

Early Pleistocene climate changes in the central Mediterranean region as inferred from integrated pollen and planktonic foraminiferal stable isotope analyses

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Abstract

Vegetation inherited from a Pliocene subtropical climate evolved through obliquity oscillations and global cooling leading to modern conditions. An integrated, highly time-resolved record of pollen and stable isotopes ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ of *Globigerina bulloides*) was obtained to understand vegetation responses to Early Pleistocene climate changes. Continental and marine responses are compared in the Central Mediterranean region with a particular consideration of environmental changes during anoxic events.

Pollen data illustrate vegetation dynamics as follows: [1] development of mesothermic elements (warm and humid conditions); [2] expansion of mid- and high-altitude elements (cooler but still humid conditions); and [3] strengthening of steppe and herb elements (cooler and dry conditions). These successions correlate with precession. $\delta^{18}\text{O}$ variations recorded by *Globigerina bulloides* define two cycles (MIS 43–40) related to obliquity. At northern low- to mid-latitudes, the pollen signal records temperature and wetness changes related to precession even during global climate changes induced by obliquity. This may result in unexpected increasing wetness during glacial periods, which has to be considered specific to the Central and Eastern Mediterranean region. Lastly, an analysis of anoxic events reveals that enhanced runoff is indicated by increasing frequency of the riparian trees *Liquidambar* and *Zelkova*.

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Introduction

Pleistocene climates were characterized by the alternation of glacial and interglacial periods driven by the expansion and retreat of continental ice sheets over northern latitudes (e.g., Ruddiman, 2003; Berger and Loutre, 2004). It is well established that these alternations were controlled by the astronomical cycles of eccentricity, obliquity and precession (e.g., Milankovitch, 1941; Hays et al., 1976). These orbit-related alternations have been the focus of intensive studies in deep-sea sediments, providing abundant information on the

evolution of Pleistocene marine-related climate (e.g., Ruddiman et al., 1989). For the Middle and Late Pleistocene, spectral analyses on foraminiferal oxygen isotope records have suggested that eccentricity was the dominant parameter controlling glacial–interglacial changes (Imbrie et al., 1993; Ashkenazy and Tziperman, 2004), whereas obliquity was the dominant forcing parameter during the Early Pleistocene (Pisias and Moore, 1981; Kroon et al., 1998; Ruddiman, 2003). Recent debates nevertheless suggest that the 100,000 yr glacial–interglacial cycles that characterize the Middle and Late Pleistocene may be more closely linked to precessional forcing, being limited by each fourth or fifth precessional cycle (Ruddiman, 2003; Maslin and Ridgwell, 2005).

Pollen records obtained from the Mediterranean region have provided a framework to identify climatically-related vegetation

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changes that can be used to correlate the evolution of the Mediterranean climate with global climatic cycles (Suc and Zagwijn, 1983; Combourieu-Nebout and Vergnaud Grazzini, 1991; Mommersteeg et al., 1995; Tzedakis et al., 1997, 2003; Subally et al., 1999; Okuda et al., 2002; Suc and Popescu, 2005). From these reconstructions it is clear that the Mediterranean vegetation experienced major modifications during the Early Pleistocene (Suc, 1984; Combourieu-Nebout, 1990, 1993; Capraro et al., 2005). For instance, in the Crotona area of southern Italy, the Late Pliocene to Early Pleistocene vegetation exhibited a transitional flora, since the subtropical-dominated floral associations (Combourieu-Nebout, 1993) inherited from the Middle Pliocene did not survive the long-term global cooling that took place subsequently (Ruddiman, 2003). This long-term cooling and related vegetation changes occurred when high-amplitude climatic 100,000 yr cycles became predominant at $\sim 0.9\text{--}0.8$ Ma (Von Grafenstein et al., 1999; Ruddiman, 2003; Mudelsee and Statterger, 1997; Maslin and Ridgwell, 2005).

Notwithstanding recent efforts (e.g. Tzedakis et al., 1997; Bar-Matthews et al., 2003; Suc and Popescu, 2005), the relationship between long-term vegetation changes and astronomical forcing during the Pleistocene is insufficiently understood due to the limited number of high-resolution continental records. In the present study, such a relationship is explored in the Central Mediterranean, a region where the overlap of precessional and obliquity cycles is expected to be marked (Kroon et al., 1998). We have focussed our investigation on a short-term interval ($\sim 75,000$ yr) of the Early Pleistocene recovered from the Santa Lucia Section (Crotona). Our primary goal was to test whether obliquity was the major parameter influencing changes in vegetation as documented in the sediments of the Vrica and Semaforo sections (Combourieu-Nebout and Vergnaud Grazzini, 1991; Lourens, 1994). Moreover, we aimed to shed new light on the vegetation response in relation to the repetitive, precession-controlled, occurrence of sapropels in the Crotona series (Combourieu-Nebout, 1987; Hilgen, 1990, 1991; Lourens et al., 1996a,b, 1998). For these purposes, pollen and forami-

niferal $\delta^{18}\text{O}$ analyses were performed on the same horizons to unravel the marine–continental interrelationships for the Early Pleistocene.

Lithostratigraphy and chronologic framework

The Santa Lucia Section is located close to the southern part of Crotona (behind the Santa Lucia Church; Fig. 1). It consists of late Early Pleistocene laminated grey marls (total thickness of 24.4 m) in which three sapropels are intercalated (Fig. 2). These sapropels can be stratigraphically correlated in the field to the “t”, “u” and “v” sapropels in the Vrica C and Crotona sections (Lourens et al., 1996b). Accordingly, sapropels “t”, “u” and “v” are dated at 1.356, 1.315 and 1.280 Ma, and correspond to insolation cycles i-130, i-126 and i-122, respectively (Lourens et al., 1996b).

In the Eastern Mediterranean, at Ocean Drilling Program (ODP) Sites 967 and 969, a short influx of the planktonic foraminiferal species *Globorotalia crassaformis* has been recorded between insolation cycles i-126 and i-122 (Lourens et al., 1998). In the Santa Lucia Section, we found numerous specimens of *Gt. crassaformis* within two samples (SL15 and SL16) located between sapropels “u” and “v” (i-126 and i-122). Although this influx was not found at the Vrica C and Crotona sections because of the lack of high-resolution sampling (see Lourens et al., 1998), our data are in agreement with those obtained from ODP Site 964 (Sprovieri et al., 1998) and show that this event is clearly recorded in the Central Mediterranean. Based on the age estimates of sapropels “u” and “v” and assuming a synchronous deposition for these sapropels, we estimate an age of ~ 1.303 Ma for the influx of *Gt. crassaformis* recorded at the Santa Lucia Section. This is consistent with estimates of ~ 1.299 Ma and ~ 1.295 Ma (Lourens et al., 1998) for the same event at ODP Sites 967 and 969, respectively.

Materials and methods

Our investigations are based on the analysis of 33 samples with an average sample spacing of ~ 1 m between sapropels “t”

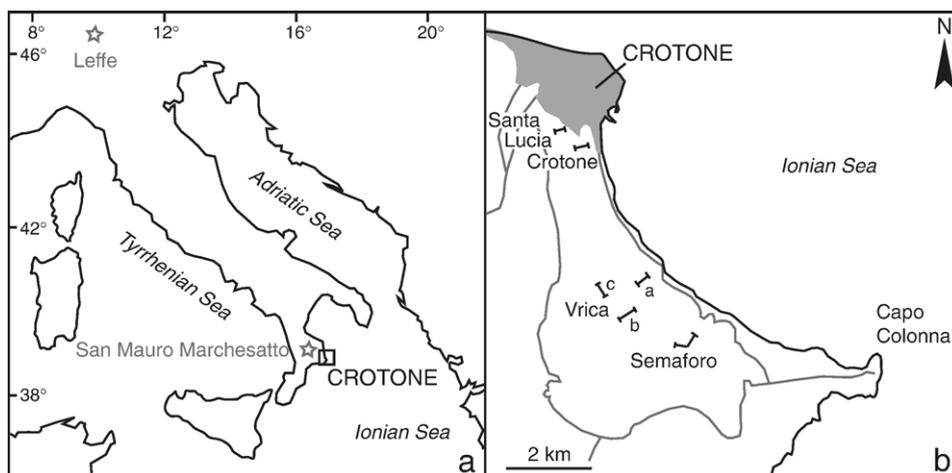


Figure 1. Geographical location of (a) Crotona, San Mauro Marchesato and Lefte series; (b) the different sections of the Crotona series: Santa Lucia, Crotona, Vrica and Semaforo.

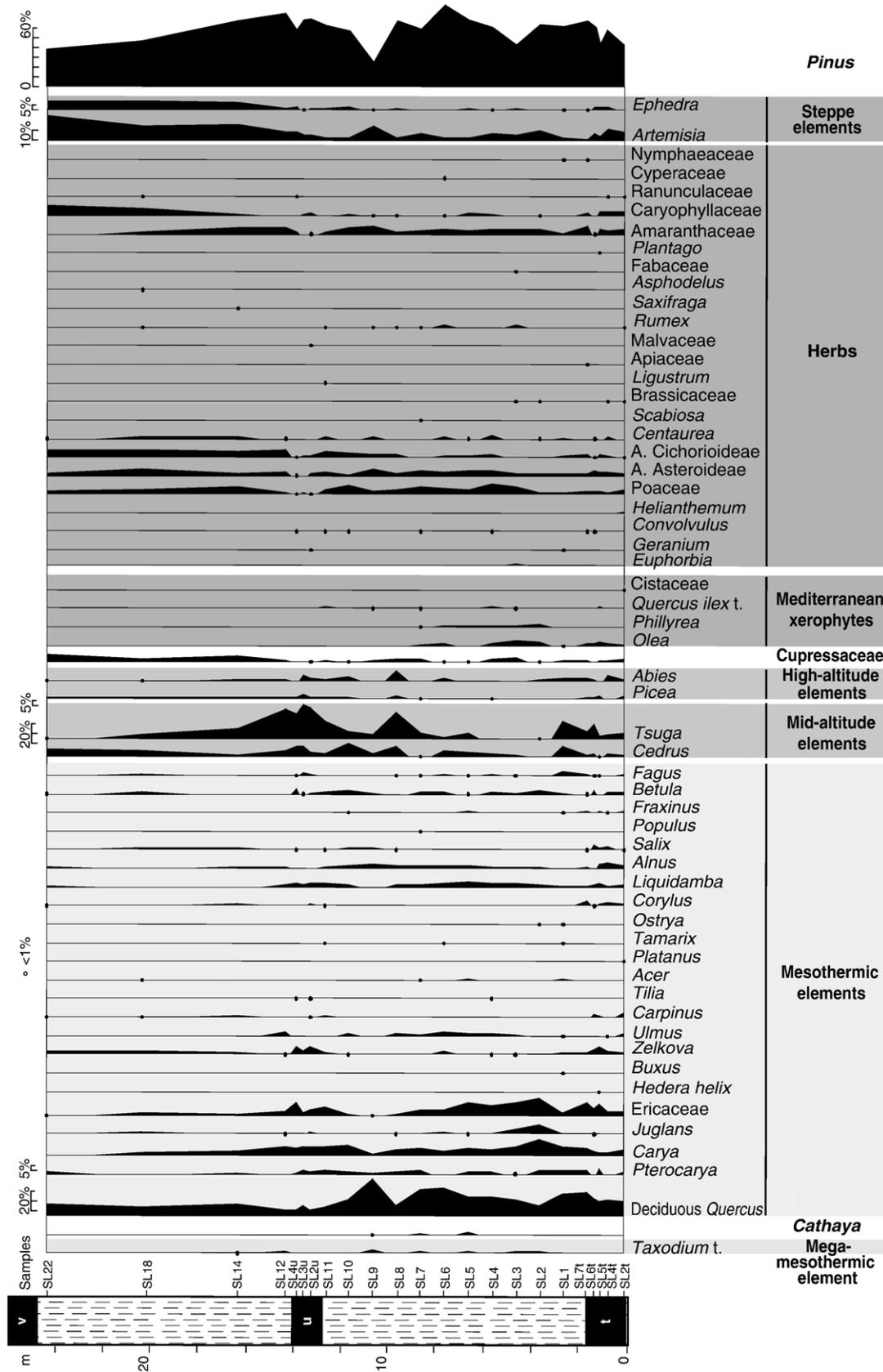


Figure 2. Detailed pollen diagram from the Santa Lucia Section. All taxa (except *Pinus*) are represented in relative percentages calculated according to the total counted pollen grains minus *Pinus*. Only *Pinus* has a relative percentage based on the total of counted pollen grains. Taxa are grouped ecologically using the ecological significance of their present-day representatives: mesothermic elements (including deciduous *Quercus*, *Carya*, *Pterocarya*, etc.), mid-altitude elements (*Cedrus* and *Tsuga*), high-altitude elements (*Picea* and *Abies*), Mediterranean xerophytes (such as *Olea*), herbs (including Poaceae, Asteraceae Asteroideae, etc.) and steppe elements (*Artemisia* and *Ephedra*).

and “v”. We sampled with a higher resolution (~30 cm) in the vicinity of sapropels “t” and “u”. Sapropel “v” was not sampled, because of the poorly preserved surface of the outcrop.

Pollen analysis

For pollen analysis, samples collected were prepared using a standard chemical technique adapted from Cour (1974). Following HCl then HF treatments, palynomorphs were separated from mineral particles using ZnCl₂. The residue was sieved and the size fraction 160–10 μm was used for further pollen investigations. Only 23 samples from the Santa Lucia Section (SL) provided enough pollen grains for quantitative analysis. They were abundant and well preserved in the sapropels as well as in samples SL1, SL2, SL11, SL12, SL14, SL18 and SL22. Pollen grains were moderately preserved in samples SL3 to SL10 and not preserved in most samples collected from the top of the section (SL13, SL15–17, and SL19–21). More than 9000 pollen grains were counted for the whole section, which corresponds to at least 150 per sample, plus *Pinus* since this genus is generally over-represented. Indeed, the relative abundance of *Pinus* pollen grains is mostly

controlled by dispersal bias, such as the distance from river mouths, because of their high buoyancy (Heusser and Balsam, 1977; Beaudouin et al., in press). A rich pollen flora of 60 taxa (see the detailed diagram in Fig. 2) was documented (at least 20 taxa per sample), including herbaceous and arboreal plants that live today over a large range of latitudes. Percentages of taxa were calculated with respect to the total sum of pollen grains excluding *Pinus*, while variations in the *Pinus* abundance were normalized to the total sum of pollen grains. Following Suc (1984) and Combourieu-Nebout (1987), taxa have been grouped according to their estimated ecology determined on the base of their representatives in present-day plant associations (Fig. 2).

The abundance of each ecological group is shown in Figures 3 and 4. Palynofacies analysis was furthermore used for assessment of the type of organic matter (Fig. 4), as determined by visual comparative evaluation. Four standard constituents of palynofacies were considered in this work (Combaz, 1991): [1] Cellular Organic Matter (COM) mainly made of pollen grains, spores, dinoflagellate cysts, cuticle fragments, and plant small particles; [2] Woody Organic Matter (WOM) showing pieces of wood; [3] Black Organic Matter (BOM) constituting coaly

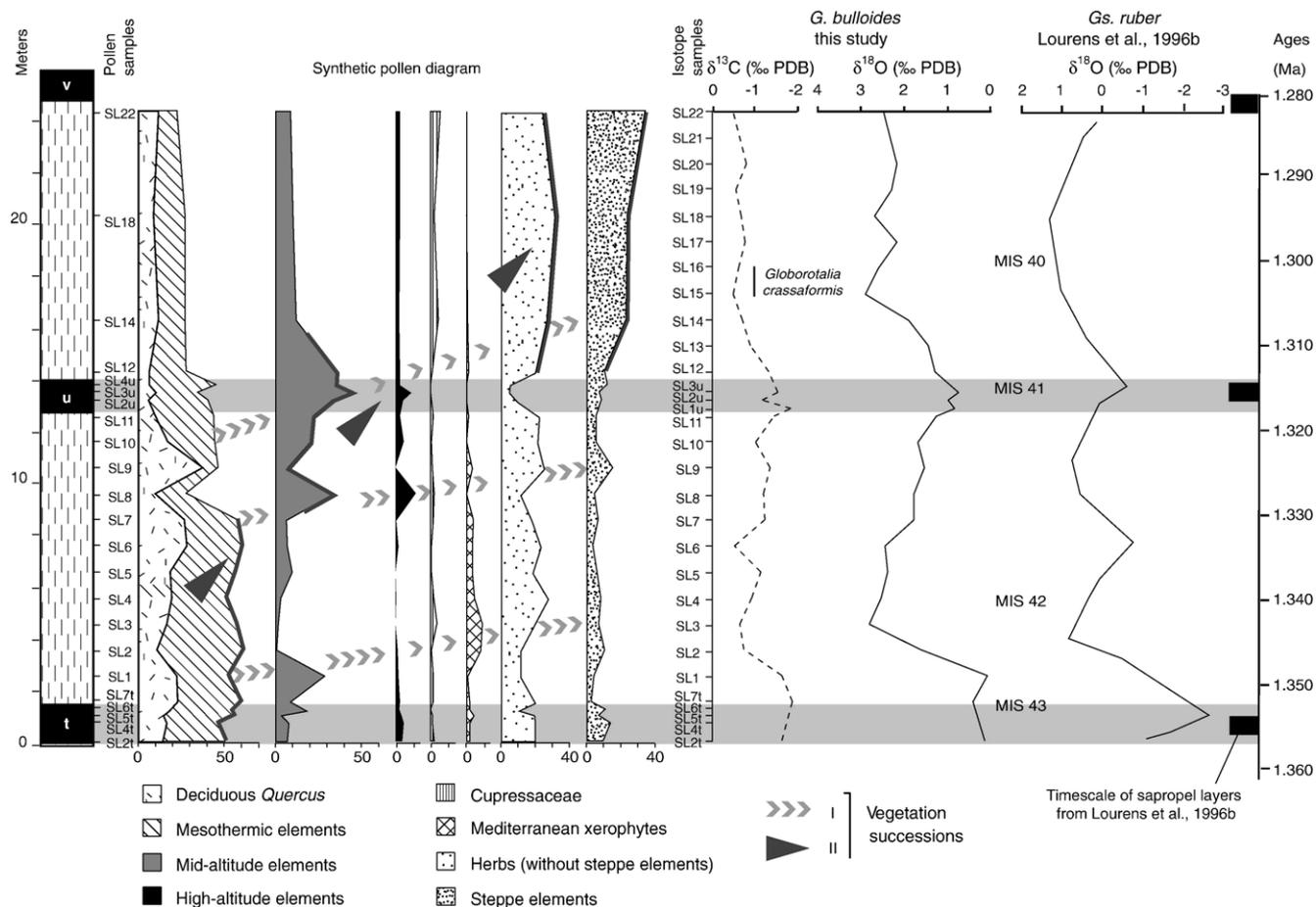


Figure 3. Synthetic pollen diagram, with individual groups given in percentages based on total pollen except *Pinus*. The vegetation has evolved through two kinds of vegetation successions (I and II, indicated by chevrons and arrow heads respectively), and is compared with oxygen and carbon isotopic data obtained from *Globigerina bulloides* in this study. All data are correlated with oxygen isotopic data from Lourens et al. (1996b) from which the marine isotope stages (MIS) are identified. Sapropels “t” and “u” are represented in grey.

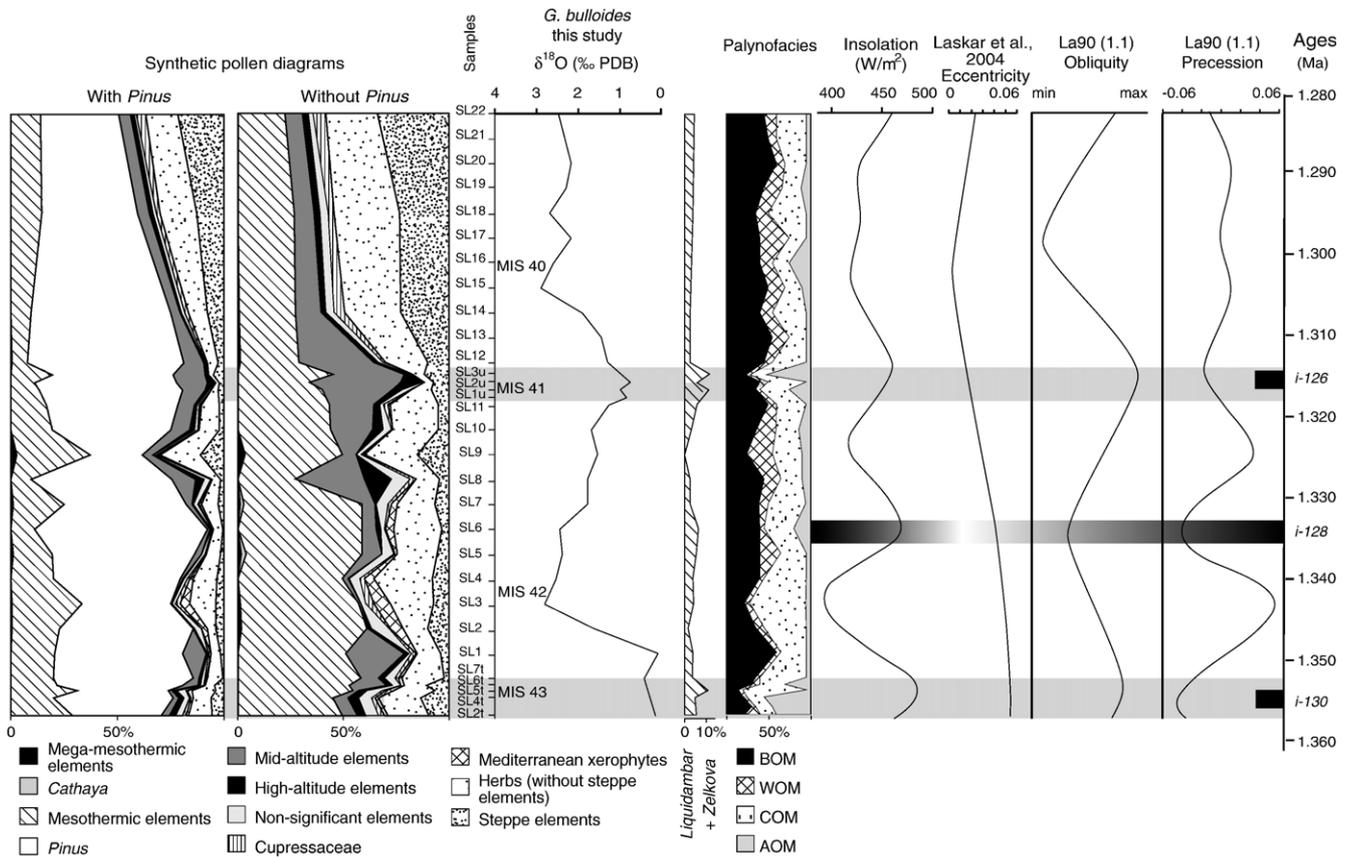


Figure 4. Synthetic pollen diagrams (with and without *Pinus*) compared to isotopic results, *Liquidambar*+*Zelkova* percentage variations, palynofacies diagram, and variations of insolation, eccentricity, obliquity and precession between 1.360 and 1.280 Ma (extracted from Laskar et al., 2004). The relative amounts of the four kinds of organic matter (i.e. BOM, WOM, COM and AOM) have been estimated following Shvetsov (1954) and Sittler and Schuler (1991). On the whole, a prevalent COM indicates a relatively short transport of particles from land. High amounts of WOM indicate longer transport of particles. High amounts of BOM indicate low sea-level stand and intense fluvial erosion and transport. Finally, high amounts of yellow and fleecy AOM are generally related to anoxic conditions (see Caratini et al., 1983; Poumot and Suc, 1994). Note that in the Mediterranean sediments, increasing amounts of yellow-fleecy AOM generally corresponds to sapropel deposits. They are linked to marine water stratification and are often related either to a sea-level rise (Combourieu-Nebout, 1987; Suc et al., 1991; Poumot and Suc, 1994; Suc et al., 1995) or an increase in runoff (Hilgen, 1991).

organic fragments and sometimes pyrite grains; and [4] Amorphous Organic Matter (AOM) which results from the disintegration of organisms by anaerobic bacteria.

Stable isotope analyses

Carbon and oxygen isotope compositions have been measured from 26 samples of the nonsymbiotic, shallow-dwelling planktonic foraminiferal species *Globigerina bulloides*. All measurements were performed using specimens picked from a restricted size range (250–350 μm). At least 30 specimens of *G. bulloides* were necessary to yield sufficient calcium carbonate and to minimize inter-specimen variations in their $\delta^{18}\text{O}$ values. The specimens selected were free of carbonate infilling or visible dissolution. Samples were reacted off-line with 100% anhydrous phosphoric acid at 25°C over a period of 24 h. After two on-line distillation steps to obtain pure CO_2 , gas samples were analysed using a GVI ISOPRIME mass spectrometer with Dual Inlet system at the University of Lyon 1. Isotopic compositions are quoted in the standard δ notation relative to Pee Dee Belemnite (PDB). Carbon and oxygen isotope measurements were calibrated to the international standard NBS-19. Reproducibility

for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of NBS19 is 0.09‰ and 0.03‰ (1σ ; $\nu=10$), respectively.

Results

Pollen

Pollen flora includes typical mesothermic (i.e. warm-temperate) and mid-altitude taxa still found in the Early and Middle Pleistocene of the region, such as *Carya*, *Zelkova* and *Pterocarya*, *Cedrus* and *Tsuga* respectively. Despite a large amount of arboreal pollen, small quantities of *Cathaya* (a subtropical mid-altitude conifer restricted to China today) and Taxodiaceae (a mega-mesothermic, i.e. subtropical, element) were found (Fig. 2).

Three vegetation successions were observed and are illustrated by chevrons indicating level I in Figure 3. These vegetation successions are characterized by dominance of mesothermic elements, followed by mid- and high-altitude elements with *Pinus*, and ending in herb and steppe element maxima. Clearly, these three vegetation successions show different patterns. The first one shows an increase in mesothermic

elements ending in a Mediterranean xerophyte (*Olea* mostly), herb (Poaceae mainly), and little steppe episode. The second one is characterized by a clear mid- and high-altitude culmination ending with a high relative abundance of steppe elements. The third one is characterized by an increase in the relative abundance of deciduous *Quercus* (about 35% in sample SL9) associated with lower amounts of total mesothermic elements. Altitudinal and herb-steppe phases are also more developed in this latter succession. Differences in relative abundance between the three successions allow the definition of a long-term vegetation succession (level II, marked by solid arrow heads in Fig. 3). This long-term succession starts with high relative abundance of mesothermic elements (>50% in SL2t–SL7), then mid- and high-altitude elements become abundant (24% in SL11 to 54% in SL3u except in sample SL9), and lastly herb and steppe elements are the most important (SL14–SL22).

Figure 4 shows variations in palynofacies content. Greater increases in AOM correlate with sapropel samples. Abundant AOM is also observed in sample SL6. The other samples mainly comprise BOM and COM. The sapropel samples correlate not only with AOM but also higher percentages of *Liquidambar*+*Zelkova* (Fig. 4), which are trees of the riparian vegetation (Quézel and Médail, 2003). Moreover, they are correlated ($r=0.60$; $p<0.01$), particularly in sapropel “u” (samples SL2u and SL4u).

Stable isotopes

Carbon and oxygen isotope compositions of *Globigerina bulloides* are correlated ($r=0.87$; $p<0.001$) throughout the section (Table 1; Fig. 3). The oxygen isotope record shows an alternating pattern of low and high values with the lowest peak values corresponding to the sapropels “t” and “u”. More specifically, the lower part of the section records low $\delta^{18}\text{O}$ values ($\sim 0.2\text{‰}$ from sapropel “t” to sample SL1). An increase of $\sim 2.5\text{‰}$ occurs between samples SL1 and SL3. Between sample SL3 and sapropel “u”, $\delta^{18}\text{O}$ values decrease to reach a minimum of 0.75‰ in sample SL3u. This is followed by an increase of $\sim 2.1\text{‰}$ between samples SL3u and SL15, the latter reaching a maximum value of 2.9‰ . Finally, the upper part of

the section (SL15–SL22) shows fluctuating $\delta^{18}\text{O}$ values around an average value of 2.5‰ .

The $\delta^{13}\text{C}$ values measured in Santa Lucia samples show similar variation trends to those of the $\delta^{18}\text{O}$ values. Sapropels “t” and “u” recorded the lowest $\delta^{13}\text{C}$ values of the whole section (-1.86‰ and -1.82‰ , respectively).

Discussion

Vegetation successions and climate changes

Pollen grains recorded in the deposits of the Crotona Basin originate from the coastal plain and slopes of the Sila Mountains (Combourieu-Nebout and Vergnaud Grazzini, 1991), which were about 1500 m high during the Late Pliocene (Ciaranfi et al., 1983). Since vegetation is controlled by changes in temperature and precipitation with increasing altitude (Ozenda, 1975), the three short-term vegetation successions (level I; Fig. 3) described above have probably been amplified by the expansion and contraction of altitudinal vegetation belts. Accordingly, pollen variations in a single locality reflect strengthening and elevation of the corresponding vegetation belts, from the coastal assemblage to the mountainous one. Each of the short-term vegetation successions shows a similar and repetitive three-step pattern organized as follows: [1] warm-related forest, [2] cooler and more humid related forest, and [3] cool to cold dry related open vegetation. This vegetation dynamic is consistent with previous highly time-resolved pollen studies dedicated to the Early and Middle Pleistocene continental and marine sections in the Central Mediterranean region (Okuda et al., 2002; Capraro et al., 2005; Fig. 1; Table 2). Most studies have nevertheless evidenced vegetation successions showing a four-step pattern during the Late Pliocene (Combourieu-Nebout, 1993) and the Pleistocene (Ravazzi and Rossignol-Strick, 1995; Tzedakis and Bennett, 1995). In fact, these studies have divided the interglacial-related forest phase into three steps: deciduous forest, subtropical-humid forest, and altitudinal coniferous forest. This last step always constitutes the transition toward the fourth step, which is glacial-related open vegetation. Finally, these studies often express the vegetation response in terms of forest/open vegetation (e.g. Tzedakis, 1993). In Santa Lucia, increases in *Pterocarya*, *Carya*, and *Juglans* do not systemically follow the deciduous *Quercus* peaks. Here, we prefer to interpret the signal simply as having three phases.

Each succession has involved different dominant taxa and particularly during interglacial periods. Indeed, at Semaforo and Leffe (Ravazzi and Rossignol-Strick, 1995), *Carya* was more profuse than deciduous *Quercus*, while the contrary is true for Santa Lucia (the present study) and San Mauro Marchesato (Capraro et al., 2005). Transitions from interglacial to glacial conditions were marked by cool to cold environment-related taxa (particularly *Abies* at San Mauro Marchesato). Finally, in all sections, glacial periods showed similar assemblages including *Artemisia* and herbs [at the latitude of Leffe, Ravazzi and Rossignol-Strick (1995) consider *Betula* as another marker of glacial periods], although the relative abundance of these taxa

Table 1
 $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values obtained on foraminiferal tests of *Globigerina bulloides*

Samples	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	Samples	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
SL11	1.27	-1.41	SL22	2.44	-0.51
SL10	1.69	-0.99	SL20	1.88	-0.88
SL9	1.53	-1.33	SL19	2.28	-0.56
SL8	1.79	-1.19	SL18	2.66	-0.69
SL7	1.78	-1.21	SL17	2.15	-0.76
SL6	2.40	-0.56	SL16	2.58	-0.63
SL5	2.38	-1.12	SL15	2.87	-0.49
SL4	2.49	-0.91	SL14	1.90	-0.71
SL3	2.78	-0.66	SL13	1.46	-0.87
SL2	1.63	-0.75	SL12	1.29	-1.29
SL1	0.11	-1.61	SL3u	0.75	-1.53
SL7t	0.42	-1.86	SL2u	0.99	-1.16
SL2t	0.15	-1.61	SL1u	0.83	-1.82

Table 2
Prevalent taxa of vegetation successions in the Central Mediterranean region from the Late Pliocene to the Middle Pleistocene

Sites phase	2.470 to 2.300 Myr, Semaforo Combourieu-Nebout (1987)	1.600 Myr Lefè Ravazzi and Rossignol-Strick (1995)	1.360 to 1.280 Myr Santa Lucia (this study)	0.870 to 0.730 Myr San Mauro Marchesato Capraro et al. (2005)
Glaciation	<i>Artemisia</i> , other herbs	<i>Artemisia</i> , <i>Betula</i>	<i>Artemisia</i> , other herbs	<i>Artemisia</i> , <i>Amaranthaceae–Chenopodiaceae</i> , other herbs
Transition Interglaciation	<i>Cedrus</i> , <i>Tsuga</i> , <i>Abies</i> and <i>Picea</i> b-Taxodiaceae , <i>Cathaya</i> , a-deciduous Quercus ; <i>Ulmus–Zelkova</i> , <i>Carya</i>	<i>Picea</i> , <i>Tsuga</i> , <i>Cedrus</i> and <i>Pinus</i> Deciduous Quercus , <i>Carpinus orientalis</i> , <i>Carya</i>	<i>Tsuga</i> , <i>Cedrus</i> , <i>Pinus</i> <i>Carya</i> , <i>Ericaceae</i> , deciduous Quercus	<i>Abies</i> , <i>Picea</i> Cupressaceae, evergreen Quercus , deciduous Quercus

For each period, dominant taxa are shown in bold characters.

might have increased progressively with time because glacial periods became characterized by colder and drier conditions since the Late Pliocene. This climatic evolution, resulting from a one million year global cooling (e.g. Nikolaev et al., 1998), was responsible for the ending of the common occurrence of *Cathaya* and Taxodiaceae at around 1.320 Ma in the Central Mediterranean region.

As shown by the oxygen isotope compositions of *Globigerina bulloides* (Fig. 3), two climatic cycles (i.e. interglacial–glacial periods) are recorded in the Santa Lucia Section. These cycles correspond to Marine Isotopes Stages (MIS) 43–42 and MIS 41–40, respectively, and are correlated with two short-term vegetation successions (first and third; Fig. 3). Interestingly, the second vegetation succession is apparently not associated with a climatic cycle (Fig. 3). This succession, supported by several samples (SL4 to SL9), suggests a cooling and an increasing xericity when $\delta^{18}\text{O}$ data suggest warmer conditions. A comparison between the oxygen isotope records of *Globigerina bulloides* from the Santa Lucia Section (this work) and *Globigerinoides ruber* from the nearby Crotona Section (Lourens et al., 1996b) is shown in Figure 3. Data measured on *Gs. ruber* suggest a cooling event correlative to the second vegetation succession.

Sapropel formation

It is generally accepted that sapropels were formed when Northern Hemisphere summer insolation was at a maximum during precession minima (i.e., Rohling and Hilgen, 1991). This astronomical configuration resulted in maximum monsoon activity (Prell and Kutzbach, 1987; Rossignol-Strick and Paterne, 1999). As mentioned by these authors, seasonal contrast enhanced thermal differences between land and the Atlantic Ocean, leading to increasing precipitation in North Africa and a northward shift of the African monsoon. It also led the circum-Mediterranean climate to become increasingly wet (Rohling and Hilgen, 1991; Rossignol-Strick and Paterne, 1999; Bar-Matthews et al., 2003), which resulted in enhanced continental runoff (Rossignol-Strick and Paterne, 1999). Subsequently, the thermohaline circulation may have weakened or even stopped, oxygen concentrations at depth decreased, and marine productivity in the (sub)sea surface may have enhanced (see Rohling and Hilgen, 1991 and references therein).

Lourens et al. (1996b) showed that low $\delta^{18}\text{O}$ values recorded within sapropels “t” and “u” were predominantly controlled by precession, but co-occurred with the obliquity-controlled interglacial MIS 43 and 41. Our results obtained from Santa Lucia show that $\delta^{18}\text{O}$ depletions during sapropels “t” and “u” are larger than 2‰, which probably result from the drop in sea surface salinity as described by the generally accepted scenario discussed above. The decrease in $\delta^{13}\text{C}$ values recorded by *Globigerina bulloides* in sapropels “t” and “u” (Fig. 3) is also consistent with the proposed enhanced marine productivity conditions during sapropel formation (Vergnaud Grazzini et al., 1990; Schenau et al., 1999). Moreover, the high amounts of AOM found within these sapropels (Fig. 4) may be explained by enhanced preservation under dysoxic/anoxic bottom water conditions (Caratini et al., 1983; Poumot and Suc, 1994). Evidence for enhanced humidity in the study area during sapropel formation originates from the increased percentages of *Liquidambar* and *Zelkova*, suggesting the development of riparian forest (Fig. 5a). These taxa are part of the modern north-eastern Mediterranean riparian associations (Quézel and Médail, 2003), and particularly *Liquidambar orientalis*, to which our pollen grains belong, which prefer river banks (Alan and Kaya, 2003).

They both require precipitation or alluvial water all the year long and particularly during summer (Quézel and Médail, 2003).

Lourens et al. (1996b) interpreted depleted $\delta^{18}\text{O}$ values of *Globigerinoides ruber* between sapropels “t” and “u” also as reflecting the influence of a precession-related wet phase of circum-Mediterranean climates, although a sapropel was not found in the central Mediterranean region. This is in contrast to the sedimentary succession at ODP Site 967 (Eastern Mediterranean), which clearly showed a distinct, but relatively thin, sapropel layer (Fig. 5b) between relatively thick sapropels correlative to “t” and “u” (Lourens et al., 1998). The absence of a sapropel in the Vrica/Crotona region and the relative thinness of that recovered at Site 967 might be explained by the fact that the controlling precession minimum occurred during an obliquity minimum, which could have resulted in a reduced maximum monsoon activity over northern Africa and only a slight gain in wetness over the Mediterranean region. This hypothesis receives some support from the slight rise in the relative abundance of *Liquidambar+Zelkova* pollen grains as well as in AOM in sample SL6 (Fig. 4). The oxygen isotope

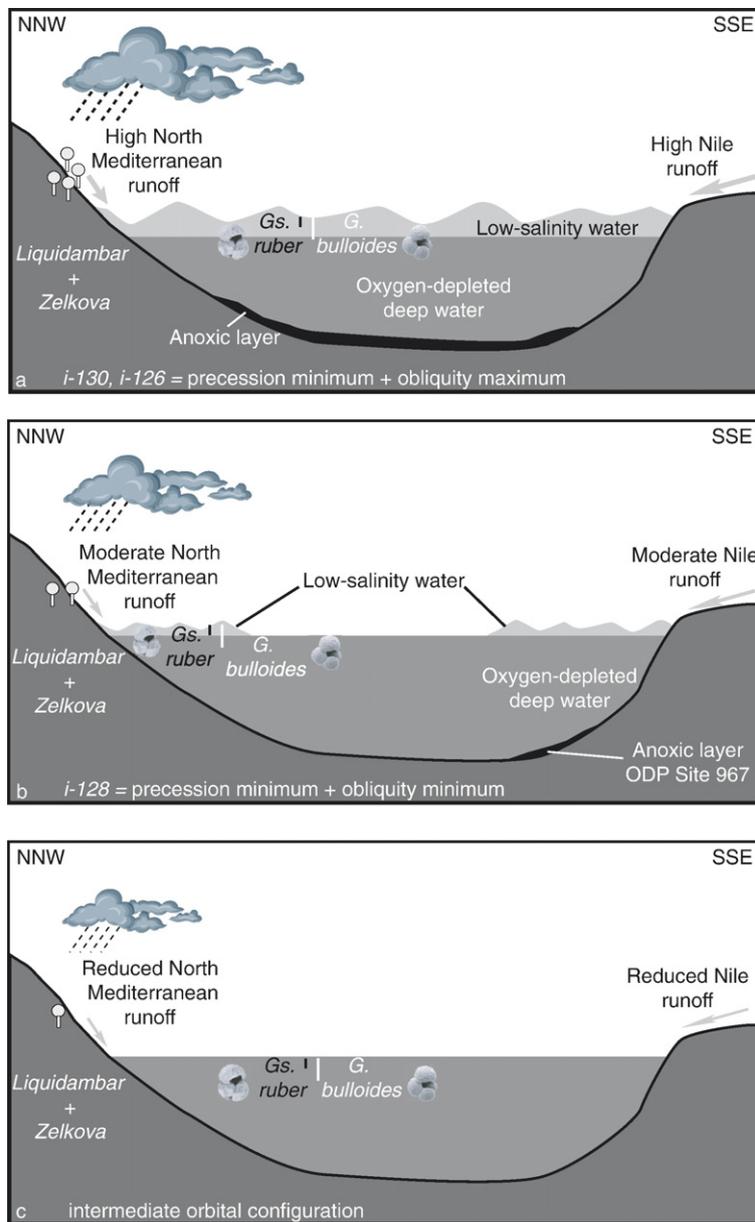


Figure 5. Tentative evolutive orbit-related model for the Early Pleistocene oceanic environment and climatic conditions causing an anoxic event which resulted in (a) sapropel deposition in the Central and Eastern Mediterranean; (b) sapropel deposition circumscribed to the easternmost Mediterranean; (c) no sapropel deposition.

record of *Globigerina bulloides* at Santa Lucia, however, does not reveal depleted values at this level (Fig. 4). Although both *G. bulloides* and *Gs. ruber* are shallow-dwellers in the modern ocean, the differential isotopic response recorded between the two species could originate in their ecology, such as slight differences in depth-related specialisation. *Globigerinoides ruber* is a subtropical, symbiotic species living in the photic zone of the water column, primarily in the upper 50 m (Bé, 1977). It primarily secretes its test during the summer months in the Mediterranean (Pujol and Vergnaud Grazzini, 1995) as well as in the NE Atlantic (Ganssen and Kroon, 2000). *Globigerina bulloides* is a subpolar species lacking symbionts and occupies intermediate depths of the photic zone (Bé, 1977; Hemleben et al., 1989). It calcifies primarily during the spring bloom (Pujol

and Vergnaud Grazzini, 1995; Ganssen and Kroon, 2000). In well stratified and productive water masses, *G. bulloides* preferentially grows in a depth interval between 50 and 100 m (Bé, 1977; but see Rohling et al., 2004) within waters enriched in nutrients. It may have occupied even deeper environments of the water column at the onset of the Pleistocene (see for example Nikolaev et al., 1998). Recently, Rohling et al. (2002) argued that the uppermost surface waters were more frequently renewed than deeper environments of the photic zone because of atmosphere contact. In this context, changes in water salinity during the i-128 cycle might only have affected the upper part of the photic zone, where *Gs. ruber* calcified, while the $\delta^{18}\text{O}$ of the deeper species *G. bulloides* recorded obliquity changes (Fig. 5b).

Potential astronomical forcing

Any step [1] of the short-term vegetation succession (see above), associated with increasing precipitation, is correlative to a precession minimum. Step [3], interpreted as the development of xeric conditions (see Subally and Quézel, 2002), is correlative to precession maxima (La90^{1.1}, Laskar et al., 1993; Fig. 4). Nevertheless, Figures 3 and 4 show the first and third vegetation successions starting during obliquity maxima (interglacial time, MIS 43, 41) and ending during obliquity minima (glacial time, MIS 42, 40). These successions may have been potentially influenced by the concomitant effects of obliquity and precession. The second short-term vegetation succession occurred at a glacial–interglacial transition. Because *Globigerina bulloides* did not record depleted $\delta^{18}\text{O}$ values within the second vegetation succession, an internal oscillation of climate cannot be involved at that time. On the other hand, the succession is correlative to an opposed orbital configuration resulting in contradictory conditions. In the Mediterranean area and particularly at the latitude of southern Italy (~40° N), precession was more influential on insolation than obliquity (Rossignol-Strick and Paterne, 1999; Shackleton et al., 1999; Maslin and Ridgwell, 2005). In this context, precession-related insolation and wetness changes may have forced i-128 and associated vegetation succession. The development of steppe elements evidenced at the end of this second vegetation succession may finally correspond to the record of precession-related drying conditions occurring during the obliquity-controlled warming. In this case, as a steppe assemblage has a very wide thermal range (Subally and Quézel, 2002), it essentially constitutes a sensitive proxy of xericity. This constitutes the first evidence that Early Pleistocene vegetation changes have been related to precession forcing at middle northern latitudes, when climatic cycles were controlled by obliquity.

The stable oxygen isotope composition of *Globigerinoides ruber* at the Vrica and Croton sections suggests a long-term temperature decrease, from 1.430 to 1.220 Ma (Lourens et al., 1996b). A part of this progressive cooling is apparently correlative to the long-term vegetation succession (level II; Fig. 3) and to an eccentricity decrease (extracted from Laskar et al., 2004; Fig. 4). Since insolation is mainly forced by precession, which is modulated in terms of amplitude by 100,000 yr eccentricity, climatic changes reconstructed from pollen records at Santa Lucia may have simultaneously been controlled by short-term precession changes and long-term precessional amplitude changes (i.e. eccentricity). This preliminary observation, still based on a short-term interval (~75,000 yr) of the Early Pleistocene, needs further investigations on longer records.

According to the orbital configuration, precession and obliquity may produce various effects, ranging from complete convergence to total divergence. In such propitious areas as the Mediterranean, this results in the occurrence of similar, or different, environmental changes. Such a complexity demonstrates the absolute necessity to be cautious in considering regional vs. global environmental changes with respect to orbital

parameters. Hence, it appears highly fruitful to combine marine and continental proxies. This new understanding of environmental changes constitutes a likely response to the continuing debate on the proposed climatic opposition in dryness/wetness between the Western and Eastern Mediterranean regions (Horowitz, 1989; Subally et al., 1999; Suc and Popescu, 2005).

Conclusions

We have conducted a detailed, integrated pollen and stable isotope ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$) investigation of the Early Pleistocene marine section recovered at Santa Lucia (Croton, Italy), in order to analyse and compare vegetation responses to climatic changes in the Central Mediterranean. Our main results are summarized as follows:

- (1) Stable isotope data has led to the identification of two climatic cycles (MIS 43–42 and MIS 41–40). The marine response ($\delta^{18}\text{O}$ of *Globigerina bulloides*) was probably forced by obliquity. Pollen data, however, record three vegetation successions, mainly forced by precession. Two of these vegetation successions (and the forcing precession changes) were in phase with obliquity changes, and one was not. This last succession thus occurred in an opposed thermal trend.
- (2) Two kinds of vegetation succession are revealed: short-term vegetation successions correlated with precession (20,000 kyr), and long-term vegetation succession that may potentially be correlated with a decrease in precessional amplitude.
- (3) The expansion of *Liquidambar* and *Zelkova*, trees related to a riparian environment, is the first irrefutable pollen evidence of development of a riparian forest and, as a consequence, of increasing runoff during periods of precession minima.
- (4) Oxygen isotope compositions of *Globigerinoides ruber* are found to correlate with precession, which is more influential on insolation and wetness at low- to mid-latitudes. The obliquity minimum interferes with the precession minimum. This interference probably did not lead to a strong decrease in sea surface salinity. Only the upper part of the surface waters, where *Gs. ruber* calcified, was affected by insolation and salinity changes. That is the reason why this species more likely recorded precession climatic changes when obliquity influenced *Globigerina bulloides*.
- (5) The proposed climatic opposition in dryness/wetness between the Western and Eastern Mediterranean regions cannot be directly related to glacial–interglacial cycles. It receives for the first time a plausible explanation based on complex precession vs. obliquity-specific effects on the Mediterranean climate.

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