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Millennial-scale climatic cycles in the Early Pliocene pollen record of Ptolemais, northern Greece

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Abstract

Early Pliocene lacustrine sediments from the Ptolemais Basin, northern Greece, exhibit a climatically induced cyclicity, which can be correlated with the orbital cycle of precession. Superimposed on precession-controlled cycles, palynological time-series data reveal a higher-order climatic cyclicity with periodicities of ~10, ~2.5, and ~1.5 ka. These millennial-scale vegetation changes are likely to reflect changes of the soil-moisture gradient on mountain slopes, caused by fluctuations in orographic winter-precipitation. Such fluctuations corroborate the concept of a NAO-like North Atlantic climatic teleconnection during Early Pliocene times. The periodicities are similar to those of climate oscillations inferred from Quaternary records. The occurrence of millennial-scale cyclicity in a time interval when the Northern Hemisphere was essentially ice-free, implies an ultimate forcing mechanism that operated independently of changes in the thermohaline circulation in the Atlantic Ocean. The cycles are likely to be related to long-period variations in solar activity.

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1. Introduction

The role of orbital forcing in driving long-term climate changes has become well established. Not only in the Quaternary, but also throughout the Cen-

ozoic, Mesozoic and Palaeozoic, sedimentary and biotic responses to cyclic changes in insolation associated with eccentricity (~400, ~100 ka), obliquity (~41 ka) and precession (~21 ka) have been convincingly detected. In the past decades, high-resolution $\delta^{18}\text{O}$ records from Greenland ice cores and records of drift ice measured in North Atlantic sediment cores, revealed also millennial-scale climatic oscillations during Late Quaternary times. Well-documented examples of quasi-periodic climatic cyclicity include

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the Bond cycles (6–10 ka; Bond et al., 1992, 1993; Broecker, 1994), the Dansgaard Oeschger cycles (1–3 ka; Dansgaard et al., 1984, 1993; Mayewski et al., 1997), and the Holocene ‘1500 year’ cycles (~1.5 ka; Bond et al., 1997; O’Brien et al., 1995). The forcing mechanisms of this ‘sub-Milankovitch’ cyclicity are still poorly understood. The cycles are generally associated with changes in the North Atlantic thermohaline circulation (Bond et al., 1997; Broecker, 2000; deMenocal et al., 2000; Keigwin and Boyle, 2000). Some authors however (Keigwin and Pickart, 1999; Giraudau et al., 2000), attributed millennial-scale perturbations of the North Atlantic surface hydrology to long-term modulations of the atmospheric processes associated with the North Atlantic Oscillation (NAO). This North Atlantic component of the Arctic Oscillation represents the difference in pressure between the Azores High and the Icelandic Low (Hurrell, 1995; Visbeck et al., 2001; Wanner et al., 2001; Marshall et al., 2001). Despite controversies, there is increasing evidence that these pressure differences are externally determined by variation in solar activity (Mayewski et al., 1997; Suess and Linick, 1990; Van Geel et al., 1999; Kodaera and Kuroda, 2005).

Effects of millennial-scale climate changes are increasingly detected on land. Pollen records of the last glacial period and the Holocene seem to confirm a coupling between North Atlantic climate variability and vegetation development in Europe. Notably the concurrent analysis of land-derived pollen assemblages and marine environmental proxies from sediment cores off Portugal (Sánchez Goñi et al., 2000; Boessenkool et al., 2001; Roucoux et al., 2001; Turon et al., 2003) and the Alboran Sea (Sánchez Goñi et al., 2002; Combourieu Nebout et al., 2002) provides direct evidence of vegetation responses to warm and cold modes of the North Atlantic climate. In southern Europe, millennial-scale North Atlantic signals have been inferred from pollen records derived from lake and peat deposits in Italy (Allen et al., 1999) and Greece (Tzedakis et al., 2002, 2004). Periodicities corresponding to extreme discharge of ice-rafted debris into the North Atlantic Ocean, known as Heinrich events (Bond et al., 1997; Elliot et al., 1998; Van Kreveld et al., 2000), are particularly apparent. Vegetation responses indicate significant changes in precipitation in the Mediterranean region, which may support the notion of a NAO-driven coupled system

(Sánchez Goñi et al., 2002; Combourieu Nebout et al., 2002).

Despite the relevance of Late-Quaternary pollen records in detecting responses of terrestrial ecosystems to North Atlantic climate oscillations, extreme environmental effects of Northern Hemisphere glaciation may obscure correlation of changes in sea surface temperature and vegetation development. In order to eliminate such effects, detection of millennial-scale climate cycles on land can be best performed on the basis of palynological data from time-intervals preceding the development of a permanent polar ice cap, about 2.75 million years ago (Jansen and Sjöholm, 1991; Larsen et al., 1994).

An accurately dated sequence of Early Pliocene lignites and lacustrine marls is well-exposed in a series of lignite quarries in the Ptolemais Basin of northern Greece. Superimposed on precession-controlled cycles (van Vugt et al., 1998; Steenbrink et al., 1999), colour-reflectance time-series data for this sequence indicate the existence of a higher-order sedimentary cyclicity corresponding to lake-level fluctuations that could reflect external (i.e., climate-related) processes (Steenbrink et al., 2003). In the Ptolemais Formation, vegetation responses to precession-controlled climate changes are significantly reflected in the palynological record (Kloosterboer-van Hoeve, 2000). In the present paper, we analyze the pollen record from a single precessional cycle, spanning the period from 4.33 to 4.31 Ma, in order to (1) corroborate the presence of millennial-scale climate cycles in the Mediterranean region, (2) clarify the nature of this cyclicity, and (3) contribute to an assessment of the forcing mechanisms of millennial-scale cyclicity in the North Atlantic region.

2. Study area

The Ptolemais Basin (40°30'N, 21°40'E) is a distinctive intramontane depression flanked by the mountain ranges of Vermio (2052 m) to the east and Askio (2111 m) to the west (Fig. 1). It is part of a 250-km long graben system that opened in the Late Miocene and was divided into sub-basins during the Pleistocene (Mercier et al., 1989; Pavlides and Mountrakis, 1986). The 500–600 m thick Late Miocene–Early Pliocene basin-fill is well-exposed in a series of

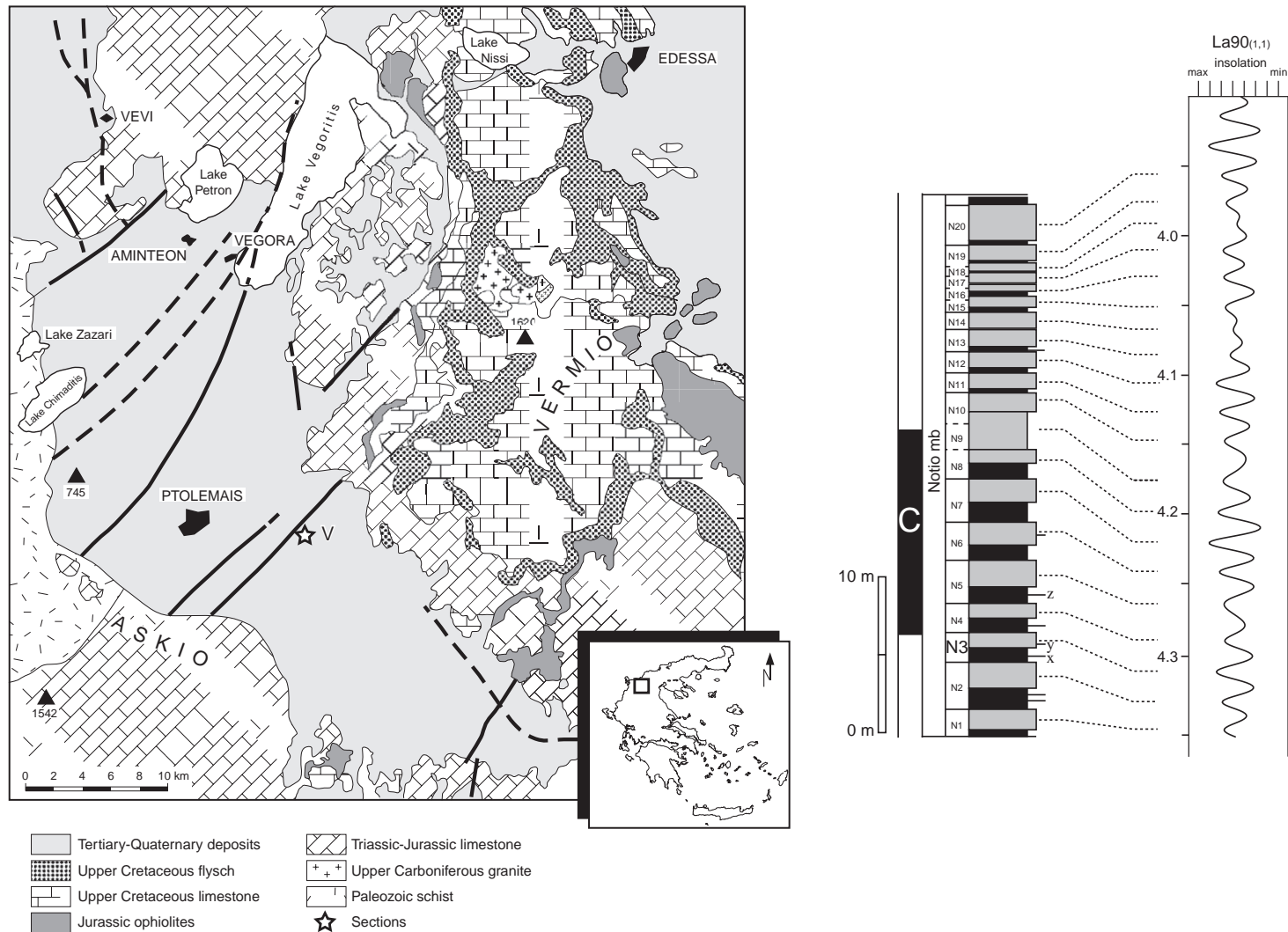


Fig. 1. (Left) Geological sketch map of the Ptolemais Basin with V the location of the Vorio section (modified after (Papakonstantiou, 1979)). (Right) Part of the Ptolemais composite section showing the succession of lignite–marl cycles in the Notio member (cycle N1–N20) of the Ptolemais Formation. Magnetic polarity and stratigraphic members are indicated to the left of the sedimentary cycle numbers. In the polarity column black (white) indicates normal (reversed) polarity. C indicates the Cochiti Subchron (van Vugt et al., 1998), x, y and z are ash layers (see Steenbrink et al., 1999: x=SR3L, y=SR3M and z=SR5L). The Ptolemais composite section is correlated with the 65°N summer insolation curve (after van Vugt et al., 1998; Steenbrink et al., 1999).

open-pit lignite mines. It formed in a closed-basin lake environment and exhibits a marked cyclicity. Controlled by lake-level fluctuations, dark-colored organic-rich and light-colored carbonate-rich deposits alternate in a rhythmic pattern. The organic-rich facies, ranging from lignitic marls to massive lignite seams, correspond to lowstand conditions with concomitant development of fringing swamp environments; carbonate-rich lithologies reflect relatively raised lake-levels (van Vugt et al., 1998; Steenbrink et al., 1999). Cyclicity is most pronounced in the upper part of the sequence, the Ptolemais Formation. On the basis of a basin-wide cyclostratigraphic analysis, 56 lignite–marl couplets, each with a thickness of 2 m, could be detected within this formation (Fig. 1). Twenty interbedded volcanic ash layers verify that these rhythmic alternations are synchronous (van Vugt et al., 1998; Steenbrink et al., 1999).

Magnetostratigraphy (van Vugt et al., 1998) and $^{40}\text{Ar}/^{39}\text{Ar}$ dating of the interbedded ash beds (Steenbrink et al., 1999) point to an Early Pliocene age for the Ptolemais Formation and indicates that the average duration of a single lignite–marl couplet is ~21.7 ka, which equals the average period of orbital precession. Couplets can be tuned to computed astronomical target curves enabling accurate astrochronological age estimates for the formation (5.23 to 3.94 Ma) as well as for its component cycles (van Vugt et al., 1998; Steenbrink et al., 1999).

Within some segments of the Ptolemais Formation, the meter thick precession controlled lignite–marl couplets exhibit a pronounced higher-frequency lithological variation. Development of dm-scale lithological alternations is notably apparent in the Notio Member of the Ptolemais Formation. Basin-wide lithological variation has been quantified by using high-resolution colour reflectance data obtained from parallel sections (Steenbrink et al., 2003). Spectral analysis of the reflectance time-series shows significant cyclicities. A concentration of variance is observed at periodicities of approximately 11 and 5.5 ka, and in a broad band between 3 and 0.7 ka. The changes in colour-reflectance are mainly the result of variations in organic matter content. Similar to the precession-induced lignite–marl couplets, also the subordinate cycles are considered to be indicative of climate-controlled lake-level fluctuations (Steenbrink et al., 2003).

3. Palynological analysis

Material for this palynological analysis originates from the Vorio mine (Fig. 1), where the lignites of the Notio Member of the Ptolemais Formation are relatively thin and have regular intercalations of grey and beige marls. Following a pilot study covering part of the interval studied by (Steenbrink et al., 2003), precession-controlled sedimentary cycle N3 was selected for detailed study, involving analysis of 52 samples (Fig. 1). These samples, approximately 5 cm long cores with a diameter of 2.5 cm, were drilled with an interval of 2 cm within the 2 m thick fresh exposure of the cycle. Pollen samples were prepared using slightly modified (Kloosterboer-van Hoeve, 2000) standard procedures (Faegri and Iversen, 1989). Processing included carbonate and silicate removal with HCl and HF, boiling in KOH to remove excess organic fractions, and sieving over 10 and 120 μm sieving cloth to remove fine and coarse fractions, respectively. In general, preservation of palynomorphs is poor to moderate in the lignites and good in the marls. All samples were quantitatively analyzed for pollen and spores, as well as organic algal remains and fungal remains. Palynomorph concentrations were calculated through: $[p/g] = (sV)/(vW)$, where p/g represents the amount of a given palynomorph type per gram of dry sediment, V is the total volume of the solution containing the palynomorphs, v is the volume of the solution mounted on the microscopic slide, and W is the dry weight of the sample. Permanent slides are stored in the collections of the Laboratory of Palaeobotany and Palynology (Utrecht University).

Morphological characteristics of most Pliocene pollen types can directly be related to extant genera and families. This correlation potential is a sound basis for floristic analysis of the pollen record of the Ptolemais Formation and the recognition of similarities with modern vegetation types (Kloosterboer-van Hoeve, 2000). Although pollen morphology rarely allows identification at a species level, the overall taxonomic composition of the Ptolemais assemblages reflects remarkable similarities with modern plant communities characteristic of elevated terrain in the East-Mediterranean borderlands (Bottema, 1974; van Zeist et al., 1970, 1975). Notable floristic differences, however, are indicated by the presence of Taxodiaceae, *Cathaya*, *Tsuga*, *Carya*

and *Pterocarya*. In southern Europe, these taxa were widespread during the Neogene, but became regionally extinct in response to successive Pleistocene cooling phases.

Because of the presence of comparable taxa and vegetation types, environmental interpretation of the Ptolemais assemblages can benefit from detailed reconstructions of the Holocene vegetation history in the East-Mediterranean borderlands. Through analysis of surface samples, these studies have an actualistic background in which differences in the production, dispersal and deposition of pollen have been taken into consideration (Bottema, 1974; van Zeist et al., 1970, 1975). In harmony with present-day and Holocene data from Greece and Turkey, palynomorph assemblages of the Ptolemais Formation yield a variety of both (par)autochthonous and allochthonous components that reflect ecologically contrasting, local and regional communities (Kloosterboer-van Hoeve, 2000).

The (par)autochthonous components originate from plants and other organisms that live locally in the lake and its fringing wetlands. Four main categories are recognized:

- (1) *Algae*: Organic algal remains indicative of phytoplankton communities with *Spirogyra*, *Botryococcus*, *Pediastrum*, *Mougeotia*, and *Zygnema*.
- (2) *Aquatics*: Plants indicative of open-water vegetation. Pollen generally occurs in low frequencies. Characteristic elements are *Sparganium*, *Nuphar*, and Nymphaeaceae.
- (3) *Wetland elements*: Plants indicative of swamp vegetation. Dominant are Cyperaceae; also ferns are included in this category. Wetland trees are represented by stands of *Alnus* and Taxodiaceae. Megafossil evidence from earlier cycles (Velitzelos and Gregor, 1990) indicates that the Taxodiaceae-type pollen could represent *Glyptostrobus*, presently a near-extinct genus in southeastern China.
- (4) *Fungi*: Remains of fungi (spore, hyphae) indicative of decomposition of plant organic matter, notably in soil and peat.

The *allochthonous* components represent anemophilous plants of the vegetation of the relatively steep

topography flanking the intramontane Ptolemais depression. Three categories of predominantly mountainside elements may be distinguished:

- (1) *Montane elements*: Trees indicative of higher-altitude communities (above 800–1000 m). Similar to present-day vegetation of the East-Mediterranean borderlands, montane forests largely consist of moisture-exigent conifers (Pinaceae). Characteristic elements are *Pinus* and *Cedrus*, with subordinate *Picea*, *Abies*, and *Tsuga*. Throughout southern Europe, *Cedrus*, *Tsuga*, *Picea* and *Abies*, are generally regarded as higher-altitudinal elements of the Pliocene forest vegetation (Popescu, 2002). Although species of *Pinus* are known to occupy a wide variety of contrasting habitats (Farjon, 1984), analogous to present-day and Quaternary distribution patterns in Greece and Turkey (Bottema, 1974; van Zeist et al., 1975), the dominant *Pinus*-type pollen is considered to reflect to a large extent regional montane vegetation. Similarly, also pollen of *Fagus* and *Betula* is included in this category. An insignificant portion of *Pinus*-type pollen belongs to the near-extinct genus *Cathaya* rather than to *Pinus*. However, because of insufficient preservation, a record of *Cathaya* could not be reconstructed separately for the studied interval.
- (2) *Colline elements*: Plants indicative of low- to mid-altitude communities. Colline elements are dominantly represented by pollen of deciduous *Quercus*, in combination with a variety of other deciduous taxa, such as *Ulmus*, *Acer*, *Carpinus*, *Ostrya*, *Fraxinus*, *Carya* and *Pterocarya*. Similar to present-day vegetation zonation in the East-Mediterranean mountains, the limit between montane (coniferous) and colline (deciduous) forest types is likely to vary considerably depending on soil, exposure and topography. Natural transitions are gradual with wide tracts of co-occurring deciduous trees and *Pinus*. The altitudinal range of this transition may be estimated between 800 and 1000 m. Complementary to deciduous *Quercus*, the colline pollen record includes subordinate percentages of evergreen *Quercus*. At present, evergreen species of *Quercus* are an

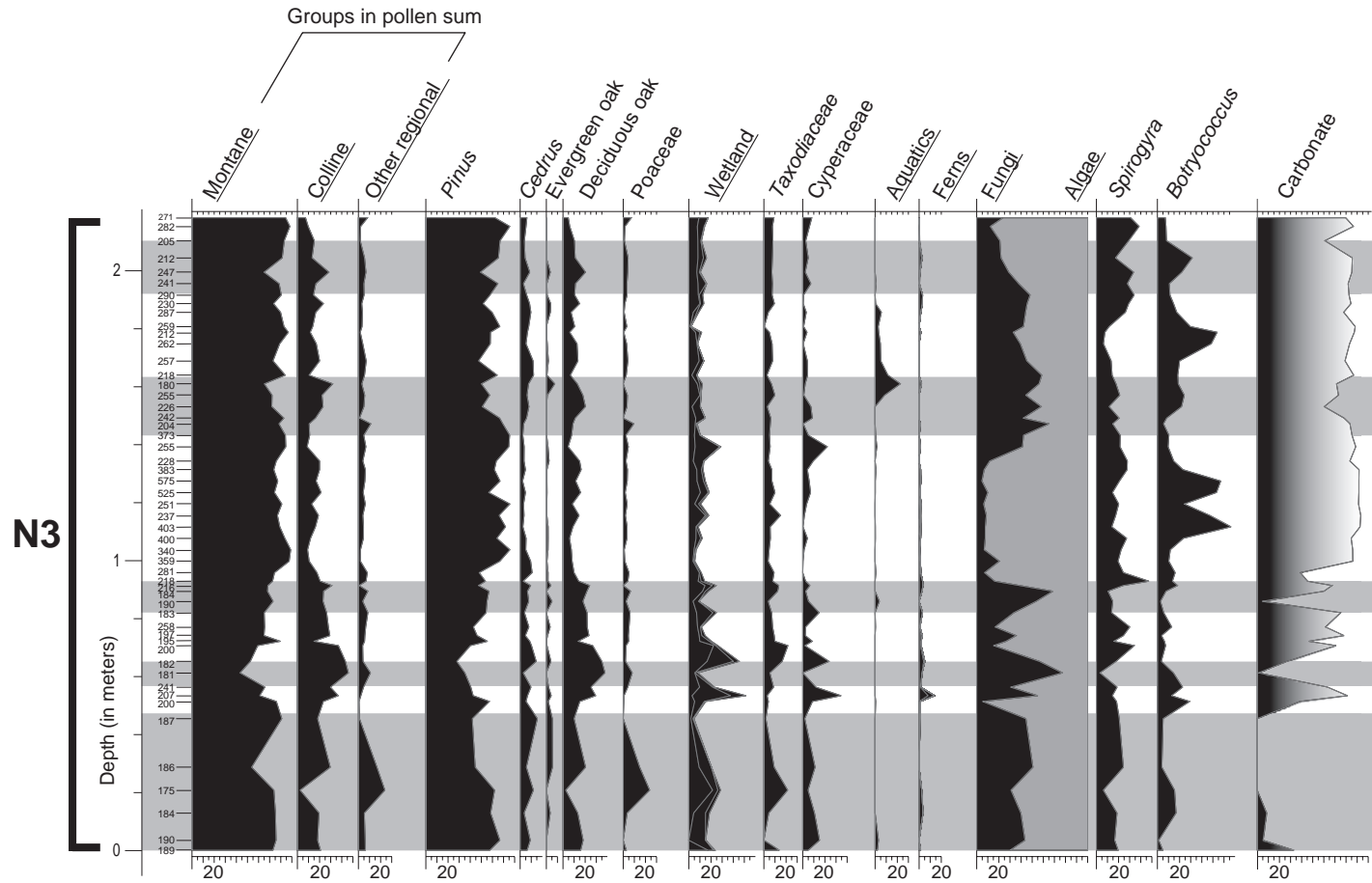


Fig. 2. Pollen diagram of Ptolemais cycle N3. Pollen data are represented as percentages (calculated on a pollen sum including all regional elements; montane and colline trees and other regional elements). The groups (underlined) are further explained in the text. Total sporomorph numbers are indicated on the left. The relative frequencies of algae and fungi are expressed as percentages of a separate palynomorph sum. The right graph indicates the carbonate content (%). The dark horizontal bands indicate the organic rich intervals.

important element of a broad category of sclerophyllous trees and shrubs that together constitute the typical, aridity-tolerant Mediterranean evergreen vegetation. In Greece, sclerophyllous communities are concentrated in a zone ranging from sea-level up to about 400 m. However, above 400 m, evergreen *Quercus* and a few other sclerophyllous elements may continue to occur together with deciduous trees (Bottema, 1974).

- (3) *Other regional elements*: In the East-Mediterranean borderlands, species of *Juniperus* occupy a variety of mountainside habitats, ranging from underwood in colline vegetation, to large trees that occur together with *Pinus*, *Abies* and *Cedrus* in the coniferous forest zone (van Zeist et al., 1975). Similarly, many subordinate pollen types of herbs are difficult to categorize in terms of montane or colline plants. Although

treated as a regional component, part of the pollen of Poaceae may also originate from the local wetland vegetation around the lake.

A palynomorph percentage diagram for Ptolemais cycle N3 is presented in Fig. 2. The pollen sum, the calculation base for both regional and local pollen curves, consists of the three categories of allochthonous pollen types that reflect regional mountainside vegetation (montane, colline, other regional). Relative frequencies of algal and fungal remains are expressed as percentages of a separate palynomorph sum. In Fig. 3, calculated pollen concentration and summarised percentage data for cycle N3 are compared with the colour reflectance (Steenbrink et al., 2003) and carbonate content. Periodicities in the palynological records were investigated by applying spectral analysis on time-series data of selected pollen types (*Pinus* and *Cedrus*) or palynomorph groups

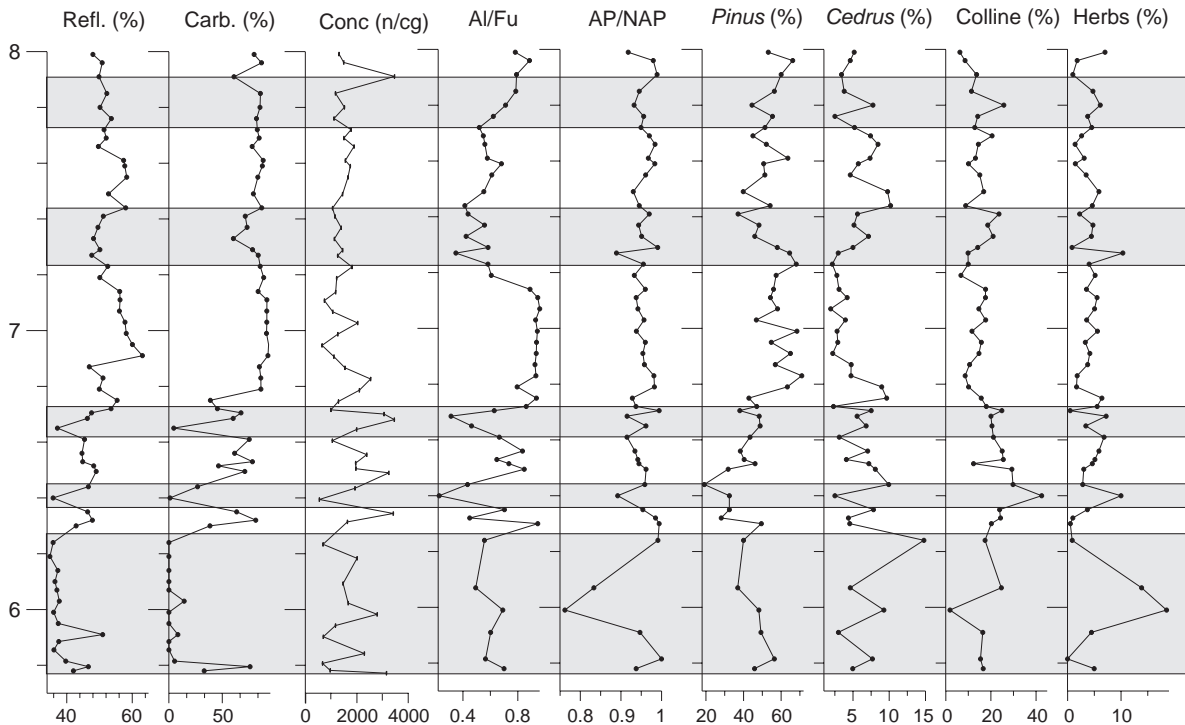


Fig. 3. Graph combining sedimentological data (after Steenbrink et al., 2003) with palynological data from cycle N3. Refl (%) are colour reflectance values; the lower the percentage, the darker the sediments. Carb (%) is the carbonate content. Conc (n/cg) gives the calculated total pollen concentration. Al/Fu=(total percentage of algae)/(total percentage of algae and fungi) and AP/NAP=(total percentage of regional arboreal pollen)/(total percentage of regional arboreal and non-arboreal pollen). The dark bands indicate the organic-rich intervals.

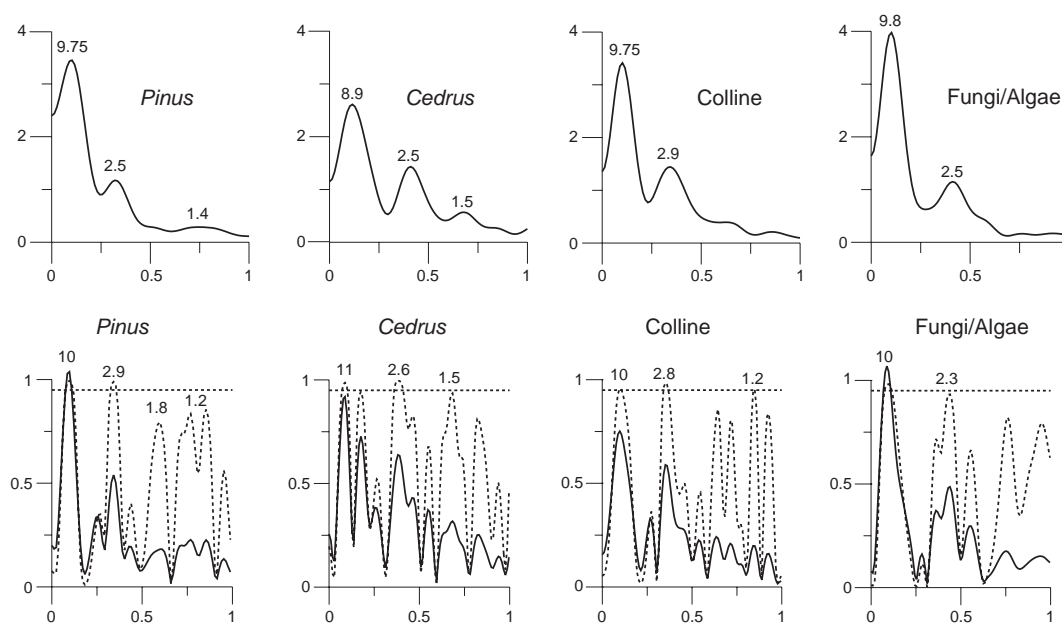


Fig. 4. Power spectra for selected palynomorph categories from cycle N3 using (top) Blackman Tukey methods (band width 0.254972) and (bottom) Multi Taper Method (95% confidence level indicated with the horizontal dotted line) using the Analyseries (Paillard et al., 1996). Palynomorph time series were generated from the astronomical-tuned age model, where midpoints of lignites approximate precession maxima and NH summer insolation minima (van Vugt et al., 1998).

(colline trees, fungi and algae) (Fig. 4). For each time series, the main frequency components have been extracted using a Gaussian bandpass filter (Fig. 5).

4. Results and discussion

4.1. Cyclic vegetation changes

On average, calculated total pollen concentration is higher than 1000 pollen grains/centigram of dry sediment, but values show significant fluctuations. There is no apparent link between concentration and lithology. The random fluctuations in the organic-rich facies are an artifact caused by varying amounts of wood debris in the palynological samples and should therefore not be attributed to variable sedimentation rates. Concentrations of individual pollen categories (not shown) show parallel patterns.

The cumulative curves of the principal pollen categories show a general trend of relatively high percentages for colline trees (deciduous *Quercus* dominant),

regional herbs (Poaceae dominant) and wetland elements (Taxodiaceae and Cyperaceae dominant) in the first half of the precession-controlled sedimentary cycle (lignite phase), and high frequencies of montane elements (*Pinus* dominant) in the second half of the cycle (marl phase). The organic-rich layers, notably those of the lignite phase that are characterized by relatively low reflectance values and low carbonate content, display low Arboreal/Non Arboreal (AP/NAP) ratios and low Algae/Fungi (Al/Fu) ratios. The carbonate-rich intervals with high reflectance values have generally high Al/Fu ratios and also to some extent higher AP/NAP ratios. Regular oscillations are objectively confirmed by spectral analysis of the palynological time-series data. The resulting spectral peaks for the records of *Pinus*, *Cedrus*, colline trees, and fungi/algae reveal distinct periodicities of approximately 10, 2.5 and 1.5 ka (Fig. 5). Filtering over these periods shows that the palynological records are well explained by (parts of) the filtered record (Fig 5). Because the data are restricted to one precession cycle, the 10 ka cyclicity needs further confirmation.

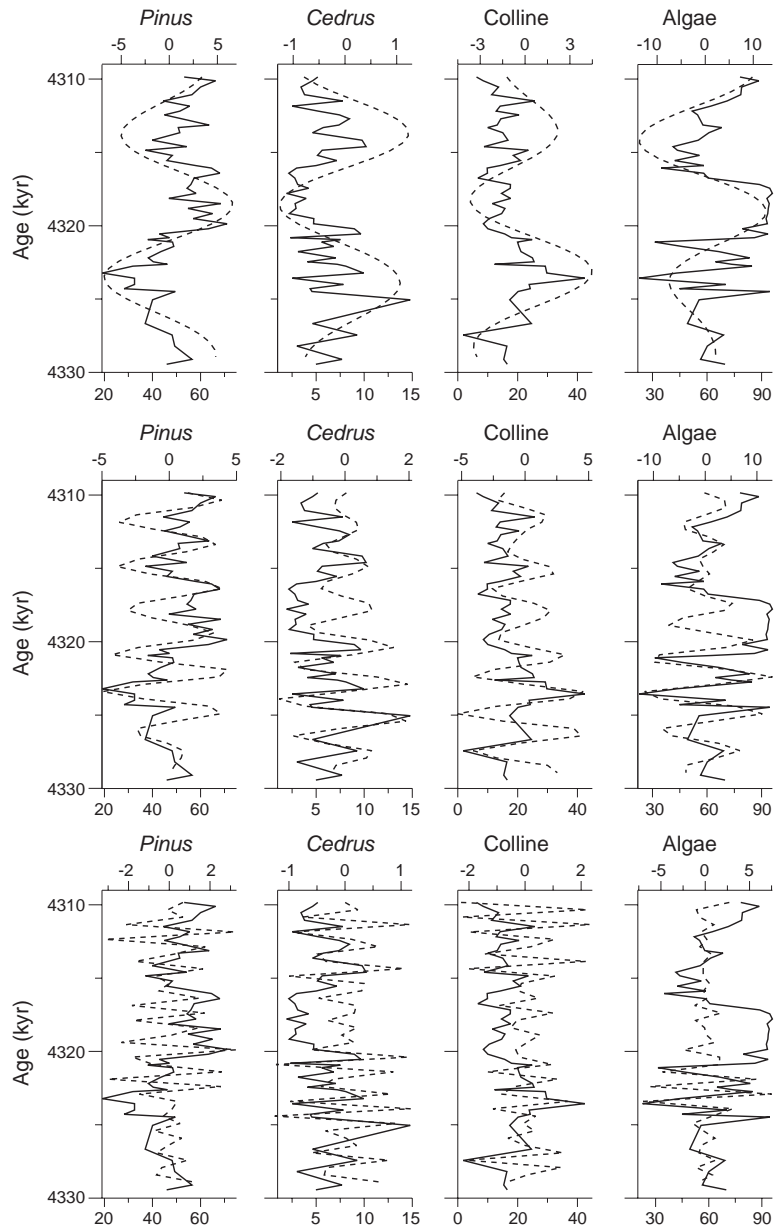


Fig. 5. Filtered record of selected palynomorph categories of cycle N3 with a Gaussian bandpass filter centered around (top) 9.5 ka, (middle) 2.5 ka and (bottom) 1.2 ka. Palynomorph time series were generated from the astronomical-tuned age model, where midpoints of lignites approximate precession maxima and NH summer insolation minima (van Vugt et al., 1998).

Trends in the palynological record of fungi and algae from the Ptolemais N3 cycle are directly coupled to lake hydrology. Lowstand conditions support the expansion of wetland ecosystems characterized by widespread peat formation, promoting preservation

of large amounts of autochthonous saprophytic fungal remains. Together with calcareous algae (*Chara*) and gastropods (Steenbrink et al., 1999), proliferation of organic algal remains reflects relatively raised lake-levels. The (par)autochthonous pollen record does not

provide evidence for significant changes in temperature during a precession cycle. At lake level, equable winter temperatures above 0 °C are constrained by the consistent presence of thermophilous Taxodiaceae in the wetland ecosystem. Modern *Taxodium* and *Glyptostrobus* are not adapted to winter frost. Average temperatures for the coldest winter month in natural habitats of the two taxa are +6 °C and +5–10 °C, respectively (Mai, 1995).

In Early Pliocene palynological records from the West-Mediterranean region, the presence of wetland vegetation with abundant *Taxodium* has been interpreted in terms of rainy summers (Suc, 1984). However, although *Taxodium* and associated wetland elements require year-round high soil moisture levels, this does not necessarily translate into high summer precipitation (Thompson et al., 2000). In more recent reviews of the West-Mediterranean records the concept of rainy summers is no longer maintained (e.g., Suc et al., 1995).

Changes in relative abundance of dominant allochthonous pollen-types are likely to document range-expansion or range-contraction of mountainside communities along elevational gradients. In the Mediterranean region water is the limiting factor for plant life. Quaternary pollen data from Greece and Turkey support the view that vegetation changes are driven primarily by changes in water availability (Bottema, 1974; Tzedakis, 1994; Tzedakis and Bennett, 1995). There may be a supportive role for temperature changes, particularly at higher elevations where changes in frost regimes could play a role in the expansion or contraction of forest belts.

Tree-ring analysis of *Fagus* from central Italy confirms that tree growth in Mediterranean mountain forests is largely determined by the availability of soil moisture at the beginning of the growing season (Biondi, 1993; Piovesan and Schirone, 2000). Scant Mediterranean summer precipitation, insufficient to balance evapotranspiration, is only useful in alleviating water stress. The recharge level of soil water is controlled by winter precipitation. It is likely, therefore, that the millennial-scale vegetation changes reflect steepening or weakening of the soil-moisture gradient on mountain slopes, caused by fluctuations in orographic winter-precipitation. Not only rain, but also snow should be taken into consideration as a principal source of soil-moisture in the spring (Biondi,

1993). Rejuvenation of modern *Cedrus* forests, for example, would be impossible without water supply from snowmelt (Farjon, 1990).

In Ptolemais, cyclic vegetation responses that may be related to increased soil moisture are particularly apparent for the combined records of montane (*Pinus*, *Cedrus*) and colline elements (Fig. 5). Analogous to Holocene pollen records from the East-Mediterranean uplands (Bottema, 1974; van Zeist and Bottema, 1982), a marked increase in *Pinus* pollen points to a broadening of the *Pinus*-dominant forest belt. Intensified winter precipitation at higher elevations, possibly in combination with reduced frost occurrence, may be responsible for an expansion of *Pinus*, both up-slope at the expense of *Cedrus*, and down-slope, well into the mid-altitude forests at the expense of deciduous *Quercus*. Independently of the responses of the mountainside vegetation, enhanced precipitation is also reflected in the increased abundances of algal remains resulting from rising lake-levels.

4.2. Mechanisms of millennial-scale climatic variability

The palynological data from the Ptolemais Formation extend the record of millennial-scale cyclicity as far back as ~4.3 Ma, well into the period preceding the onset of Northern Hemisphere glaciation, ~2.75 Ma ago. Records of precipitation and Tigris–Euphrates streamflow volumes from Turkey (Cullen and deMenocal, 2000), as well as sedimentological/hydrological data from Crete (Maas and Macklin, 2002) demonstrate that variation in winter-precipitation in the East-Mediterranean region is largely modulated by the North Atlantic Oscillation (NAO). An enhanced North Atlantic pressure gradient (positive NAO; stronger than normal Azores High and weaker than normal Icelandic Low) is leading to a more northeast oriented transport of moist Atlantic air into Europe. This results in wetter conditions in northern Europe and drier conditions in the Mediterranean region (Hurrell, 1995; Hurrell and Van Loon, 1997). Conversely, under a weak pressure gradient (negative NAO), heat/moisture transport takes a more southern trajectory, forcing an increase in the intensity of Mediterranean winter cyclogenesis and associated precipitation (Trigo et al., 2000, 2002). Tree-ring analysis has shown that

plant growth in Mediterranean mountain forests is affected by NAO dynamics. Multiannual variation of tree-ring growth in *Fagus* correlates with short-term NAO-controlled changes in winter precipitation (Piovesan and Schirone, 2000). Because the current precipitation variance in the Mediterranean region can largely be explained by the NAO, it is conceivable that a similar North-Atlantic teleconnection is responsible for the reconstructed cycles in Greece in the Early Pliocene. In a Quaternary perspective, this interpretation would corroborate the notion of NAO-induced millennial-scale climate variation in the North Atlantic/Mediterranean realm (Keigwin and Pickart, 1999; Giraudau et al., 2000; Sánchez Goñi et al., 2002; Combourieu Nebout et al., 2002).

Quaternary millennial scale cyclicity is often linked to changes in the North Atlantic thermohaline circulation (Bond et al., 1997; Broecker, 2000; deMenocal et al., 2000; Keigwin and Boyle, 2000). However, because North Atlantic deep-water formation is largely dependent on the presence of Arctic ice, the Early Pliocene data support an ultimate forcing mechanism that operated independently of changes in thermohaline circulation. The present data therefore corroborate the concept that the millennial-scale cycles are the result of variations in insolation. Among the mechanisms that could theoretically cause this variation (see Steenbrink et al., 2003), it is plausible that fluctuations in solar activity played a major role. Despite controversies, there is compelling empirical evidence of sun-climate relationships at decadal to centennial time-scales (Lean and Rind, 1999), while modelling studies predict that even the modest fluctuations in solar energy related to the 11-year solar (sunspot) cycle may directly affect atmospheric circulation patterns (Haigh, 1996, 1999; Shindell et al., 1999). But also proxy evidence of solar forcing on a millennial scale is increasingly provided by records of the cosmogenic radionuclides ^{14}C and ^{10}Be , measured in wood remains, sediments and ice cores.

Notably the Holocene ‘1500 year’ cycles of the North Atlantic realm coincide with significant fluctuations in the ^{14}C and ^{10}Be isotope records (Van Geel et al., 1999; Bond et al., 2001). Similarly, a 2.3–2.5 ka cyclicity has been explained in terms of variation in solar activity (Karlen and Kuylenstierna, 1996; Magny, 1993, 2004; Mayewski et al., 1997; Renssen et al., 2000). Although not documented by ^{14}C or

^{10}Be signals, also climatic oscillations with periodicities of ~10 ka have been related to long-period self-variations of solar emission (Gauthier, 1999; Shopov et al., 1998, 1999; Stoykova et al., 1998).

5. Conclusions

The principal conclusions of the present investigation may be summarised as follows:

1. Palynological analysis of Early Pliocene lignites and lacustrine marls of the Ptolemais Basin in northern Greece indicates that millennial-scale climate cyclicity occurs as far back as 4.3 Ma, during times when the Northern Hemisphere was essentially ice-free.
2. Both colour (Steenbrink et al., 2003) and palynological reflectance time series demonstrate distinct periodicities around 11–10 and 2.5–1.5 ka. This implies that local conditions (depositional environment as reflected in the lithology) as well as regional conditions (climate as indicated by the pollen record) were paced by this millennial-scale cyclicity.
3. In the East-Mediterranean region, cycles with periodicities of ~10 and ~2.5 and ~1.5 ka are mainly expressed by changes in winter precipitation that may reflect long-term trends in a NAO-like North Atlantic teleconnection.
4. The cycles occur independently of changes in the North-Atlantic thermohaline circulation; their ultimate forcing mechanism is likely to be related to long-period variations in solar activity.

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