedimenten bestuderen en gebruiken om het klimaat in het verleden te reconstrueren. In navolging van Milankovitch hebben astronomen zeer nauwkeurige de variaties in procesie, obliquiteit en excentriciteit voor miljoenen jaren terug in de tijd berekend. Uitgaande van de relatie tussen deze astronomische curves en de sedimenten is het dus mogelijk om zeer nauwkeurig oude sedimenten te dateren door de patronen opgeslagen in deze gesteenten te vergelijken met de berekende astronomische curves. Deze zogenaamde astronomische 'tuning' van de sedimentaire opeenvolging resulteerde in tijdschalen welke totaal onafhankelijk zijn van traditionele tijdschalen, gebaseerd op radioactief verval. Gedurende de laatste decennia kwam er een grote doorbraak in het opstellen van dit soort astronomische tijdschalen. In eerste instantie richtte het onderzoek zich vooral op de mogelijke relatie van/tussen de astronomische forcering en het optreden van ijstijden in het jongste geologische verleden (de afgelopen ca. 2,5 miljoen jaar). Hierna heeft het onderzoek zich verder terug in de tijd uitgebreid, aanvankelijk tot de basis van het Plioceen (ca. 5 miljoen jaar terug) en later ook tot de basis van het Miocceen (ca. 23 miljoen jaar terug). Men maakte hierbij gebruik van paleoklimatologische gegevens uit zeer diepe boringen in de Stille en Noord Atlantische Oceaan en van sedimentaire patronen in opeenvolgingen die te zien waren op het land in het Middellandse Zee gebied (Figuur 1).

Voor studies gericht op de reconstructie van het paleoklimaat en paleomilieu is de toepassing van de astronomische tijdschaal fundamenteel. Tot nu toe is deze tijdschaal volledig gebaseerd op diepmariene afzettingen. Het is echter evident dat, indien we ons begrip van de processen die een rol spelen bij klimaatsveranderingen willen vergroten, het hele scala aan gegevens gebruikt moeten worden (bijvoorbeeld de gegevens van de diepsee, van het land als ook van de ijskappen). Sterker nog, het land lijkt de voor de hand liggende plek om de Milankovitch cycli en hun relatie tot klimaatvariaties te bestuderen. Want door het ontbreken van oceanografische processen, die gekenmerkt zijn door gecompliceerde, niet lineaire respons mechanismen, kan hier een meer directe registratie van astronomisch gestuurde veranderingen worden verwacht. Mogelijke en serieuze nadenken van het gebruik van continentale successies zijn echter vaak het ontbreken van een directe en voldoende nauwkeurige tijdscoure en de aanwezigheid van hiaten. Niettemin hebben een aantal klassieke studies de aanwezigheid van Milankovitch cycli in continentale successies reeds aangetoond. Deze voorbeelden dateren evenwel uit het verre verleden. Astronomische forcering in continentale sedimenten uit het Pleistoceen zijn de laatste jaren bestudeerd en komen over het algemeen vrij goed overeen met de diepsee gegevens op de Milankovitch tijdschaal. In de deze Pleistoceene sedimenten opgeslagen klimaatsveranderingen worden echter beïnvloed door gecompliceerde (non-lineaire) respons mechanismen die samenhangen met de aanwezigheid van grote ijskappen gedurende die tijd. Om meer inzicht te krijgen in de relatie tussen wisselende externe factoren en het klimaat op aarde kunnen we kijken naar de periode van vóór 2.75 miljoen jaar geleden, toen er zich nog geen omvangrijke ijskap bevond op het noordelijke halfrond. Als we kunnen aantonen dat de processen die zich in die tijd afspeelden overeenkomen met meer recente processen, dan kunnen we de rol van de ijskap en de invloed ervan op het klimaat beter beoordelen. Diep mariene sedimenten van voor het ontstaan van deze ijskappen zijn bestudeerd in het Middellandse Zee gebied en zeer nauwkeurig gedateerd
door middel van astronomische ‘tuning’ van de cyclische veranderingen in deze sedimenten. Deze sedimenten hebben nu reeds belangrijke nieuwe inzichten verschaf in de rol van de verschillende processen achter klimaatveranderingen op Milankovitch schaal. Waar de zee al tal van geheimen heeft prijsgeslagen in de wetenschap tot nu toe de gegevens over sedimenten van dezelfde ouderdom op het land. Een multidisciplinair onderzoeksprogramma, uitgevoerd aan de Universiteit Utrecht, heeft als doel zulke informatie te genereren door middel van hoge resolutie studies aan laat Neogene continentale afzettingen in het gebied rondom de Middellandse Zee.

Figuur 1: Milankovitch cycli in het marien bereik: Capo Bianco, Sicilië

In dit proefschrift worden de resultaten gepresenteerd van een studie in het kader van dit programma betreffende de laat Neogene bekkeninvulling van het intramontane Florina- Ptolemais-Servia (FPS) bekken. Het bekken is geïsoleerd in het noordelijk grensgebied van de Middellandse Zee in noordwest Griekenland en biedt een uitstekend geologisch archief voor informatie over het paleoklimaat en het paleomilieu. Het FPS bekken werd om verschillende redenen als studiegebied geselecteerd. Allereerst zijn tijdsequivalente afzettingen intensief bestudeerd in het mariene Middellandse Zee gebied. Deze sedimenten dienden als basis voor de astronomische tijdschaal. Ze blijken zeer geschikt om astronomisch geïncludeerde variaties in het regionale klimaat te reconstrueren, vanwege de breedtegraad en semi-ingesloten bekken-configuratie. Evenzo is het aannemelijk dat de breedtegraad en bekkenconfiguratie van het
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intramontane FPS bekken, een gesloten bekken op ca. 500 m hoogte en gelegen door bergen van ca. 2000 m hoogte, het registreren mogelijk maakt van subtiele variaties in regionaal klimaat. Eerder werk in het gebied toonde de mogelijkheden van palynologische studies aan om dit soort klimaatvariaties in kaart te brengen. Tevens hebben vondsten van kleine zoogdieren en fossiele bladeren een ruwe ouderdomsbeperking opgeleverd. Verder zorgen een groot aantal bruinkool dagbouw mijnen, verspreid over het bekken, voor uitzonderlijk grote, onverwachte en toegenkelijke ontwikkelingen (Figuur 2). Hierdoor is het mogelijk om de laterale continuiteit en verscheidenheid van de sedimenten te bestuderen. De sedimentaire invulling van het bekken wordt gekarakteriseerd door de aanwezigheid van regelmatige afwisselingen in kleur op verschillende schalen die mogelijk een uiting zijn van astronominische gestuurde klimaatscyci. Tenslotte hebben pilot-studies de geschiktheid van de sedimenten voor magnetostratigrafisch onderzoek aangetoond. Ook maken ingeslagen vulkanische afdalingen het mogelijk om het gesteente onafhankelijk te dateren met behulp van de "Ar/Ar"-methode.

Figuur 2: Milankovitch cycli in dagbouw mijnen in het Florina-Ptolemais-Servia bekken.

Ons onderzoek richtte zich in eerste instantie op het centrale deel van het FPS bekken, waar een sequentie van afwisselend ligniet (= bruinkool) en lacustriene mergel ontsloten is in een aantal grote dagbouw mijnen. In de eerste twee hoofdstukken bestuderen wij de rol van astronominische forcering in drie van deze dagbouw mijnen. In hoofdstuk 1 worden de sedimentologie en de cyclostatigrafie van drie parallelle secties bestudeerd. Wij definiëren drie sediment typen: ligniet, grijs mergel en beige mergel, die samen twee typen sedimentaire cycli vormen: ligniet-grijze mergel en ligniet-beige mergel cycli. De lignieten zijn gevormd in een rietmoeras; de grijze mergels (een mengsel van kalk en organisch materiaal) werden afgezet in een ondiep meer met
grote hoeveelheid plantengroei; de beige mergels (bijna volledig bestaande uit kalk) representeren meer open lacustriene condities. Wij combineren de consolideerde cyclus patronen van de drie parallel secties in een cyclostratigrafische composiet sectie. De correlaatte posities van een groot aantal vulkanische aslagen in de secties ondersteunen onze cyclostratigrafische correlaties en tonen aan dat de enkele meters dikke sedimentaire cyci het resultaat zijn van externe (klimaats-) variaties en niet van laterale facies verschuivingen.

De "Ar"/Ar ouderdommen van negen vulkanische aslagen welke ook gepresenteerd worden in hoofdstuk 1, komen in het algemeen goed overeen met de stratigrafische positie. Zij laten ook zien dat de bestudeerde secties het tijdinterval beslaan tussen ca. 5 en 4 miljoen jaar geleden. Met behulp van deze ouderdomsbepalingen kan de gemiddelde duur van een sedimentaire cyclus worden uitgereken. Het blijkt dat deze duur precies overeenkomt met die van de precies beweging (21.000 jaar). Deze dateringen hebben voor het eerst, totaal onafhankelijk van andere daterings- of tuningmethoden, de astronomische theorie van de klimaatveranderingen bevestigd. Opmerkelijk genoeg laten de "Ar"/Ar ouderdomslateringen een constant ouderdomverschil zien van ca. 200.000 jaar met de astronomische dateringen van dezelfde aslagen. Dit verschil wordt in detail behandeld in hoofdstuk 1, maar blijft moeilijk te verklaren.

In hoofdstuk 2 wordt de magnetostratigrafie behandeld van de secties waarvan in hoofdstuk 1 de cyclostratigrafie is besproken. De correlatie van de magnetische polariteitspatronen in de composiet sectie van Ptolemais met de astronomische (polariteit-) tijdschaal suggereert - zoals ook volgt uit hoofdstuk 1 - dat de sedimentaire cyci gecontroleerd werden door precies gestuurde variaties in het klimaat. Wij hebben de sedimentaire cyci in de composiet sectie gecorreleerd met de insolatie (insolation curve) die voor die tijd berekend is, en naar de mariene referentie sectie: de Rowello sectie op Sicilië. Wij bespreken twee verschillende fase relaties tussen de sedimentaire cyclusiteit en insolatie. Van de twee modellen geeft een veel hogere overeenkomst. Hieruit volgt dat ligtiet ontstaan is tijdens periodes van minimale zomerinsulatie op het noordelijk halfrond, en dat mergel tijdens maximale insulatie. Dit impliceert dat de neerslag in Griekenland tijdens het vroeg Plioceen toenam gedurende periodes met warme zomers. Dit bevestigt de resultaten van eerdere studies in het Middellandse Zee gebied.

In hoofdstuk 3 wordt geanalyseerd in hoeverre klimaatvariabelen op tijdschalen van enkele duizenden jaren (aangenomen sub-Milankovitch variabiliteit) ook aanwezig zijn in Ptolemais. Daarvoor hebben wij een interval bestudeerd van vijf precies gestuurde sedimentaire cyci in negen parallelle secties. Hoge resolutie kleurenanalyse zijn gebruikt om deze variabiliteit te kwantificeren en om de laterale continuïteit ervan te bepalen. Een groot deel van de variabiliteit kan vervolgens worden gespecificeerd tussen de verschillende parallel secties. Hieruit blijkt dat deze veranderingen grootschalige variaties in milieucondities representeren, gerelateerd aan (regionale) klimaatvariabiliteit. De ingekleurde vulkanische aslagen tonen aan dat deze variaties synchroon verlopen. Spectraal analyse aan de kleurenspectrum laten een gooi delijke concentratie van variabiliteit zien met perioden van ca. 11, 5,5 en 2 duizend jaar. Het vóórkomen van klimaatvariatie met perioden van enkele duizenden jaren voordoet er grote ijskappen ontstonden op het noordelijk halfrond impliciteert dat deze variaties niet alleen gestuurd kunnen zijn door interne ijskapp dynamiek. Mogelijke mechanismen die deze veranderingen mede kunnen verklaren zijn harmonische (boven- of combinatie) tonen van de belangrijkste Milankovitch cyci, variaties in de intensiteit van de zon, of periodieke bewegingen in het aarde–maan systeem.

Het verband tussen astronomische forcering en sedimentatie is verder onderzocht in de meetafzettingen in het zuidelijke gedeelte van het FPS bekken (hoofdstuk 4). Een kleine dagbouwmijn in de buurt van het dorpje Lava geeft toegang tot een opeenvolging van lacustriene
Samenvatting

mergels, regelmatig afwisseld met donkere kleiige afzettingen. Wij hebben verschillende
methodes gebruikt om deze subtiele lithologische veranderingen te kwantificeren. De sectie geeft
een goed paleomagnetisch signaal en in combinatie met kleine zoogdieren kan een zeer
nauwkeurige ouderdomsbepaling (6.9–6.2 miljoen jaar oud) voor de sectie worden vastgesteld.
Spectraalanalyse van de in het gesteente opgeslagen gammastraling toont aan dat de lithologische
cycli dezelfde periode hebben als de precessie, en dat ook obliquiteit invloed heeft op de
afzettingen. Palynologische gegevens suggereren dat de donkergelkleurde lagen periodes
representeren met verlaagde humiditeit. De correlatie van de sedimentaire cycli met de
instralingcurve resulteert in een zeer nauwkeurige ouderdomsbepaling voor de magnetische
polarteits omkeringen.

In hoofdstuk 5 presenteren wij de resultaten van een studie van drie secties en twee
boorkernen in het FPS bekken, die tot doel heeft om het ontbrekende deel in zijd tussen de
erder beziene de Polemais en Lava opeenvolgingen te dichten. Verder geeft een derde boring
ons de mogelijkheid om de Lava opeenvolging naar beneden toe uit te breiden tot de basis van de
sedimentaire opeenvolging in het bekken. Samen met de eerder bestudeerde secties resulteren de
additionele gegevens in een continue sedimentaire opeenvolging die de geschiedenis van het FPS
bekken tussen 8 en 4 miljoen jaar geleden documenteert. Wij concluderen dat precessie gestuurde
varieties in het (regionale) klimaat verantwoordelijk zijn geweest voor de varieties in het gesteente
op meterschaal. De 100.000 en 400.000 jaar excentriciteits cycli hebben een duidelijke invloed
gehad op het ontstaan van de grotere schaal afwisselingen in het gesteente in (een deel van) de
opeenvolging. Wij zien een duidelijke overeenkomst tussen de ouderdommen van fundamentele
veranderingen in het lacustrie afzettingsmilieu tussen het Florina-Poolemais-Servia bekken en
de mariene afzettingen in het Middellandse Zee gebied. Hieruit kunnen wij afleiden dat deze
veranderingen mogelijk een gelijke, mogelijke tektonische oorzaak hebben gehad.

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ΕΛΛΗΝΙΚΗ ΠΕΡΙΛΗΨΗ

Τροχιακές Παράμετροι σε λημναία ιζήματα

Η Λεκάνη του Αυ. Νεογενούς Φλώρινα-Πτολεμαίς-Σέρβια (ΒΔ. Ελλάς)

Οι κινήσεις της Γης γύρω από τον άξονα της και γύρω από τον ήλιο δεν είναι σταθερές. Περιοδικές μεταβολές προέρχονταν κλιματικές αλλαγές στην Γη, όπως οι παγετώδεις εποχές. Τέτοιοι είδους αλλαγές αναγνωρίζονται στη γεωλογία, ιδιαίτερα σε ιζήματα που έχουν αποτεθεί στον βυθό της θάλασσας, μίας λίμνης ή ενός βάλτου. Μελετώντας τέτοιο είδους ιζήματα, οι γεωλόγοι συλλέγουν πληροφορίες για τις κλιματικές συνθήκες πριν από εκατομμύρια χρόνια. Οι επιστήμονες, βασισμένοι σε αυτές τις πληροφορίες, κάνουν καλύτερες προβλέψεις για τις μελλοντικές κλιματικές αλλαγές. Επιπλέον, η ειδική περιοδικότητα των κλιματικών αλλαγών προφέρει την δυνατότητα της απόλυτης χρονολόγησης των ιζηματογενών στρομάτων.

Οι πιο σημαντικές μεταβολές της τροχιάς της Γης γύρω από τον Ήλιο είναι η εκκεντρότητα και τη μετάπτωση των ισημεριών. Η εκκεντρότητα μετράει το πόσο επιμήκης είναι η τροχιά, π.χ. εάν είναι κυκλική ή ελλειψοειδής. Η εκκεντρότητα αλλάζει περιοδικά και ένας πλήρης κύκλος διαρκεί 100000 χρόνια. Επί αυτού βρίσκεται ένας άλλος κύκλος διάρκειας 400000 χρόνων. Η μετάπτωση των ισημερινών περιγράφει ένα πλήρη κύκλο ανά 210000 χρόνια. Οι παράμετροι αυτές άραμε όταν γνωστές από τους αρχαίους Έλληνες και περιλαμβάνονται στο γεωκαινηρό σχέδιο του σύμπαντος από τον Κλαύδιο Πτολεμαίο.

Οι αστρονομοικοί κύκλοι προκαλούν περιοδικές μεταβολές στην ποσότητα της ηλιακής θερμότητας που φθάνει την επιφάνεια της Γης σε ένα ορισμένο γεωγραφικό πλάτος και κατά συνέπεια στο κλίμα. Οι παγετώδεις εποχές π.χ. είχαν σαν απίστευτα μεγάλες περιόδους με κρύα καλοκαιριά στο Β. Ημισφαίριο, όπου και το χιόνι του κειμόνα δεν έλιωνε, προκαλούντας μεγάλες αποθέσεις πάγου. Οι γεωλόγοι, αναγνωρίζουν τις παγετώδεις εποχές σαν ικές ξυσίματα στα πετρώματα ή σαν μοραίες. Λιγότερο έντονες κλιματικές αλλαγές έχουν επίσης αφησεί τα ικές τους στην γεωλογία και κυρίως στα ιζηματογενή στρώματα. Ιζήματα που σκηνοτοπήθηκαν πριν από 5 εκ. χρόνια βρίσκονται και στην περιοχή της Μεσογείου. Μεγάλο μέρος αυτών των ιζημάτων αποτελούν μεν τότε στον βυθό της θάλασσας αλλά σήμερα βρίσκονται εκτεθειμένα στην ξηραία και είναι εύκολα να μελετηθούν. Μία ομαλή ακολουθία ακουράκων στρωμάτων σε αυτά τα ιζήματα συμπίπτει με τις περιοδικές τροχιακές μεταβολές της Γης. Είναι φανερό ότι η
σύσταση των ιζημάτων επηρεάσθηκε από το κλίμα που άλλαξε από ασφυκτικές άτιμες. Η θάλασσα λοιπόν είναι ένα είδος φωτογραφικής μηχανής με τα ιζημάτα σαν το φιλμ που αποτύπωσε τις κλιματικές αλλαγές. Θέλαντος το φιλμ ανά εικόνα, δηλαδή μελετάντας τα ιζημάτα ανά στρώμα, αναπαριστούμε τις κλιματικές αλλαγές των τελευταίων 5 εκ. χρόνων.

Οι κλιματικές αλλαγές είναι πιο έντονες στην ήπειρο από ότι στην θάλασσα. Είναι σαν να η φωτογραφική μηχανή να έχει ένα φίλμ που επιτρέπει μόνο σε ορισμένες εικόνες να περάσουν. Αν θέλουμε να δούμε την μεγάλη εικόνα πρέπει να δούμε φίλμ από άλλες μηχανές με άλλα φίλμα. Έτσι μελετάμε τα ιζημάτα που σχηματίσθηκαν στην ήπειρο, σε λίμνη ή σε βάλτο, ώστε να συμπληρώσουμε την κλιματική εικόνα. Η διατριβή αυτή παρουσιάζει τα αποτελέσματα της μελέτης των ιζημάτων του Αν. Νεογενώς της Λεκάνης Φλώρινα-Πολεμιαίας-Σέρβια.

Η εργασία αρχίζει στο κεντρικό τμήμα της λεκάνης, όπου εμφανίζονται περίπου 100 μ. εναλλασσόμενα στρώματα λιγνίτου και λιμνιακός μάργαρος, σε ορυχεία λιγνίτου.

Τα πρώτα δύο κεφάλαια μελετούν τον ρόλο της τροχιακής επίδρασης σε τρία από τα ορυχεία. Το Κεφάλαιο 1 αναφέρεται στην ιζηματολογία και την κυκλοσφυγμομεταγραφή τριών παράλληλων τομών στα ορυχεία Βόρειο, Κούμας και Τσιέα 6. Δίδονται τα αποτελέσματα χρονολόγησης με 40Arg/38Arg σε εννέα ενιαία στρώματα πραιστικής τέφρας. Επίσης γίνεται η προσδιορισμός τριών τύπων ιζημάτων: λιγνίτης, σκουρά μάργαρα και ανοικτή μάργα, που βρίσκονται σε δύο τύπους ιζηματογενών κύκλων: λιγνίτης-σκουρά μάργα και λιγνίτης-ανοικτή μάργα.

Ο λιγνίτης σχηματίζεται σε περιβάλλον βάλτου, η σκουρά μάργα (μήκια ανθρακικών και οργανικού υλικού) σχηματίζεται σε αβαθή λίμνη με μεγάλη βλάστηση και η ανοικτή μάργα (κυρίως μόνο ανθρακικά) συνθέτει ανοικτή λίμνη. Συνθέτουμε τους σταθερούς κύκλους των τριών παραλλήλων τομών σε μια κυκλοσφυγμομεταγραφική τομή. Η σύμφωνα θέση των στρώματων πραιστικής τέφρας επιβεβαιώνει την κυκλοσφυγμομεταγραφική συσχέτιση και δείχνει ότι η ιζηματογενής κυκλικότητα οφείλεται σε εξωτερικούς παράγοντες και όχι σε πλευρική αλλαγή φάσεων.

Τα αποτελέσματα της χρονολόγησης με 40Arg/38Arg της πραιστικής τέφρας παρουσιάζονται επίσης στο κεφάλαιο 1. Οι χρονολογήσεις με 40Arg/38Arg συμπίπτουν με την στρωματογραφική τάξη και δείχνουν ότι οι τομές υπό μελέτη καλύπτουν το διάστημα μεταξύ 5 και 4 κ.χ.ρόνων. Επίσης δείχνουν ότι η μέση διάρκεια ιζηματογενούς κύκλου δεν διαφέρει από την μέση διάρκεια της περίοδου κλιματικής μεταφοράς των ισχυριών. Ετσι, για πρώτη φορά, ανεξάρτητα από κάθε άλλη τεχνική χρονολόγηση, τα αποτελέσματα με 40Arg/38Arg, επιβεβαιώνουν την θεωρία των ασφυκτικών αλλαγών του κλίματος. Σημειωτέον ότι οι χρονολογήσεις με 40Arg/38Arg δείχνουν μια σταθερή απόκλιση 200 xιλ. χρόνων από
της αστρονομικής χρονολογίας των ιδίων στρωμάτων τέφρας. Η απόκλιση αυτή
συζητείται με λεπτομέρεια στο κεφάλαιο 1.

Στο Κεφάλαιο 2, μελετάται η μαγνητοστροματογραφία των τομών που
παρουσιάζονται στο κεφάλαιο 1. Ο συσχετισμός της μαγνητικής πολικότητας της
σύνθετης τομής της Ηπειρώτικης Παλαιομίας προς την χρονολογική κλίμακα της
αστρονομικής πολικότητας (APTS) αποδεικνύει ότι η ιζημογένες κυκλικότητα
ελέγχεται από τις αλλαγές του κλίματος λόγω των μετατάσσεσ των ισημερινών.
Οι ιζημογενείς κύκλοι της Παλαιομίας συγκρίνονται προς την ηλιακή ενέργεια του
Β. μισοφαιρίου και την θαλάσσια τομή αναφοράς Ροσέλλο της Σκελίας. Η
σύγκριση αυτή δείχνει αύξηση της βροχόπτωσης με περιόδους θερμών
καλοκαιριών κατά το Κ. Πλευκάκιο στην ηπειρωτική Ελλάδα και επιβεβαιώνει
προηγούμενες παρατηρήσεις στην Μεσόγειο αυξημένης υγρασίας κατά το
μέγιστο της ηλιακής ενέργειας στην διάρκεια του καλοκαιριού.

Εις το Κεφάλαιο 3, εξετάζονται τις αποδείξεις της κλίμακας θαλασσίων (sub-
Milankovitch) κλιματικών αλλαγών σε στροματογραφικό διάστημα που καλύπτει 5
ιζημογενείς κύκλους μετάπτωσης σε 9 παράλληλες τομείς στα ορυχεία Βόρειο
και Κοράνος. Καταγράφουν υψηλής ευκρίνειας χρονικών αντανακλάσεων
χρησιμοποιήθηκαν για τον ποσοτικό έλεγχο έως-κυκλικών μεταβολών και για τον
προσδιορισμό της πλευρικής συνέχειας. Οι περισσότεροι έως-κυκλικές μεταβολές
συσχετίζονται μεταξύ των παράλληλων τομεών, το οποίο σημαίνει ότι οι αλλαγές
αυτές αντικατοπτρίζουν περιβαλλοντικές συνθήκες, σε όλο το μήκος της λεικής,
σχετιζόμενες με κλιματικές διακυμάνσεις. Το ενδιάμεσο στρώμα τέφρας
deίχνουν συχνοκινημάτων αυτών των διακυμάνσεων και μια ειδική ανάλυση του
χρόνου των αντανακλάσεων δείχνει σημαντική συγκέντρωση έως-κυκλικών
μεταβολών σε περιόδους 11, 5,5, και 2 δι ηρών, Η παρουσία κλιματικών
μεταβολών σε κλίμακα θαλασσίων σε χρόνο πριν από την εμφάνιση
των παγετώνων στο Β. ημιφαίοριο δηλώνει ότι δεν είναι δυνατόν να προηγηθείν από
μόνο την δυναμική των πάγων. Πιθανοί υποψήφιοι είναι αρμονικές η συνδυασμός
αρμονικών των τροπικών κύκλων, μεταβολές της ηλιακής ενέργειας, ή περιοδικές
κίνησες Γης και Σελήνης.

Η σχέση μεταξύ τροπικών επιδράσεων και ιζημογένεσης ερευνάται επιπλέον
στα λιμναία ιζηματία του Μεσογείου στο νότιο τμήμα της λεικής της
Παλαιομίας (Κεφάλαιο 4). Το μικρό ορυχείο της Λάβας με συμπαγή λιγότερο δίνει μια
ακολουθία από λιμναίες μάργες με ενδιάμεσες στρώματα από σκούρες μάργες.
Πα
να δούμε την ποσοτική αλλαγή της λιθολογίας χρησιμοποιούμε καταγραφής
ακτινών Τ" και μαγνητικής ευαξιοποίησης. Η τομή δίνει καλό σήμα
παλαιογενεσιακού το οποίο μαζί με την πανδίκη των μικρών θηλαστικών θάνους
ακριβή χρονολόγηση. Οι λιθολογικοί κύκλοι έχουν την ίδια περιοδικότητα όπου
και η μετάπτωση των ισημερινών. Η παλαιολογική ανάλυση δείχνει ότι τα
στρώματα σκούρου χρώματος αντιπροσωπεύουν περιόδους μεωμένης υγρασίας.
Ο συσχετισμός των κύκλων προς την καμπύλη της ηλιακής ενέργειας έχει σαν αποτέλεσμα την ακριβή χρονολόγηση των αναστροφών πολικότητας επιβεβαιώνοντας και βελτιώνοντας την χρονολογική κλίμακα της ασφρονομικής πολικότητας (APTS) του Μεσογείου.

Εις το Κεφάλαιο 5, παρουσιάζονται τα αποτελέσματα της μελέτης σε 3 τομείς και 2 γεωργίες από την λεκάνη ΦΠΣ χρησιμοποιώντας συνδεσμο δυναμό κυκλοσφυγμογραφίας, μαγνητισμογραφίας και 40Arg/39Arg ώστε να κλείσει το κενό μεταξύ των ακολουθίων της Πολεμαϊδας και της Λάβας. Μια επιπλέον γεώργια μας επέτρεψε να επεκτείνουμε προς τα κάτω την ακολούθια της Λάβας μέχρι την αρχή της ιζημιασύνης της λεκάνης. Μαζί με τις ίδρυμα με τις τομές έκανε μια συνεχή ακολούθια που εκφράζει την ιζημιασύνη της Νεογεννούς λεκάνης μεταξύ 8 και 4 εκ. χρόνων. Από την χρόνο-στρωματογραφική εργασία συμπεραίνουμε κυρίως ότι οι μεταβλητές του κλίματος που προκαλούνται από τη μεταπτώσεις επιδρούν στην λιθολογία, ενώ οι κύκλοι εκκεντρόπτες 100 και 400 χλ. χρόνων έχουν επιδράσει σε μεγάλης κλίμακας λιθολογικές διαφοροποιήσεις σε τμήματα της ακολούθιας. Μια σημαντική ομοιότης στις ηλιακές θεμελιωδην απεικονίζει μια περιβάλλοντα απόθεση μεταξύ της Φλόρινας-Πολεμαϊδος-Σέρβια λεκάνης με της θαλάσσιες λεκάνες της Μεσογείου δείχνει ότι έχουν μια κοινή, μάλλον τεκτονική προέλευση.
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Curriculum Vitae