Vegetation changes during the late Early Pleistocene at Montalbano Jonico (Province of Matera, southern Italy) based on pollen analysis

Sébastien Joannin [a,*], Neri Ciaranfi [b], Simona Stefanelli [b]

[a] *Université de Lyon, F-69622, Lyon, France; Université Lyon 1, Villeurbanne, France; CNRS, UMR 5125, PEPS, France*
[b] *Dipartimento di Geologia e Geofisica, Universita di Bari, Via Orabona 4, 70125 Bari, Italy*

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ABSTRACT

Pollen analysis of the Early Pleistocene Montalbano Jonico section in southern Italy reveals cyclic changes driven by climate and eustasy, as illustrated by mesothermic vs. steppe elements for climate, and *Pinus* vs. Caryophyllaceae, Amaranthaceae–Chenopodiaceae and *Ephedra* for eustasy. These results are directly compared with oxygen isotope data on *Globigerina bulloides* constrained within a biostratigraphic framework based on nannofossils and foraminifers, facilitating a new age calibration for the section. Marine isotopic stages 37 to 23 (1.250–0.900 Ma) are recorded, and compared with global and Mediterranean oxygen isotope curves. High-frequency changes in pollen are related to the Mediterranean curve (*Globigerinoides ruber*) from ODP Site 967, and superimposed the LR04 stack curve. During the Early Pleistocene, pollen recorded global and regional climate changes related to obliquity and precession, respectively, and regional tectonic evolution. Precession forcing was caused by Mediterranean wetness related to precession. The intensified precession effect over climatic cycles, that is expected during the Middle Pleistocene Transition, is not recorded in the Montalbano Jonico interval A vegetation changes.

1. Introduction

Since the Late Pliocene (i.e. about 2.6 Ma), Earth's climatic changes have been affected by periodic Northern Hemisphere ice sheet expansions and contractions (Ruddiman, 2003; Berger and Loutre, 2004). These have resulted in changes to the oxygen isotopic composition of seawater, where marine foraminifers live (Lisiecki and Raymo, 2005). Climatic cycles are under the control of changes in orbital parameters, these being precession (period: 20 kyrs) also modulated by the eccentricity (Maslin and Ridgwell, 2005), and obliquity (period: 41 kyrs). Obliquity and precession are dominant influences on the duration of the climatic cycles (eccentricity paces but does not drive climate, Maslin and Ridgwell, 2005). The Mid-Pleistocene Transition (MPT), also called Mid-Pleistocene Revolution, is a period of change from an earlier "obliquity world" towards the subsequent 100 kyr cycles related to precession (Maslin and Ridgwell, 2005). The MPT occurred broadly between 1.200 and 0.500 Ma (Head and Gibbard, 2005) and more narrowly between 0.900 and 0.650 Ma (Maasch and Saltzman, 1990; Mudelsee and Stattegger, 1997; Maslin and Ridgwell, 2005). The Early-Middle Pleistocene boundary should be placed during the MPT at the Matuyama–Brunhes magnetostratigraphic boundary (Head and Gibbard, 2005), which is dated at 0.773 Ma (Channel et al., 2004). Since 1.200 Ma to the MPT's end, climatic cycles have had a relatively variable time-duration (Maslin and Ridgwell, 2005).

Climate reconstruction is also attainable using vegetation changes observed from pollen in continental and marine sediments. In the Mediterranean region, vegetation changes have so far been observed for the Pliocene, the Early Pleistocene and after the MPT (Wijmstra and Smit, 1976; Suc and Zagwijn, 1983; Suc, 1984; Combourieu-Nebout and Vergnaud Grazzini, 1991; Russo Ermolli, 1994; Ravazzi and Rossignol-Strick, 1995; Tzedakis and Bennett, 1995; Subally et al., 1999; Okuda et al., 2002). In contrast, vegetation changes are relatively poorly understood during the MPT itself (Suc and Popescu, 2005), except for a few studies on brief time intervals carried out in Italy (Ravazzi et al., 2005; Capraro et al., 2005). Here, the most continuous section is the Semaforo-Vrica section, which includes the Global Stratotype Section and Point (GSSP) of the Plio-Pleistocene boundary (Aguirre and Pasini, 1985). Combourieu-Nebout and Vergnaud Grazzini (1991) have shown the record of climatic cycles through pollen and geochemical analyses from 2.470 to about 1.400 Ma (age of the Sapropel "*"). Lourens et al. (1996a,b, 1998) extended this section upward towards Crotone (Fig. 1a), i.e. up to 1.210 Ma. Joannin et al. (2007a) compared the pollen signal with isotope measurements in the Santa Lucia section (Fig. 1a), which is an equivalent of the uppermost part of the Crotone series (between sapropels "t" to "v", 1.356 and 1.280 Ma respectively). The Montalbano Jonico section (Southern Italy; Fig. 1a-b) is geographically close enough to the Crotone area to extend it stratigraphically. Montalbano Jonico is accordingly expected to record environmental changes that occurred
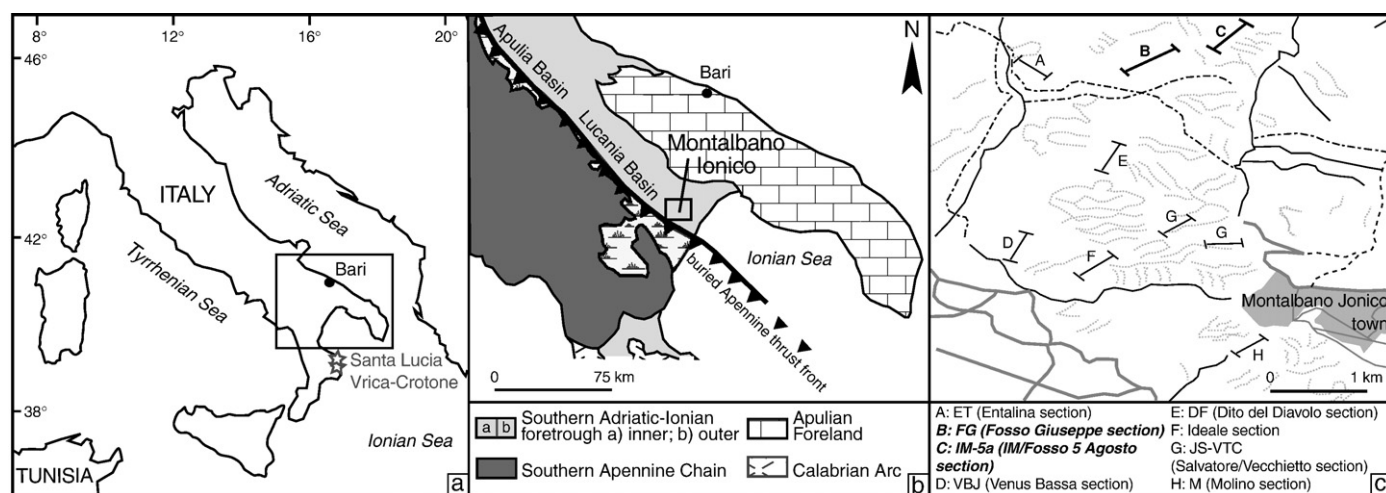
Fig. 1. a: Geographical location of the studied area. b: Schematic geological map of the South-Eastern Italy. c: Enlargement showing Early to Middle Pleistocene sediments of the Montalbano Jonico composite section. The two sections analysed in this study are in bold.

during the late Early and early Middle Pleistocene (Ciaranfi et al., 1996, 1997, 2001; Ciaranfi and D'Alessandro, 2005). The Montalbano Jonico section has been proposed as the GSSP for the Early-Middle Pleistocene boundary (Ciaranfi and D'Alessandro, 2005), although, the age of its base is not well constrained (Stefanelli et al., 2005). The present work concerns the high-resolution pollen analysis of the lower part of the section (interval A). This study aims to link climatic cycles observed from vegetation with oxygen isotopic changes measured on the planktonic foraminifer species *Globigerina bulloides* (Brilli et al., 2000; this work) and biostratigraphic events based on nannofossils (Ciaranfi et al., 1997, 2001; Maiorano et al., 2004; Ciaranfi and D'Alessandro, 2005) and foraminifers (this work). These data are compared with global (LR04 stack; Lisiecki and Raymo, 2005) and regional (Mediterranean ODP Site 967; Kroon et al., 1998) oxygen isotope curves (from benthic and planktonic foraminifers, respectively) in order to apply new time constraints on the Montalbano Jonico interval A. In addition, this study is expected to improve the chronological relationship between Montalbano Jonico and the uppermost Crotone series. Moreover, vegetational changes indicated by pollen analysis along the continuous 167 m thick Montalbano Jonico interval A should provide new information on the responses of taxa to successive coolings and warmings caused by climate cycles during the beginning of the MPT.

## 2. Geographical and stratigraphical context

The Montalbano Jonico section is situated at 40°17′N and 16°34′E in the Lucania basin (Fig. 1b), which is bounded westward by the Apennine thrust. This basin was affected by the Apennine chain uplift, which resulted in a relative sea-level fall during the late Early Pleistocene. Initially, the centre of the basin subsided, allowing the deposition of hemipelagic sediments. A shallowing phase then occurred during the Middle Pleistocene leading to the emergence of sediments. This was possibly related to the beginning of the infilling phase of the southern part of the Apennines Foredeep (Ciaranfi and D'Alessandro, 2005). The Montalbano Jonico section comprises 10 subsections that belong to the Argille Subapennine Formation (Ciaranfi et al., 1997, 2001). This continuous marine succession is 450 m thick and divided into intervals A and B. Interval A ends at about 0.9 Ma (Stefanelli et al., 2005) and includes the Fosso Giuseppe section (FG) and IM/Fosso 5 Agosto (IM-a) section (Figs. 1c and 2).

Nannofossil analysis assigns interval A to the "small *Gephyrocapsa*" Zone and lowermost part of *Pseudoemiliania lacunosa* Zone (Ciaranfi et al., 1997, 2001; Maiorano et al., 2004; Ciaranfi and D'Alessandro, 2005). The base of interval A cannot be older than 1.257 to 1.241 Ma because the "small *Gephyrocapsa* Zone" began during marine isotope

stages (MIS) 38–37 (Lourens et al., 1998; De Kaenel et al., 1999; Real and Monechi, 2005). The last occurrence (LO) of Large *Gephyrocapsa* (>5.5 μm) is found at 41.22 mcd (1.257 Ma; Lourens et al., 1998) at ODP Site 967 that is located at 34° 04′ N and 32° 43′ E. Two nannofossil bioevents were recognized in the IM-a section (uppermost part of interval A), the first common occurrence (FCO) of *Gephyrocapsa* sp. 3 and the last common occurrence (LCO) of *Reticulofenestra asanoi* (Maiorano et al., 2004). They occur within two sapropel layers identified by peculiar benthic foraminiferal assemblages (Stefanelli et al., 2005). Hence, based on published correlations between calcareous nannofossil events, oxygen isotope stages, sapropel stratigraphy and insolation cycles (Lourens et al., 1996a; Kroon et al., 1998; De Kaenel et al., 1999; Pierre et al., 1999), the two sapropel layers are correlated to MIS 25 and 23 and associated with insolation cycles 90 (0.955 Ma) and 86 (0.908 Ma) (for further details, see Maiorano et al., 2004; Stefanelli et al., 2005; Maiorano et al., 2008). Three further sapropel layers are recognized in the FG section again on the basis of particular benthic foraminiferal assemblages. Since it was not possible to correlate these layers following the above-mentioned criteria, they were assigned as sapropels S, SI, SII (Stefanelli et al., 2005). In the Eastern Mediterranean, brief influxes of the planktonic foraminifer *Globorotalia crassaformis* have been identified at ~1.135 Ma and ~1.140 Ma from Ocean Drilling Program (ODP) Sites 967 and 969, respectively (Lourens et al., 1998). These ages are in agreement with insolation cycles i-108 and i-106 (De Kaenel et al., 1999) and to MIS 35–34 (Kroon et al., 1998). A climatostratigraphic interpretation of pollen results from the Montalbano Jonico interval A (see below) predicted that the *Gt. crassaformis* influxes might occur between sapropels S and SII, and this was confirmed by re-examination of residues: the influxes are documented by numerous specimens of *Gt. crassaformis* in nine samples (FG 77-79 and FG 84-89). These two series formed one influx from 51.1 to 59.6 m (Fig. 3).

3. Materials and methods

The 202 samples collected along the 168.7 m thick interval A were previously used for biostratigraphic and isotope analyses performed on tests of planktonic foraminifers (*Globigerina bulloides*). Pollen analysis was performed on 139 samples which are shown in Fig. 2. These samples were processed using a standard method adapted from Cour (1974). HCl and HF treatments were followed by sieving at 160 μm and 10 μm respectively and by enrichment procedures (ZnCl₂). A minimum of 20 taxa per sample were identified. More than 35,500 pollen grains were counted in the whole section, which corresponds to at least 150 per sample (for more details, see Fig. 2), plus *Pinus* since it
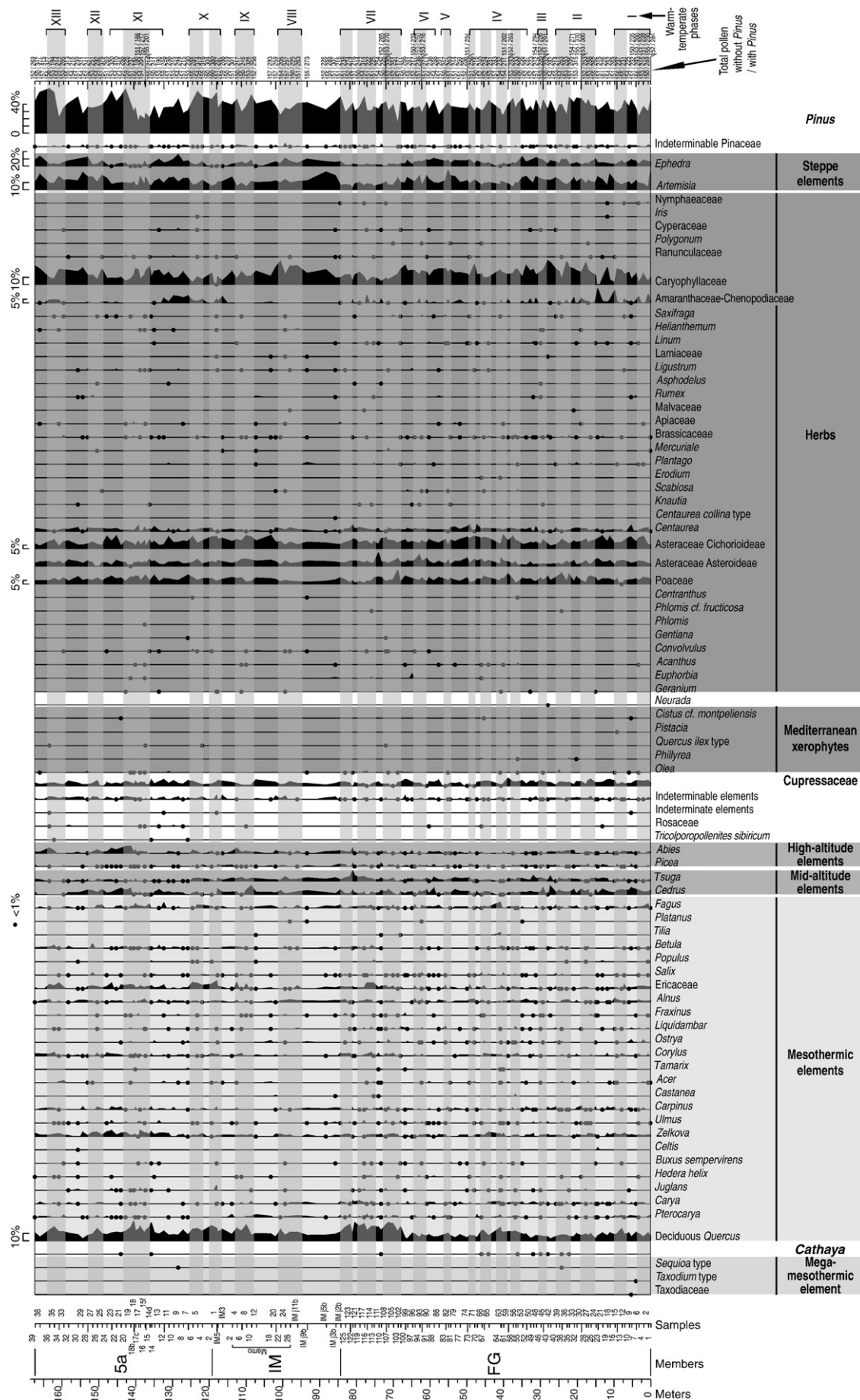
is generally over-represented in marine sediments (Heusser, 1988; Beaudouin et al., 2007).

Pollen grains in coastal marine terrigenous deposits mostly come from rivers (Heusser and Balsam, 1977; Cambon et al., 1997) and are representative of the drainage basin vegetation (Heusser and Balsam, 1977; Beaudouin et al., 2005). The proportion of *Pinus* pollen grains is affected by both production and preservation (Beaudouin et al., 2005), and mostly controlled by the distance from river mouths because of their high buoyancy (Heusser and Balsam, 1977; Beaudouin et al., 2007). *Pinus* percentages are calculated on the total pollen sum while percentages of other taxa are calculated on the total pollen sum without *Pinus*. All percentages are shown in a detailed diagram (Fig. 2).

Taxa have been classified considering their tree or herbs and shrubs nature from the base to top in the Fig. 2. Following Suc (1984) and Combourieu-Nebout (1993), they have been grouped according to their ecology as estimated from their representatives in present-day plant ecosystems (Fig. 2). Ecological constraints such as latitudinal zones, altitudinal belts and edaphic associations (Ozenda, 1975) are easily provided for taxa which are still represented in the European and the Mediterranean regions such as *Zelkova* or *Cedrus*. Many studies estimated ecological constraints for taxa which grow nowadays elsewhere in the world (see Fauquette et al., 1998). For example, *Tsuga* is still growing in a high altitudinal belt in Northern America and Eurasia. Thus, providing these groups helps to extract the ecological constraints for plant development. Variations of these groups can synthesize changes in temperature, precipitation, and increasing altitude (Joannin et al., 2007a,b). Based on a statistical analysis of the pollen database, we formulate two ratios of clearly opposite taxa or groups of taxa, which simplify the environmental information. These ratios are shown in Figs. 3 and 4, using a logarithmic representation: mesothermic vs. steppe elements and *Pinus* vs. Caryophyllaceae, Amaranthaceae–Chenopodiaceae and *Ephedra*.

4. Results

4.1. Pollen

Some taxa that disappear from the Mediterranean region during the Mid-Pleistocene are still recorded at Montalbano Jonico in relatively high abundances. They are mesothermic taxa (such as *Carya*, *Zelkova*, *Pterocarya* and *Liquidambar*), and mid-altitude taxa (such as *Cedrus* and *Tsuga*). Some pollen of the Taxodiaceae (a mega-mesothermic, i.e. subtropical element) and *Cathaya* (a subtropical mid-altitude conifer that today is restricted to China) were found (Fig. 2). All these taxa have since disappeared from Italy (Suc et al., 1995; Svenning, 2003), except for *Zelkova* which is restricted to Sicily (Di Pasquale et al., 1992).

Fig. 2 indicates that the most abundant taxa recorded in the Montalbano Jonico interval A are the mesophilous deciduous tree *Quercus* (11.3% on average), and herbaceous elements Poaceae (6.7% on average), Asteraceae (5.7% on average), Caryophyllaceae (15.1% on average) and *Artemisia* (11.4% on average). Deciduous *Quercus* is the most representative taxon of the mesothermic plants. High percentages of this taxon in pollen records indicate warm-temperate periods associated with significant wetness (Rossignol-Strick and Paterne, 1999). Other mesophilous trees are also indicative of warm and wet conditions such as *Carpinus*, *Alnus*, and *Fagus* but their variability appears not to be consistent with that of deciduous *Quercus*. *Cedrus* abundance is relatively high during the studied interval (3.4% on average). It is generally accepted that the Mid and High-altitude groups need cooler and still humid conditions compared to mesothermic elements. If the ecological meaning of the Poaceae and Asteraceae is unconstrained (Beaudouin et al., 2007), *Artemisia* can grow over a large

thermic range and is often linked with xeric conditions (Subally and Quézel, 2002). As a consequence, steppe elements are separated from the herbs group and their increases record cold and dry conditions in the Montalbano Jonico section (Maiorano et al., 2008).

We used the ratio of mesothermic to steppe elements, since these are anti-correlated ($r = -0.64$; $p < 0.001$), to discriminate warm-temperate from cold phases (Fig. 2). Twenty one short-lived warm-temperate pollen phases (grey shapes in Figs. 2–4) have been identified along the studied section. However, some of these phases, which are close, can be grouped together. From base to top, this results in thirteen main warm-temperate phases: I from about 0.6 to 9.7 m, II: 16.2 to 25.65 m, III: 29.8 to 31.8 m, IV: 36.1 to 49.2 m, V: 55.7 to 57.6 m, VI: 60.2 to 64.1 m, VII: 70 to 84.3 m, VIII: 96 to 100.6 m, IX: 109.9 to 112.5 m, X: 118 to 124.5 m, XI: 132.3 to 146.6 m, XII: 150.5 to 151.8 m and XIII: 159.6 to 163.5 m.

4.2. Vegetation and oxygen isotopes

On the whole, the mesothermic vs. steppe ratio and oxygen isotopic compositions made on *Globigerina bulloides* are correlated ($r = 0.54$; $p < 0.001$). Hence, high percentages of mesothermic elements correlate with low values of $\delta^{18}O$, which indicate warm-temperate phases (Figs. 3 and 4). This correlation is clearly evident for: I, IV, VI, VII, IX, X, XI and XIII, while pollen phases II, III, V, VIII and XII are not supported by low $\delta^{18}O$ values. In contrast, steppe elements together with high $\delta^{18}O$ values indicate colder phases. As shown on Fig. 4, several decreases in $\delta^{18}O$ values immediately precede the corresponding warming in the pollen curve, such as at the beginning of warm-temperate pollen phases I, IV, VII, IX, X and XIII. The beginning of phase II correlates with an isotopic ratio indicating warm conditions in one sample (16.2 m), but correlation in the following samples is less clear. Phase VIII is not obviously expressed by low $\delta^{18}O$ values, except in one isolated sample (at 101.9 m) located at the end of the related phase.

4.3. Global and Mediterranean isotopic correlations

4.3.1. LR04 stack

The correlation of data between Montalbano Jonico and the LR04 oxygen isotope stack (Lisiecki and Raymo, 2005) (Fig. 3), which is based on benthic foraminifera, needs well-constrained ages. At Montalbano Jonico, warming phases XIII and XI are contemporaneous with two bioevents that correlate with warm marine isotopic stages 23 and 25, respectively (see above). These odd-numbered MIS characterize interglacial periods. Using this MIS correlation and the position of the beginning of the brief influx of *Gt. crassaformis*, which precisely correlates with the MIS 35–34 transition (Lourens et al., 1998), six warm-temperate pollen phases are recorded within only four warm MIS. Here, pollen warm-temperate phases IX and V are not related to any warm MIS, because of their low-amplitude variation. In addition, they are not well supported by oxygen isotopes measured on *Globigerina bulloides*. Hence, warm events X, VIII, VII, and VI are attributed to MIS 27, 29, 31, and 33, respectively. In more detail, warm-temperate pollen phases IX and X might be related to double $\delta^{18}O$ depletion which characterizes MIS 27. Warm-temperate pollen phases IV, II and I can't be related to MIS 35, 37 and 39 because of the MIS 39 location within the "large *Gephyrocapsa* zone" (Lourens et al., 1998; De Kaenel et al., 1999; Real and Monechi, 2005). However, warm-temperate pollen phases IV and I show high values of pollen ratio which should be characteristic of an interglacial period. Hence, the two long-lasting warm events corresponding to phases IV and I should correlate with 35 and 37, respectively. Such an interpretation is consistent with the last occurrence of Large *Gephyrocapsa* (>5.5 μm) recorded at 1.257 Ma in ODP Site 967 (Fig. 4; Lourens et al., 1998). Warm-temperate pollen

Fig. 2. Detailed pollen diagrams from the Montalbano Jonico section (interval A). All taxa (except *Pinus*) percentages have been calculated using the sum of pollen counted without *Pinus*. *Pinus* percentage calculation has been done using the total pollen sum. Taxa groups are based on the ecological significance of their present-day representatives: mesothermic, mid-altitude, and high-altitude elements, Mediterranean xerophytes, herbs and steppe elements.
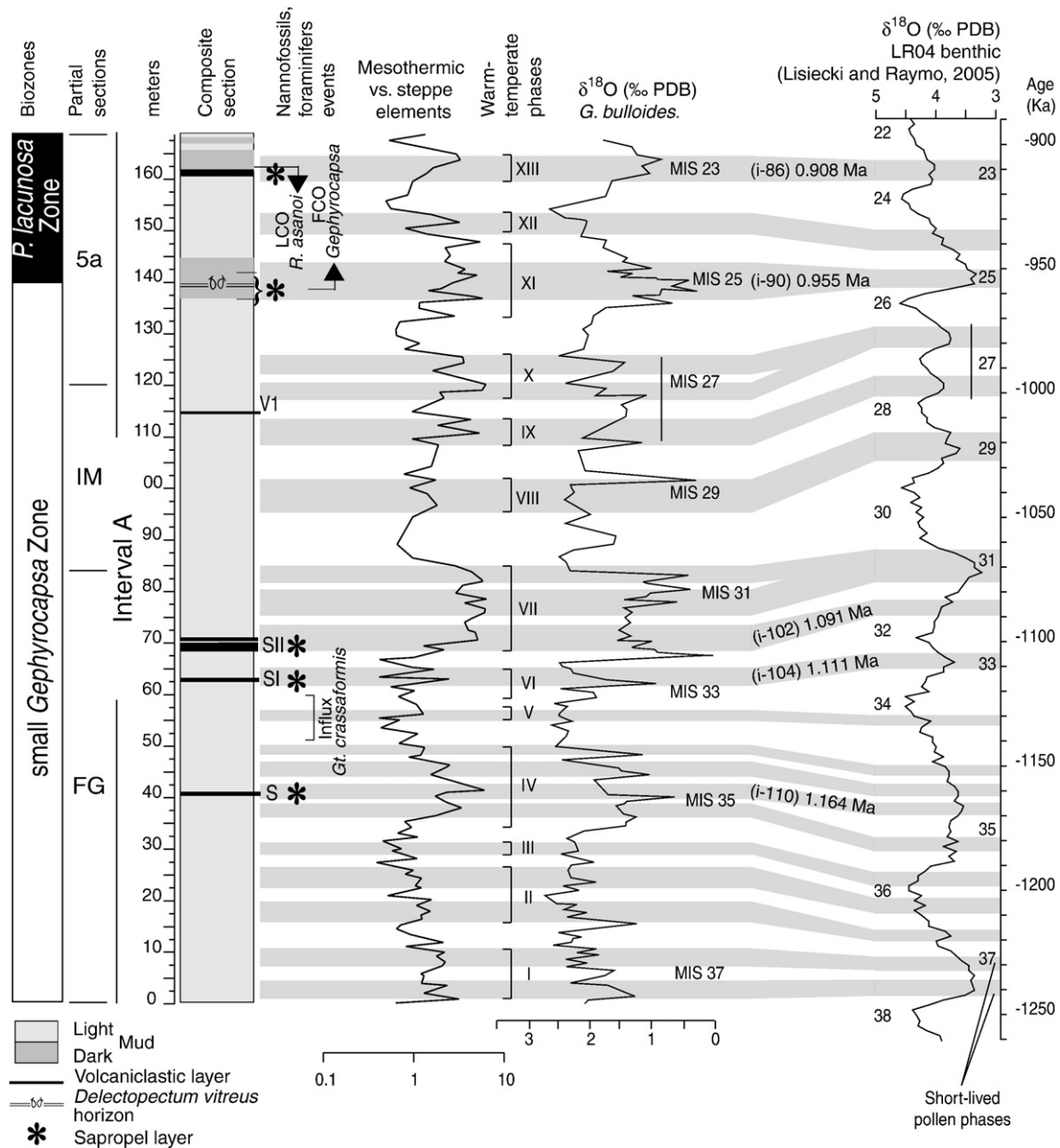
Fig. 3. Lithology, biostratigraphical events, pollen ratio of mesothermic vs. steppe elements, and main warm-temperate pollen phases (using roman numbers) compared to oxygen isotope records from the same samples. Short-lived warm-temperate pollen phases are shaded grey. Proposed marine isotope stages are correlated with the global oxygen isotope record (Lisiecki and Raymo, 2005).

phases XII, V, III-II are recorded during progressive cooling transitions observed in the LR04 curve (MIS 25-24, MIS 35-34 and MIS 37-36, respectively).

4.3.2. ODP Site 967

The proposed calibration establishes precise ages for the entire section (Fig. 3). Using these ages, a correlation is proposed with a Mediterranean oxygen isotope curve (Fig. 4). This curve was obtained on the planktonic foraminifer *Globigerinoides ruber* from ODP Site 967 (Kroon et al., 1998), which contains several sapropelic layers. The two uppermost sapropels found in the Montalbano Jonico section are correlated with insolation cycles i-86 and i-90 (Stefanelli et al., 2005) dated at 0.908 and 0.955 Ma, respectively (Kroon et al., 1998; Pierre et al., 1999). Accordingly, the warm-temperate phase XII might correspond to the negative oxygen isotope shift that indicates sapropel 18 in ODP Site 967. The two double short-lived warmings including in X and in IX are respectively correlated to negative $\delta^{18}O$ values

corresponding to sapropels 20 and 21. This differs from Kroon et al.'s (1998) interpretation that attributes only one negative $\delta^{18}O$ value to MIS 27 related to sapropel 21 (Fig. 4). Another discrepancy exists with the interpretation of Kroon et al. (1998): the long warm phase VII includes three short-lived pollen phases and is related to MIS 31 based on LR04 (Fig. 3). However, we correlate it with MIS 31 and a part of MIS 32-33 using the record of Koon et al. (Fig. 4). Here, the age of sapropel SII from the Montalbano Jonico section is given by correlation with curve LR04. It corresponds to sapropel 25 (i-102 dated at 1.091 Ma; Kroon et al., 1998). Warm-temperate phase VI, which occurs during the deposition of SI and corresponds to MIS 33, is equivalent to sapropel 26 (i-104 dated at 1.111 Ma; Kroon et al., 1998). Deposition of sapropel S at Montalbano Jonico occurs during warm-temperate phase IV and may correspond to sapropel 27 in the ODP Site 967 (i-110 dated at 1.164 Ma; Kroon et al., 1998). Unlike warm-temperate phase I, phase II is not well represented at ODP Site 967. There, the progressive cooling between MIS 37 and MIS 36 is
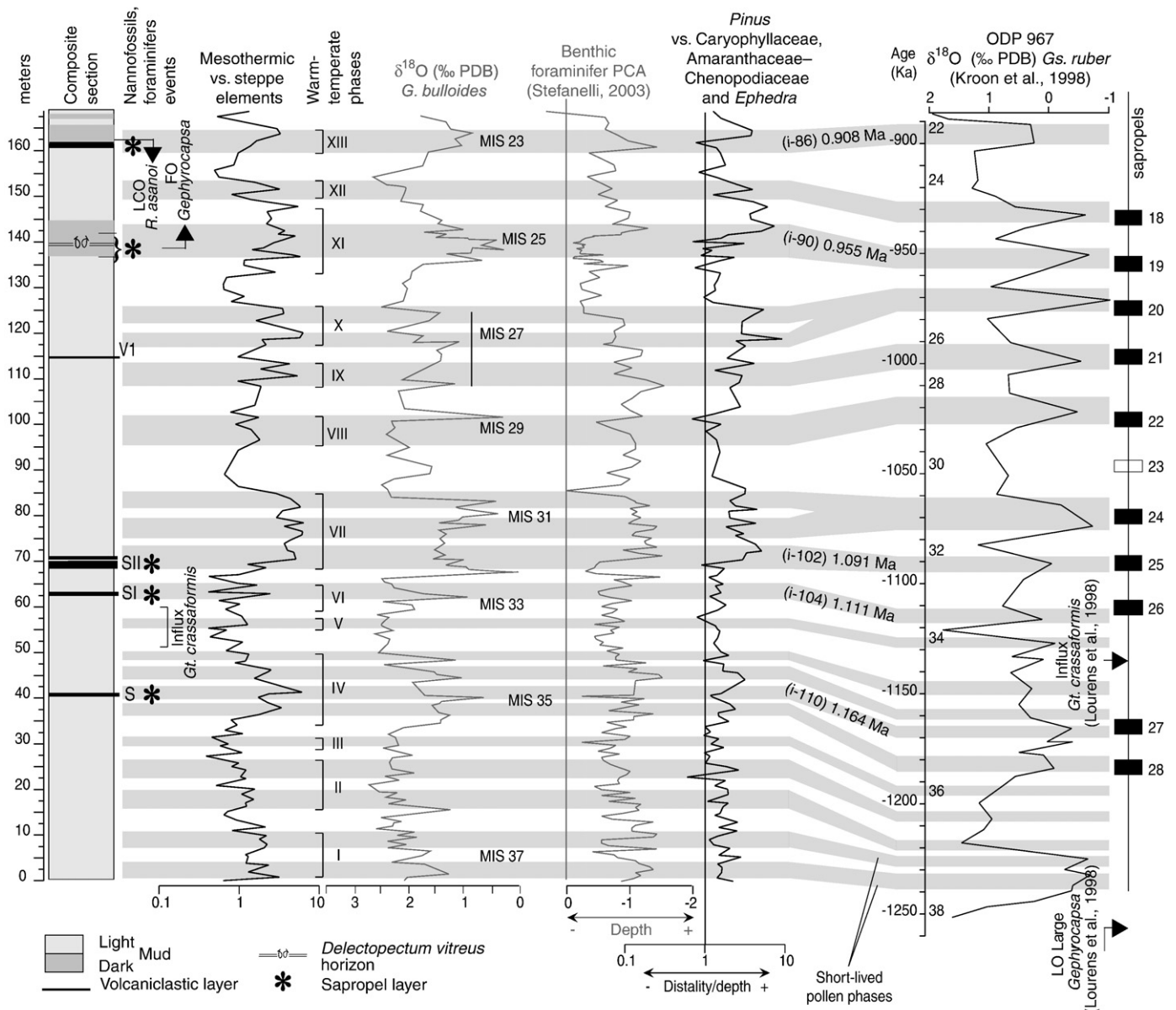
Fig. 4. Cyclostratigraphy of the Montalbano Jonico section and relative sea-level changes. Cyclostratigraphy results from the pollen ratio of mesothermic vs. steppe elements and oxygen isotope signal, with respect to the δ¹⁸O curve for ODP Site 967 (Fig. 3, Kroon et al., 1998). The ODP Site 967 sapropels are dated by Kroon et al. (1998, Table 2). Relative sea-level changes derived from the *Pinus* vs. Caryophyllaceae, Amaranthaceae–Chenopodiaceae and *Ephedra* pollen ratio compared with Factor 1 from a principal component analysis (PCA) on benthic foraminifers (Stefanelli, 2003).

surprisingly abrupt compared to observations at Montalbano Jonico section and in the LR04 curve.

In general, a better correspondence is observed between oxygen isotope records of Montalbano Jonico and the LR04 stack than with ODP Site 967. Several short-lived climate oscillations are recorded in the pollen record from Montalbano Jonico and δ¹⁸O values from ODP 967, as during the transition between MIS 25 and 24 (Fig. 4). This variation is not well expressed in δ¹⁸O values from the Montalbano Jonico section and the LR04 stack. Such a phenomenon is recorded lower in the section to a greater or lesser extent: during MIS 30, sapropel SII, and several times during MIS 35 and 37.

4.4. Sea-level changes

Fig. 4 shows a pollen ratio of *Pinus* vs. Caryophyllaceae, Amaranthaceae–Chenopodiaceae and *Ephedra*. The *Pinus* amount is generally associated with sea-level changes (inducing changes in

distality) because *Pinus* pollen percentages increase with distance from shoreline (Heusser and Balsam, 1977). Caryophyllaceae, Amaranthaceae–Chenopodiaceae, and *Ephedra* are families of herbs. Suc et al. (1995) observed that the development of these taxa was related to the important sea-level fall occurred during the Messinian crisis. These authors considered that Caryophyllaceae, Amaranthaceae–Chenopodiaceae, and *Ephedra* were halophytes as they are able to live in saline environments of newly emerged lands in littoral areas. More generally, these new lands may offer good environmental conditions (not necessary halophytic) for opportunistic taxa like herbs and steppe. As a consequence, their pollen production, which is enhanced by dry and cold climate, can be reinforced by newly available lands. As *Pinus* and Caryophyllaceae, Amaranthaceae–Chenopodiaceae and *Ephedra* are unambiguously anti-correlated ($r = -0.51$; $p < 0.001$), we can assume that increases in Caryophyllaceae, Amaranthaceae–Chenopodiaceae and *Ephedra* are expected during sea-level falls that are related to glacial periods. Consequently, the *Pinus*

vs. Caryophyllaceae, Amaranthaceae–Chenopodiaceae and *Ephedra* ratio is a robust indicator of sea-level variations. Warm-temperate phases observed from pollen and correlated with oxygen isotope composition are also expected to be related to sea-level rises. Bathymetric changes have been also inferred from benthic foraminifer principal component analysis (PCA) where Factor 1 has been regarded as a water depth indicator (Stefanelli, 2003).

The increasing distality/deepening trends are in accordance with bathymetric changes deduced from the benthic foraminifer PCA. Such increases in distality/deepening correspond to interglacial periods (MIS 35, 31, 29-27, 25 and 23; Fig. 4). Another observation is that the section records lower amplitude variations in the *Pinus* vs. Caryophyllaceae, Amaranthaceae–Chenopodiaceae and *Ephedra* ratio from the base of the section to warm-temperate phase VI than in its uppermost part, as with the mesothermic vs. steppe ratio and the oxygen isotope curve. In particular, the warm-temperate phases VII, IX, X, XI, XIII are associated with greater increases in the amplitude of the *Pinus* vs. Caryophyllaceae, Amaranthaceae–Chenopodiaceae and *Ephedra* ratio than the warm-temperate phases I and IV. Warm-temperate phases II, III, V, VI, VIII and XII correspond to low amplitude variations of the *Pinus* vs. Caryophyllaceae, Amaranthaceae–Chenopodiaceae and *Ephedra* ratio.

5. Discussion

5.1. Vegetation changes and climatic cycles

Carya, *Zelkova*, *Pterocarya*, *Liquidambar*, *Cedrus*, *Tsuga*, Taxodiaceae and *Cathaya* are still present in southern Italy during the Early Pleistocene. They progressively disappeared from Europe and Mediterranean regions because they experienced the increasing aridity and/or cold climate that were associated with glacials during the Plio-Pleistocene (Svenning, 2003).

Comparing pollen and oxygen isotopic data allows a climatostratigraphy to be established for interval A of the Montalbano Jonico section. Such progress needs (1) several accurately dated bioevents and (2) continuous climatic curves from land and marine proxies (Combourieu-Nebout and Vergnaud Grazzini, 1991). In addition, a high-resolution chronology is also needed. The studied climate proxies (i.e. pollen analysis compared with oxygen isotopic measurements on *G. bulloides*) are expected to document both regional and global climate evolution. Interglacials and glacials are major events of high amplitude within the long sedimentary records. These global events emphasize the response of climate to obliquity during the Early Pleistocene, which is reflected in fluctuations in global sea-ice volume (Pisias and Moore, 1981; Kroon et al., 1998; Ruddiman, 2003). These globally synchronous fluctuations are especially well-recorded in the stable isotopes of benthic foraminifer tests because these organisms live in deep waters that are not sensitive to local or regional climatic oscillations and/or changes in salinity or temperature (Emeis et al., 2003; Lisiecki and Raymo, 2005). For this reason, we assume that the correlations of our proxies (Fig. 3) with the LR04 stack (Lisiecki and Raymo, 2005) actually reflect the global influence on the Montalbano Jonico sediments.

In the interval A of the section, we identified several warm-temperate phases characterized by the mesothermic element dominance, mainly deciduous *Quercus*. Using the biostratigraphic events from the top of the section and the LR04 stack, we can correlate warm-temperate pollen phases XIII, XI, X–IX, VIII, VII, VI, IV and I with MIS 23, 25, 27, 29, 31, 33, 35 and 37 (interglacials), respectively. Therefore, interval A records about 350 kyrs of climatic evolution, from ca. 1.250 Ma to 0.900 Ma. The entire Montalbano Jonico section (intervals A and B) and the Semaforo–Vrica–Crotone sections (e.g. the Crotone series) (2.400-1.210 Ma) share a common interval. The total duration of these sections is longer than 1.500 Myrs within the Late Cenozoic, encompassing the Plio-Pleistocene boundary and probably the MPT (i.e. 0.900 to 0.650 Ma; Maslin and Ridgwell, 2005). The pollen record

of the Crotone series has provided outstanding insights into the development of vegetation forced by climate changes (Combourieu-Nebout and Vergnaud Grazzini, 1991; Combourieu-Nebout, 1993; Joannin et al., 2007a). Moreover, pollen investigation in marine sediments constitutes an unrivalled approach at the continental-marine interface. These comprehensive paleoenvironmental studies on the lower part of the Montalbano Jonico section clearly demonstrate the need to extend pollen studies to the entire section. These results support the candidature of the Montalbano Jonico section as the Early-Middle Pleistocene boundary stratotype (Ciaranfi and D'Alessandro, 2005).

Conversely, warm-temperate pollen phases XII, V, III and II cannot be related to interglacials of the curve LR04. These phases are placed in correspondence with progressive coolings during interglacial/glacial transitions. In addition, several of the 21 minor brief warm-temperate phases (see above) are subdivisions of interglacials (MIS 31, 35, 37) or glacials (MIS 36) and are designated by grey bands (Figs. 3 and 4). This suggests that the response of the considered proxies is not exclusively linked to global climatic changes.

5.2. Vegetation and short-lived climate oscillations

The Mediterranean region is known to record climatic effects resulting both from obliquity and precession (Kroon et al., 1998; Joannin et al., 2007a,b). It is generally accepted that precession forces changes in wetness and sea-surface salinity leading to sapropel formation (Emeis et al., 2003). Particularly, sapropels are formed when Northern Hemisphere summer insolation is at a maximum during precession minima (Rohling and Hilgen, 1991). During such an orbital configuration, any coeval increase in temperature and decrease in salinity will have caused a decrease in the $\delta^{18}O$ of planktonic foraminifers. However, *Globigerinoides ruber* records negative shifts in $\delta^{18}O$ of higher frequency than *Globigerina bulloides* (Rohling et al., 2002; Joannin et al., 2007a), which is explained by the different depths at which they live. This is also observed at Montalbano Jonico where the oxygen isotope record of *G. bulloides* and the LR04 stack are in general accordance.

Conversely, warm-temperate pollen phases are better correlated with the oxygen isotope curve of *Globigerinoides ruber* from ODP Site 967. This confirms that short-lived climate oscillations observed in the vegetation during climatic cycles are regional responses, probably due to precession changes. This is supported by the sampling resolution which is sufficient to reveal high-frequency changes in climate (139 samples for 168,7 m, i.e. ~2518 years). This is also supported by the presence of sapropels. Here, the best example is the warm-temperate phase XII correlated with the $\delta^{18}O$ negative shift from *Gs. ruber* in ODP Site 967 (ca. 0.930 Ma), between MIS 23 and MIS 25. This warm-temperate phase correlates with sapropel 18 that denotes precession influence. This climatic effect is in contradiction with the global cooling recorded in $\delta^{18}O$ (*Globigerina bulloides*) values and in LR04. This opposite signal shows that the study location is crucial for recording regional climatic events, probably related to precession, which are superimposed on the global climatic cycles. However, *G. bulloides* records decreasing $\delta^{18}O$ values associated with thick sapropels of the Montalbano Jonico section corresponding to sapropels 19 and 25 of ODP Site 967. These drops in $\delta^{18}O$ might indicate changes in intensity of precession-related wetness. However, we cannot be conclusive because considerable differences in resolution exist between ODP Site 967 and the Montalbano Jonico section.

In the Mediterranean area, it is possible to record composite responses from both global and regional climate changes according to which climatic proxy has been used. Of course, contradictory climate interpretations, such as a warm-temperate pollen phase occurring during a global cooling, in general must be considered unlikely. This discrepancy between proxies may be linked to various interfering responses of climate to obliquity and precession (Joannin et al.,

2007a). At the beginning of the MPT (i.e. when obliquity was pronounced; Maslin and Ridgwell, 2005), vegetation in the Mediterranean area responded also to precession. Such a conclusion is also supported by similar observations on the continental section of Tenaghi Philippon (Greece; Tzedakis et al., 2006; Tzedakis, 2007). In our study, precession forced vegetation changes because of the precession related wetness. We cannot determine if vegetation changes recorded the intensification of precession forcing over climatic cycles during the MPT.

Vegetation changes that are independently related to obliquity or precession are characterized by similar patterns. Mesothermic plants, mainly deciduous *Quercus*, were abundant during warm and humid time intervals that are related to precession and/or obliquity. By contrast, cold and dry climates which result from precession and/or obliquity changes were characterized by the steppe development.

5.3. Sea-level changes

Except for phase V, all the warm-temperate phases associated with interglacials clearly record water deepening based on benthic foraminifers (Stefanelli, 2003) and to some increasing distality with respect to the *Pinus* vs. Caryophyllaceae, Amaranthaceae–Chenopodiaceae and *Ephedra* ratio (Fig. 4). Accordingly, sediments of interval A record that, on the whole, climate controlled the regional sea-level variations.

A general shallowing upward trend from upper bathyal to lower circalittoral was observed for the entire Montalbano Jonico section by Stefanelli (2003). The *Pinus* vs. Caryophyllaceae, Amaranthaceae–Chenopodiaceae and *Ephedra* curve does not record this trend in interval A. The section also revealed increasing amplitudes in variations of the two relative sea-level proxies based on the mesothermic vs. steppe ratio and the oxygen isotope values, which increase in the same way. This increasing amplitude of the *Pinus* vs. Caryophyllaceae, Amaranthaceae–Chenopodiaceae and *Ephedra* ratio and benthic foraminifer PCA variations is probably related to enhanced distality/deepening conditions corresponding with interglacial periods (MIS 31, 29-27, 25 and 23).

Amplitude differences observed in the *Pinus* vs. Caryophyllaceae, Amaranthaceae–Chenopodiaceae and *Ephedra* ratio during the warm-temperate phases could be related to marine circulation changes resulting in some local distality modifications and also in the oxygen content of deep waters where the benthic foraminifer lived. Sapropel deposits may illustrate such paleoenvironmental changes. For example, the warm-temperate phase XI or interglacial period MIS 25, inferred from the mesothermic vs. steppe ratio and oxygen isotopic curve, indicates a deepening. At the same time, the *Pinus* vs. Caryophyllaceae, Amaranthaceae–Chenopodiaceae and *Ephedra* ratio and the benthic foraminifers PCA indicate a decrease in distality/deepening marine conditions during the deposition of sapropel i-90. It is now established that the onset of this sapropel deposition is related to water stratification which caused low seafloor oxygen advection (Maiorano et al., 2008), resulting in a decrease in benthic foraminifer PCA (Stefanelli et al., 2005). The decreasing in *Pinus* vs. Caryophyllaceae, Amaranthaceae–Chenopodiaceae and *Ephedra* ratio therefore indicates a reduction in sea surface circulation, probably associated with the slowing down of water mixing. The decreasing *Pinus* pollen amount may also result from differential preservation in sapropel deposits. It is well established that *Pinus* pollen grains are less degraded by oxidation than other pollen types. Thus, *Pinus* relative abundance should be less during the optimal preservation conditions that characterized sapropel deposits. A similar decrease in *Pinus* pollen abundance has previously been observed in Pliocene sapropels from Sicily (Southern Italy, Combourieu-Nebout et al., 2004). The authors' evidence that differential preservation was not predominant on *Pinus* pollen concentration, which has been mostly influenced by wind, river and marine transport. In the studied interval, reduction in sea surface circulation seems to be predominant within sapropel deposits.

It is presently difficult to find clear proof of tectonic activity in the studied section. No syn-sedimentary deformation was observed within interval A, so that seismic activity was not identified. Tectonism could result in a general subsidence of the basin as it is part of the active Appenines foredeep. But tectonic activity is difficult even to approximate. Indeed, the general shallowing upward trend observed in interval A could have been caused by the erosion of the uplifting Apennine chain followed by sediment infilling of the basin to an extent that sedimentation outpaced subsidence. Such a shallowing-upward trend might alternatively be linked to eustatic falls related to the progressive Plio-Pleistocene global climate cooling (Ruddiman, 2003). From our observations, it is only possible to claim that high-resolution climate variations are recorded in the section. Even for the present time it is difficult to separate the influences of climate, sedimentation and tectonics at Montalbano Jonico.

6. Conclusion

Fluctuations in pollen assemblages have been investigated in the Early Pleistocene Montalbano Jonico interval A. A climatically sensitive pollen ratio based on mesothermic vs. steppe elements was established to discriminate between warm-temperate and cold periods. On the basis of the biostratigraphic events found in the section, we compared first the pollen assemblages of the warm-temperate phases with the oxygen isotope record from *Globigerina bulloides* (analysed from the same samples), and then with the isotope curve from the LR04 stack. This resulted in the identification of climate cycles MIS 37 to 23.

A useful proxy for relative sea-level change was established using the ratio of *Pinus* vs. Caryophyllaceae, Amaranthaceae–Chenopodiaceae and *Ephedra*, which reflects the distance of the locality from the shoreline. This distality pollen index was compared to a benthic foraminifer curve of changes in bathymetry. Their similar trends together with some opposition to the "climatic" pollen index and the isotope curve indicate an enhanced influence of glacio-eustasy and probable reduction in marine circulation during sapropel formation. While the climatic impact on sedimentation may have been identified, deciphering the relative roles of tectonics and sedimentary supply remains difficult to explain with respect to basin infilling during interval A deposition.

The pollen ratios constructed from our detailed pollen analysis show that the marine Lucania basin was influenced by glacio-eustasy forced by obliquity during the Early Pleistocene.

The continuous interval A of the Montalbano Jonico section (167 m) was deposited from 1.250 Ma to 0.900 Ma (MIS 37 to 23). This section overlaps with but generally postdates the Vrica-Crotone series. These series together cover more than 1.500 Myrs through the Plio-Pleistocene including the entire MPT.

The positive relationships between the high-frequency pollen record and the oxygen isotope curve (*Globigerina bulloides*) constructed on the same samples is augmented by comparison with the oxygen isotope curve from ODP Site 967 (*Globigerinoides ruber*).

With respect to precession, pollen and oxygen isotopes of Site 967 have recorded the climate changes induced by wetness/insolation variations over the Mediterranean Basin which possibly led to sapropel formation. On the whole, continental responses (i.e. vegetation) record both global and regional changes, probably related to obliquity and precession, respectively. This latter forcing was caused by precession-related wetness in the Mediterranean. We did not observe the intensification of the precession effect over climatic cycles observed during the MPT.

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