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Vegetation markers of palaeoclimate cyclical changes in the Pliocene of Punta Piccola (Sicily, Italy)

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Abstract

Astronomically driven climate changes are recorded in mineralogical composition of marine sediments. In order to view the implications of precession cycles on continental vegetation, high-resolution records of pollen and fresh water algae are presented in five precession cycles (no. 104–108, age 3.00–2.92 Ma) from the central Mediterranean Punta Piccola section (Pliocene). Each cycle has been subdivided into four phases based on the pollen composition. Three phases represent the brown, laminated part of the cycle (formed during precession minima). Their pollen associations suggest relatively heavy precipitation and high temperatures. The fourth phase represents the light, carbonate-rich part of the precession cycles, and its pollen associations express arid conditions. This phase also experiences maxima in percentages of palygorskite and higher pollen input from the South.

Keywords: Mediterranean region; Pliocene; Palynology; Palaeoenvironment; Palaeoclimatology

1. Introduction

After the so-called Messinian salinity crisis, the desiccated Mediterranean basin was invaded again by the seawater whose Pliocene deposits unconformably overlay Miocene layers. These deposits are usually more or less carbonated marls, which display a rhythmic bedding emphasized by dark-colored layers enriched in organic matter, e.g., up to 30% in sediments drilled during ODP Leg 160 (Emeis et al., 1996). The term "sapropel" is frequently used to call these layers when their organic carbon content reaches 2% (Kidd et al., 1978). However, in continental outcrops like the one we study here, such high concentrations are rarely reached and the term "sapropelic sediment" is more appropriate.

Kullenberg (1952) was the first to attribute this concentration of organic matter to increased rainfall or runoff over the Mediterranean, leading to hydrological stagnation, anoxia at the sea bottom, and eventually

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preservation of organic matter. At the present time, most hypotheses incorporate this concept and/or that of increased organic matter productivity during these periods (Rohling and Gieskes, 1989; Rohling and Hilgen, 1991; Tang and Stott, 1993; Rohling, 1994). The rhythmic sequences which include the sapropelic beds can be explained by cyclical climate variations linked to the Earth's orbit parameters, particularly to the precession periodicity of approximately 22 ky (Rossignol-Strick, 1983, 1985; Hilgen, 1987, 1991).

Many palaeoenvironmental, chemical, and mineralogical studies have been performed on these orbitally driven cycles in the Pliocene Mediterranean marine sediments and have yielded information on marine environmental changes (e.g., de Visser et al., 1989; Rohling and Hilgen, 1991; Tang and Stott, 1993; Van Os et al., 1994; Versteegh, 1994; Londeix et al., 1999; Foucault and Mélières, 2000). In several Pliocene Mediterranean marine sections, it was demonstrated that clay mineral percentages, especially of palygorskite, kaolinite, smectite and chlorite, vary cyclically in relation to precession (Foucault and Mélières, 1995, 2000; Mélières et al., 1998). Foucault and Mélières (1995) suggested that these cyclical variations result from the alternation of the weak and strong rainfall periods in both the South and North Mediterranean borderlands. During periods of minimum rainfall, the aridity of the Sahara increased, reducing and scattering the vegetation in the peri-Saharan areas. Soils and outcropping rocks were far more vulnerable to wind erosion, which enhanced wind transportation into the Mediterranean Sea of minerals (palygorskite, kaolinite, etc.) characteristic of these areas (Millot, 1964; Chamley, 1971; Sassi, 1974; Blanc-Vernet et al., 1975; Burollet et al., 1979; Coudé-Gaussen, 1991; Bergametti et al., 1989; Guieu and Thomas, 1996; Ridame et al., 1999). On the northern borderlands of the Mediterranean Sea, lower rainfall probably resulted in a decrease not only in river discharge, but also in sediment load, because fluvial erosion would lose its efficiency if the vegetation was dense enough. Consequently, the detrital supply of rivers to the sea would have decreased, increasing the relative percentage of wind-transported material in the sediment. During these periods, the sediments show the highest percentages of palygorskite and related minerals (kaolinite, dolomite, quartz, and feldspar), and the lowest of smectite and chlorite. During periods of higher rainfall, the vegetation could spread over the Saharan and peri-Saharan areas, protecting soils and significantly reducing, or even preventing, aeolian erosion. On the northern margin of the Mediterranean, higher rainfall would not have notably modified the density of a preexisting vegetation, but would probably have increased fluvial erosion, supplying a heavier terrigenous load for marine sedimentation. Sapropels or gray beds were deposited during these moist periods. These findings are consistent with the results of Wehausen and Brumsach (1998) for the Pliocene section from ODP Hole 964 C (Ionian Basin), who show alternating periods of stronger Saharan dust input and periods of fluvial input from the northern borderlands expressed in terrigenous detrital matter chemistry.

This hypothesis implies that the pollen supply must be consistent with the mineralogical content. Few data show the impact of the precession-driven cycles in the Mediterranean borderland vegetation on marine sediments (with low resolution, Suc et al., 1991; Londeix et al., 1999) and on continental sections (Kloosterboer-Van Hoeve, 2000). This paper presents the pollen and fresh water algae records of the Punta Piccola Pliocene sequence. Such a high-resolution pollen record, produced on the same sampling as mineralogy, and for the first time at this resolution from pollen analyses in marine sediments of this period, will help estimate the impact of the Pliocene precession-driven cycles on the regional vegetation and examine if the vegetation changes agree with conclusions derived from the mineralogical content.

2. Lithological description

The Punta Piccola section (Fig. 1) outcrops near the South Sicily coast, and shows rhythmic alternations of light gray marls and brown laminated sediments (Brolsma 1978; Hilgen 1987).

From bottom to top, overlying Messinian deposits, two Formations have been distinguished.

The Trubi Formation consists of approximately 95 m of white and grayish marls that, according to Cita (1975), would include the Zanclean (Seguenza, 1868; Cita and Gartner, 1973) and part of the Piacenzian. Each rhythm, approximately one meter thick, shows a sequence of four facies, successively gray, white,

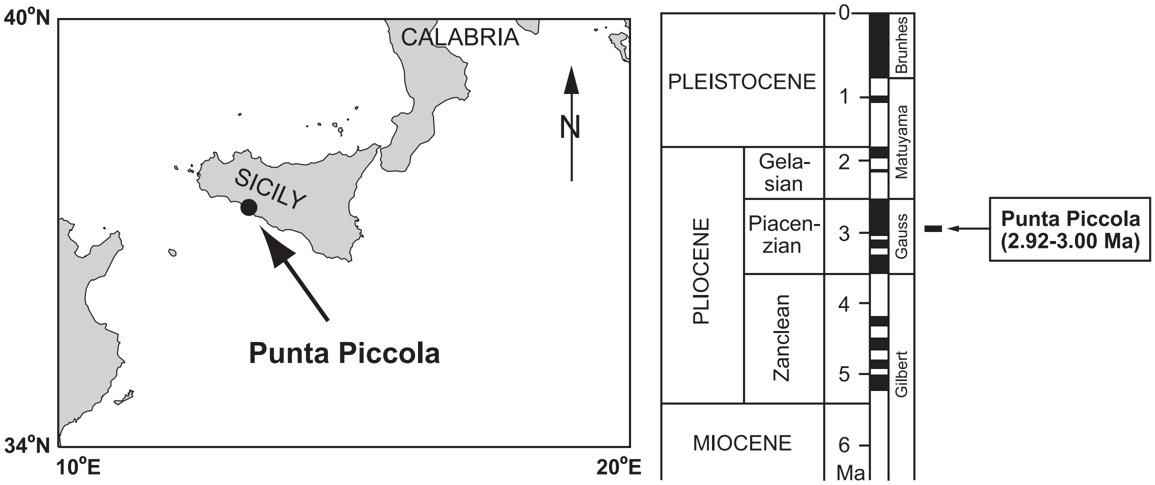


Fig. 1. Location (left) and stratigraphical position (right) of the Punta Piccola section.

beige and white (Hilgen, 1987). The last rhythm corresponds to number 95 of Langereis and Hilgen (1991).

The Narbone Formation is also made of regular alternations of marls and marl limestones. Most of the beds are light gray. Only in the first rhythms a beige layer occurs in the same sequential situation as in the underlying Formation (Van Os et al., 1994). Brown beds, sometimes very dark, especially in rhythm number 107 (bed G of Brolsma 1978), enhance the rhythmic pattern.

All these sedimentary cycles are strongly related to astronomical variations, which enabled the establishment of a chronology during the Pliocene (Hilgen, 1987; Hilgen and Langereis, 1989; Langereis and Hilgen, 1991; Lourens et al., 1996).

We study here cycles 104–108 where we collected 123 samples at 5-cm intervals as previously used for mineralogical analyses (Foucault and Mélières, 2000).

3. Methods

Pollen and fresh water algae were extracted from 59 samples. After drying and weighing, samples were processed with 25% HCl, 70% HF, and then 25% HCl and sieved at 10 μm. After each acid treatment, samples were washed with distilled water. Pollen residues were diluted in glycerin and studied on slides. The calculation of pollen concentrations was made through the addition of calibrated *Lycopodium* tablets before the chemical treatment. Due to their aptitude for transport and preservation, *Pinus* pollen grains are very abundant in the samples. At least 100 pollen grains of non-*Pinus* pollen grains were counted per slide.

Pollen percentages have been calculated on a sum excluding *Pinus*. Because 19 samples were too poor in pollen for a reliable calculation of the percentages, we did not take them into account.

4. Results

Both pollen concentration (Fig. 2) and pollen percentages (Fig. 3) show cyclical variations, which are related to the sedimentological rhythms.

Total pollen concentrations are low, varying from less than 500 up to 9000 grains per g of dry sediment. The concentrations are highest in the sapropelic layers and lowest in the white calcareous sediments. Pollen concentration is clearly dominated by *Pinus* concentration. The Prasynophyceae (fresh water algae) concentration curve displays a pattern similar to that of conifers and Pteridophyta. These three curves vary inversely to the palygorskite concentration curve.

The concentration and percentage variations for individual taxa reveal, particularly in cycles 105 and 106, four phases within each cycle, three (*a*, *b* and *c*)

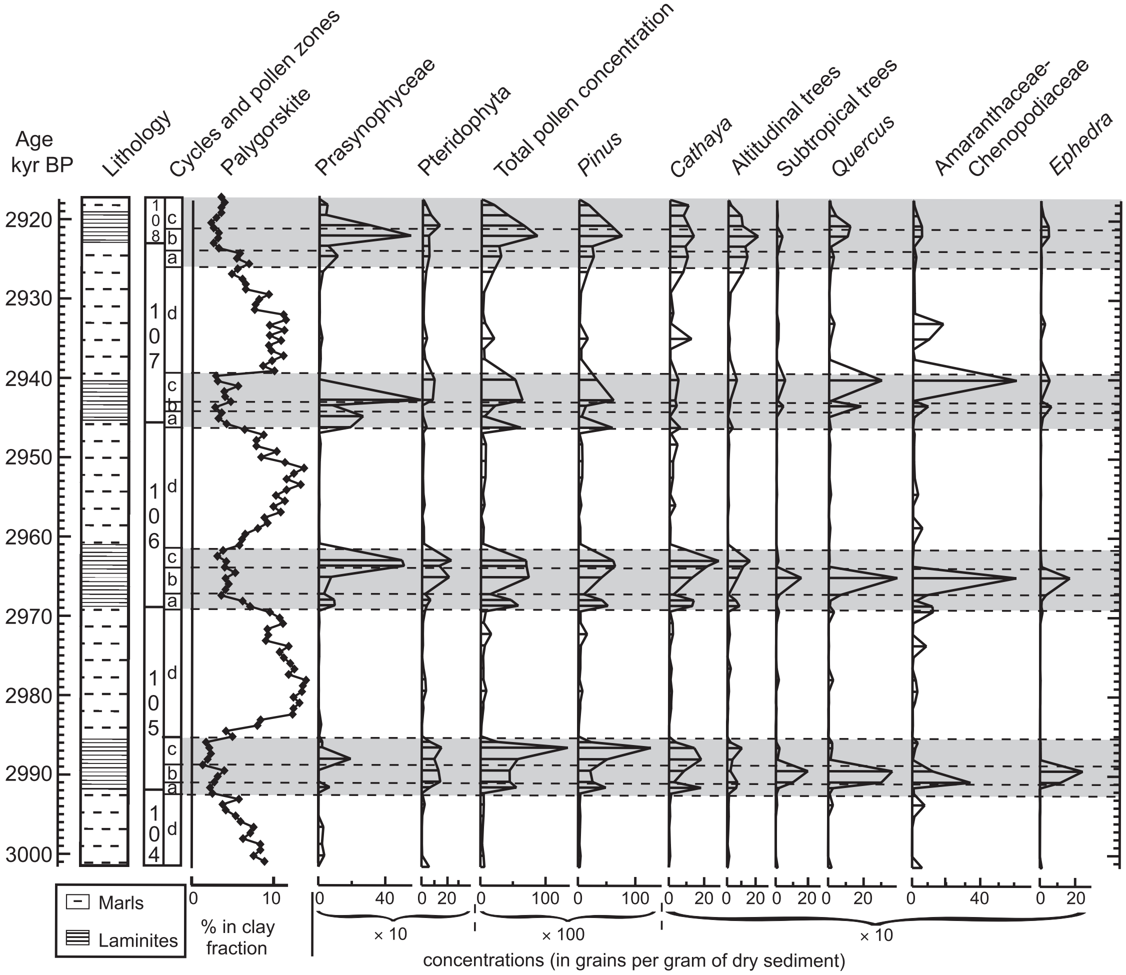
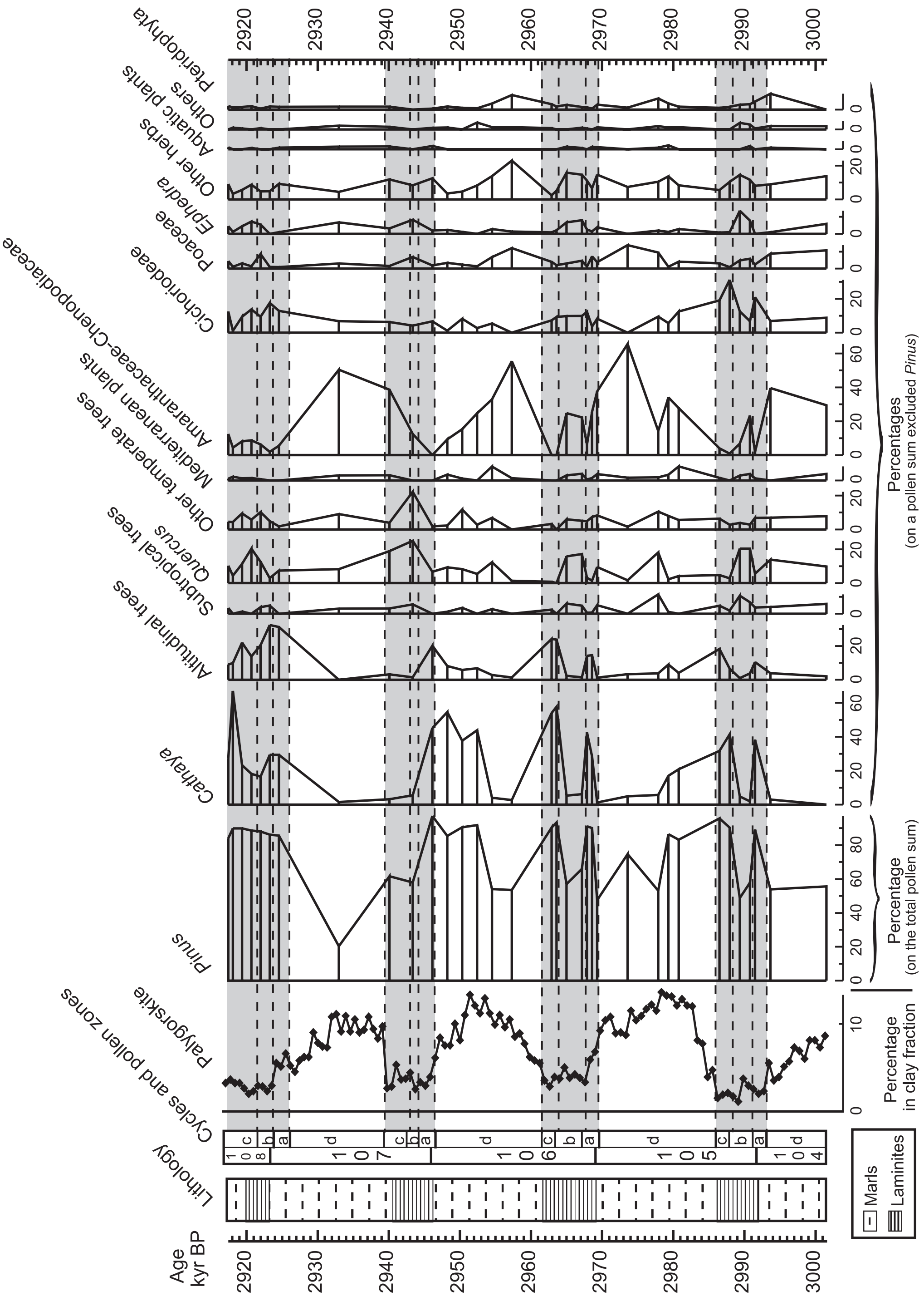


Fig. 2. Concentration of palynomorphs from the Punta Piccola section. Palygorskite proportions curve on the left is given for comparison. For pollen zones, see explanation in the text. Cycle numbers according to Langereis and Hilgen (1991). Time scale according to Lourens et al. (1996). Subtropical trees: Taxodiaceae (*Sequoia* type mainly), *Myrica*, *Engelhardtia*, *Distyllium,* Sapotaceae, Palmae, etc. Altitudinal trees: *Tsuga*, *Cedrus*, *Abies* and *Picea*.

in the dark sapropelic layers, and one (*d*) in the white calcareous sediments. We must point out that the base of phases *a* does not always correspond to those of the sapropelic layers (which were used to determine the beginning of the cycles) particularly for cycle 108. This may result from a poor estimation for the position of the base of the sapropel on the field. Nevertheless, the same cycle boundaries that were used in Foucault and Mélières (2000) are maintained in order to avoid confusion. In the following text, we consider that phases *a*, *b*, *c* and *d* belong to the same sedimentary cycle.

Fig. 3. Percentages of palynomorphs from Punta Piccola section. Palygorskite proportions curve on the left is given for comparison. For pollen zones, see explanation in the text. Lithology and cycles: same symbols and numbers as Fig. 2. Subtropical trees: Taxodiaceae (*Sequoia* type mainly), *Myrica*, *Engelhardtia*, *Distyllium,* Sapotaceae, Palmae, etc. Altitudinal trees: *Tsuga*, *Cedrus*, *Abies* and *Picea*. Other temperate trees: Betulaceae (*Alnus*, *Betula*, *Carpinus*, *Corylus*), Fagaceae (*Fagus*, *Castanea*), Ericaceae, Ulmaceae, *Acer*, *Carya*, etc. Mediterranean plants: *Quercus ilex* type, *Olea*, *Pistacia*, etc. Other herbs: Apiaceae, Asteraceae, Brassicaceae, Caryophyllaceae, Cyperaceae, *Plantago*, Urticaceae, *Erodium*, etc. Aquatic plants: Typhaceae, Ranunculaceae, Plumbaginaceae, *Potamogeton*, etc.


Age
kyr BP
2920
2930
2940
2950
2960
2970
2980
2990
3000
Lithology
Cycles and pollen zones
108
107
106
105
104
a
b
c
d
Palygorskite
Pinus
Cathaya
Altitudinal trees
Subtropical trees
Quercus
Other temperate trees
Mediterranean plants
Amaranthaceae-Chenopodiaceae
Cichorioideae
Poaceae
Ephedra
Other herbs
Aquatic plants
Others
Pteridophyta
Marls
Laminites
Percentage
in clay fraction
Percentage
(on the total pollen sum)
Percentages
(on a pollen sum excluded Pinus)
0
10
20
40
60
80

Phase *a*: The pollen concentration (Fig. 2) increases for all the conifers (*Pinus*, altitudinal forest trees, *Cathaya*) and Pteridophyta, as well as, to a lesser extent, the fresh water algae (Prasynophyceae) concentration. Other taxa are less abundant and increase slightly. The pollen percentages (Fig. 3) show a similar pattern: values are high for the conifers and for the Cichoriodeae (in the first and the fourth sapropelite), and low for the others.

Phase *b*: The pollen concentration generally decreases for the conifers and Pteridophyta, whereas it increases notably for the subtropical trees, *Quercus*, Amaranthaceae–Chenopodiaceae and *Ephedra*. Similarly, percentages are low for the conifers and high for the subtropical trees, *Quercus*, *Ephedra* and herbs.

Phase *c*: The pattern is similar to zone *a*, except for the Prasynophyceae concentrations, which are highest when the palygorskite percentage begins to reincrease.

During these three phases, palygorskite percentages are generally low.

Phase *d*: The concentrations are very low for all the pollen taxa and for Prasynophyceae. Percentages of Amaranthaceae–Chenopodiaceae are high and, with Poaceae and herbs, constitute the main part of the pollen association. During this phase, corresponding to the light gray sediments, palygorskite percentages are high.

Cycles 107 and 108 show a few differences in comparison with cycles 105 and 106: phase *c* of cycle 107 has a maximum percentage of *Quercus* and Amaranthaceae–Chenopodiaceae similar to phase *b* in cycles 105 and 106; cycle 108 is incomplete and in phase *a*, the altitudinal trees percentages are high.

5. Discussion

5.1. Preservation of palynomorphs

The total concentration record, as well as the individual ones (Fig. 2), particularly in cycles 104–106, displays large differences between sapropelitic layers and carbonate-rich intervals. In the sapropelites, palynomorphs are rather abundant, but they are scarce in the carbonate-rich layers. In fact, Punta Piccola's sapropels show similar increases in pollen concentration as those recorded in upper Pliocene and Pleistocene sapropels.

There are three possible ways to interpret these low pollen concentrations. The first is that, during this period, no pollen was produced in the borderlands; the second is that pollen was produced but not transported in the sedimentation areas; the third is that pollen was produced and carried to the site but was destroyed after deposition.

The first hypothesis can be excluded because other Pliocene records show that vegetation was largely developed on the central Mediterranean borderlands (e.g., Suc and Bessais, 1990; Suc et al., 1995, 1999; Fauquette et al., 1998; Kloosterboer-van Hoeve, 2000). The second is not realistic because it implies radical changes in the atmospheric conditions such as an interruption of wind during this period. Therefore, the third hypothesis, a postdepositional destruction of pollen, seems to be the only one that can be retained. In fact, numerous works have shown that oxidation readily degrades palynomorphs, and is far more active during deposition of carbonate-rich sediments than of sapropelitic layers (Birks and Birks, 1980; Havinga, 1967, 1984; Keil et al., 1994; Versteegh and Zonneveld, 2002; Zonneveld et al, 1997; Hopkins and McCarthy, 2002). We may conclude that these differences in pollen concentration in relation to sediment composition probably result from differential preservation.

Nevertheless, the increase in pollen concentration of *Quercus*, subtropical trees, Amaranthaceae–Chenopodiaceae and *Ephedra* in the middle sapropel (phase *b*, Fig. 2), versus the relatively low concentration of *Pinus* and other coniferous taxa, is difficult to explain by oxidation only. However, it has been demonstrated (Birks and Birks, 1980; Havinga, 1967, 1984) that there is a good relation between differential resistance of the pollen types to postdepositional degradation and pollen concentration in sediments. In our samples, all pollen grains (taking all types together) are uniformly preserved within the layers with no significant corrosion from one type in relation to another. In particular, *Pinus* pollen grains do not show the alteration after oxidation observed by Hopkins and McCarthy (2002). Thus, it seems that differential preservation was not predominant inside the sapropelic layers.

In fact, pollen concentration in the middle sapropel (phase *b*) could be explained by transport processes: *Quercus*, subtropical trees, Amaranthaceae–Chenopodiaceae and *Ephedra* pollen grains, which are well concentrated here, are mainly transported by wind (Faegri and Iversen, 1964; Erdtman, 1969; Cour, 1974). The others, such as Pinaceae, which are less concentrated in the phase *b*, are transported by wind in the same way and also by rivers (Cross et al., 1966; Heusser, 1988; Suc and Drivaliari, 1991) as well as Pteridophyta whose spores are too big to be carried by wind and fresh water algae. Thus, we considered that the mode of transport could have influenced the quantity of each pollen type in the sediment. In the middle sapropel (phase *b*), we suggest a better representation of the wind transport at the expense of river and marine circulation transports.

5.2. Vegetation and climate

As individual pollen analysis provides a somewhat distorted view of the vegetation, we have used time series of pollen concentration or percentages here, which reflect the changes in vegetation and thus can be interpreted in terms of climatic changes (Faegri and Iversen, 1964). The location of the Sicilian Punta Piccola section, in the frame of central Mediterranean Pliocene palaeogeography (Yilmaz et al., 1996, encl. 3), shows that pollen rain could have originated here from the North as well as from the South without being able to distinguish the two sources. The pollen diagrams reveal a well-diversified flora in which altitude coniferous trees, subtropical elements, temperate trees and herbs are present together, indicating an altitudinal zonation of the vegetation in the bordering lands. From coast to highlands, vegetation was organised in altitudinal belts: in the lowlands, an open vegetation; at midaltitude, subtropical forest and temperate *Quercus* forest; in the highlands, altitudinal coniferous forest. The presence of subtropical elements suggests that climatic conditions were generally wetter and warmer than presently, as generally observed for the Pliocene (Suc et al., 1995, 1999; Fauquette et al., 1998). The present-day xeric Mediterranean gradient (with less precipitation towards the South) was already settled during the Pliocene (Suc, 1989; Suc et al., 1995), and controlled the vegetation distribution: more forest in the wetter North, enhanced by the presence of mountains, and open vegetation in the dryer South.

In the brown layers, Prasynophyceae show two concentration maxima (Fig. 2), a small one in the lower part (phase *a*) and a bigger one in the upper part (phase *c*). Prasynophyceae are fresh to low-saline water algae (Londeix et al., 1999; Williams, 1978), which must have been carried by rivers to the sea. Their occurrences in phases *a* and *c* indicate periods of enhanced precipitation and continental runoff. Concentrations of *Pinus*, the major component of the assemblage, *Cathaya* and altitudinal conifers (*Cedrus*, *Abies*, *Picea*, etc.) show the same pattern, probably because these trees have bisaccate pollens which are efficiently carried by rivers (Cross et al., 1966; Heusser, 1988; Suc and Drivaliari, 1991).

The organic carbon concentrations (Fig. 4) show very similar variations. In such carbon-poor oxidised sapropelitic layers, the residual organic carbon may mainly derive from continental components, whereas organic carbon in carbon-rich sediments have mainly a marine origin (Bouloubassi et al., 1998). Thus, as for the Prasynophyceae, the maximum concentrations of organic carbon in phases *a* and *c* can be explained by enhanced runoff.

In cycles 101–102, a few meters below cycle 104, Van Os et al. (1994) showed that the barium (Ba) concentration is very low in carbonate-rich layers, and presents two maxima in the lower and in the upper parts of the sapropelitic layers, whereas it is depleted in its middle part. These authors have interpreted these maxima as markers of enhanced bioproduction. We suggest that these two Ba maxima could result from increased continental supply occurring during times equivalent to our phases *a* and *c*.

In phase *b*, percentages of *Quercus*, other temperate trees, subtropical trees, Poaceae and *Ephedra*, as well as Amaranthaceae–Chenopodiaceae (except in cycle 107), show maxima (Fig. 3). *Quercus*, other temperate trees and subtropical trees live under humid climatic conditions, whereas Amaranthaceae–Chenopodiaceae, Poaceae and *Ephedra*, live under dry climates or in saline edaphic conditions. Thus, these simultaneous maxima cannot reflect precipitation changes. Moreover, smectite and chlorite abundances (Fig. 4), correlated with precipitation intensity (Foucault and Mélières, 1995), show maximum values here, whereas palygorskite, characteristic of Saharan and peri-Saharan influx, has its minimum of abundance here. If precipitation did not decrease at this time, the change in the vegetation with the highest percentages in subtropical trees, *Quercus*, Amaranthaceae–Chenopodiaceae and *Ephedra*, may corre-

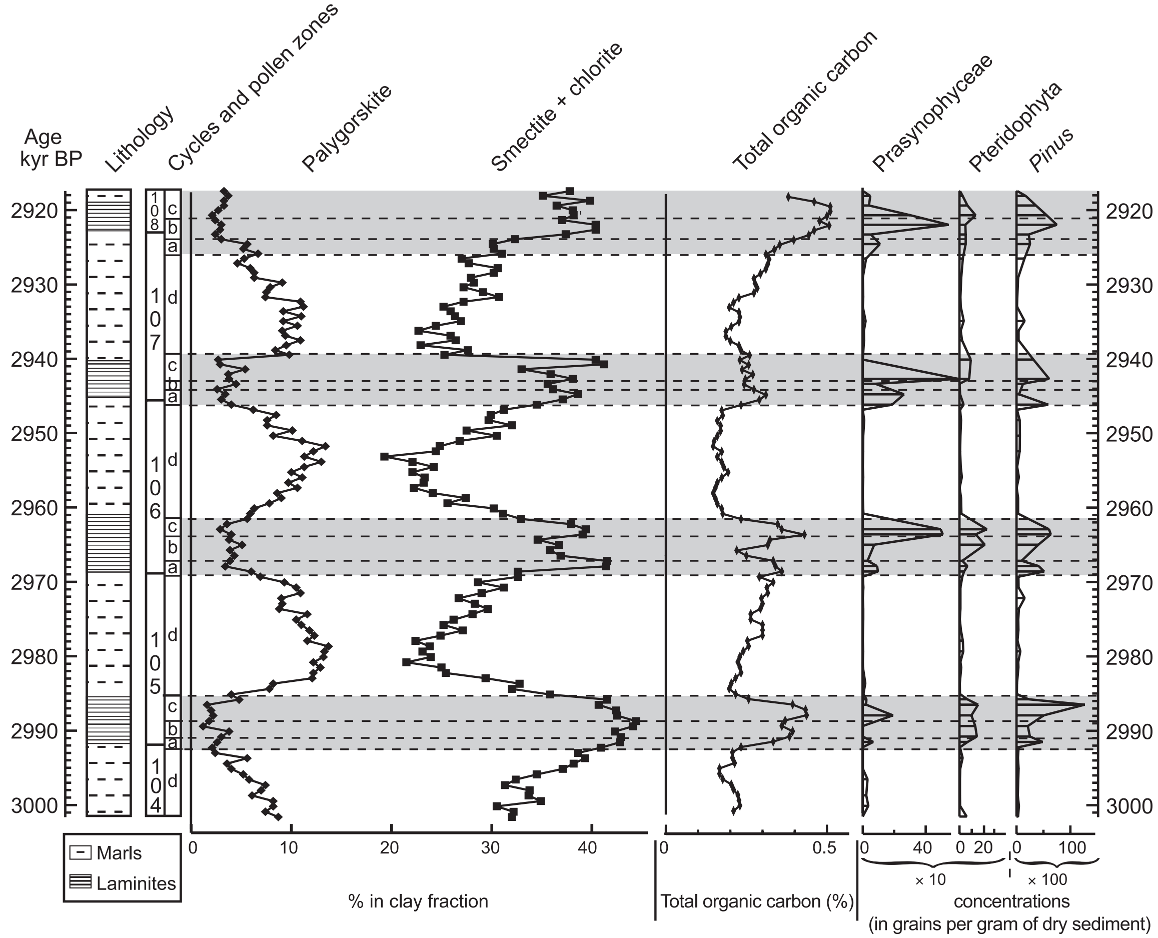


Fig. 4. Several characteristic features from Punta Piccola section content, showing correlations between clay proportions, total organic carbon content (3 value moving average), Prasynophyceae, Pteridophyta and *Pinus* concentrations.

sponds to a slight increase in temperature in the central Mediterranean.

It is not possible to interpret phase *b* in the middle sapropel as an interruption of the sapropelic sedimentation, as already observed in the recent S1 sapropel in Mediterranean cores. In the S1 sapropel, the pollen profile was completely different, indicating a slight decrease in temperature, according to pollen as well as with other data (Sangiorgi et al., in press; de Rijk et al., 1999), which is opposite to what was observed in our samples. In addition, the sapropel S1 interruption is marked by a radical return to oxic conditions, as expressed in pollen analysis by very low pollen concentration, similar to those recorded in the surrounding carbonated sediments (e.g., Combourieu-Nebout et al., 1998; Guinta et al., 2003), which is not the case in our data.

In the carbonate-rich layers (phases *d*), maxima of open vegetation percentages, mainly composed by Amaranthaceae–Chenopodiaceae and minima of percentages of arboreal taxa (Fig. 3), could be due to two causes: (1) a change in the atmospheric circulation, with a higher aeolian influx from the South where the lowlands were occupied by open vegetation; (2) a climatic change towards arid conditions which results in the spreading of the coastal open vegetation at the expense of the forest, especially in the northern borderlands.

The first hypothesis is difficult to accept without changes in the vegetation cover of Sahara and peri-

Saharan areas. If the soils had remained largely recovered by open vegetation, aeolian erosion on these soils cannot have been very strong and, whatever the wind strength, would not have allowed much dust to be carried over the Mediterranean. Consequently, the increase in palygorskite concentration, blowed as dust from Saharan and peri-Saharan areas, and observed in phase *d*, cannot be explained only by atmospheric circulation changes.

The second hypothesis, which requires dryer conditions in the Mediterranean realm, implies an aridification of Saharan and peri-Saharan areas. The scarce open vegetation does not protect the soils, which can be easily eroded by wind and be the source of dust, carried by wind over the whole of the Mediterranean. This hypothesis, which is in accordance with the increase in palygorskite in phase *d*, can be retained.

It is tempting to compare Punta Piccola's sapropels with those of Upper Pliocene and Pleistocene. Nevertheless, concerning the pollen record, this comparison remains difficult because they have not been deposited under the same global climate conditions. Upper Pliocene and Pleistocene sapropels occur during periods when climate was largely controlled by 40 ky (obliquity) and/or 100 ky (eccentricity) rhythms related to oscillations of the northern ice sheets (Paillard, 1998), which was less active during our studied period, when the 20 ky (precession) rhythm was dominant (Hilgen et al., 1993). Whereas fresh water inputs, the main cause of sapropel formation, are well recorded in the Punta Piccola's series, pollen analyses do not show any evidence of increased rainfall in the Upper Pliocene and Pleistocene sapropels. During these more recent periods, vegetation changes, deduced from pollen analysis, are mainly controlled by the global climate changes linked to the oscillations of the northern ice sheet (e.g., Combourieu-Nebout, 1987; Rossignol-Strick and Paterne, 1999), instead of the more local immediate variations in the African monsoon controlled by insolation (Rossignol-Strick, 1983) prevailing in Punta Piccola series.

6. Conclusions

Rhythmic variations of the pollen and fresh water algae content of the Punta Piccola's sediments reflect climatic changes resulting from orbital parameters and particularly precession.

Although pollen concentration variation in the Punta Piccola's sediments mainly reflects the good preservation of organic matter linked to sapropelic layer presence, a careful examination of pollen data reveals patterns of climatic variations and of differential wind transportation. In each rhythm, the pollen record displays four phases, three (phases *a*, *b* and *c*) in the wettest period (brown palygorskite-poor sediment) and one (phase *d*) in the driest period (light palygorskite-rich sediment). During phases *a*, *b* and *c*, increases in moisture are well marked by the highest fresh water inputs; phase *b*, in the middle of sapropelic layer, also shows an additional increase in temperature and is marked by a higher representation of wind input. Phase *b* could not be considered as equivalent to an interruption of the sapropelic sedimentation, as already observed in the more recent sapropel S1. During phase *d*, corresponding to the carbonate-rich sediments, arid continental environments are well developed, in particular in the South, which strengthens the previous hypothesis deduced from mineralogical analyses, with the highest inputs in palygorskite from the Sahara.

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