Quaternary Science Reviews 30 (2011) 2459–2475

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Holocene hydrological changes in south-western Mediterranean as recorded by lake-level fluctuations at Lago Preola, a coastal lake in southern Sicily, Italy

Michel Magny [a,*], Boris Vannière [a], Camilla Calo [b], Laurent Millet [a], Aurélie Leroux [a], Odile Peyron [a], Gianni Zanchetta [c,d], Tommaso La Mantia [e], Willy Tinner [b]

[a] Laboratoire de Chrono-Environnement, UMR 6249 du CNRS, UFR des Sciences et Techniques, 16 route de Gray, F-25 030 Besançon, France
[b] Paleoecology, Institute of Plant Sciences and Oeschger Center for Climate Change Research, University of Bern, Altenbergrain 21, CH-3013 Bern, Switzerland
[c] Dipartimento di Scienze della Terra, Via S. Maria 53, 56126 Pisa, Italy
[d] IGC-CNR, Via Moruzzi 1, 56100 Pisa, Italy
[e] Dipartimento di Colture Arboree, Facoltà di Agraria, Viale delle Scienze 11, I-90128 Palermo, Italy

ARTICLE INFO

Article history:
Received 9 December 2010
Received in revised form
23 May 2011
Accepted 30 May 2011
Available online 20 June 2011

Keywords:
Mediterranean
Sicily
Lake-level fluctuations
Lacustrine sediments
Palaeohydrology
Holocene
Pantelleria tephra

ABSTRACT

This paper presents a high-resolution lake-level record for the Holocene at Lago Preola (Sicily, southern Italy) based on a specific sedimentological approach, with a chronology derived from AMS radiocarbon dates. It gives evidence of three major successive palaeohydrological periods, with (1) a pronounced dryness during the early Holocene until ca 10300 cal BP, (2) a highstand from ca 10300 to 4500 cal BP, and (3) a marked lowstand from 4500 cal BP to present. Large amplitude lake-level fluctuations characterise two transition phases at ca 10300–9000 and 6400–4500 cal BP. Period 2 was interrupted between 8300 and 7000 cal BP by a dry phase that was punctuated to ca 7300 cal BP by the deposition of a tephra from neighbouring Pantelleria Island. Comparisons of the Preola record with other palaeohydrological records along north–south and west–east transects in the Mediterranean show contrasting patterns of hydrological changes: north (south) of around 40°N latitude, the records highlight a mid-Holocene period characterised by lake-level minima (maxima). Humid mid-Holocene conditions over the Mediterranean south of 40°N were probably linked to a strong weakening of the Hadley cell circulation and of monsoon winds. We suggest that the maximum of humidity in the Mediterranean during the mid-Holocene was characterised by humid winters to the north of 40°N and humid summers to the south. On a multi-centennial scale, the high-resolution palaeohydrological reconstructions in the central Mediterranean area reveal a strong climate reversal around 4500–4000 cal BP, with contrasting changes in the hydrological cycle. In addition to seasonal and inter-hemispherical changes related to orbital forcing, this major oscillation might be related to non-linear responses of the climatic system to the gradual decrease in summer insolation at northern latitudes. Another major climate oscillation around 7500–7000 cal BP may have resulted from the combined effects of (1) a strong rate of change in insolation, and (2) variations in solar activity. Finally, comparisons of the Preola lake-level record with Sicilian pollen records suggest a strong influence of moisture availability on vegetation development in Sicily. Very dry early Holocene conditions probably prevented the expansion of coastal evergreen forests, while decreasing moisture availability since the onset of the late Holocene may have exacerbated effects of intensive land-use.

1. Introduction

Understanding conditions behind hydrological changes is crucial for the Mediterranean area, particularly in the face of present-day global warming. Regional sets of palaeoclimatic and palaeoenvironmental data may provide key contributions to this understanding. As pointed out by Reed et al. (2001), Holocene lake-level data offer independent palaeohydrological data to help refine pollen-inferred studies. Detailed, systematic studies aimed specifically at lake-level reconstructions are still scarce in the Mediterranean area. In addition, they often suffer from insufficient dating and temporal resolution. In a compilation based on litho- and biostratigraphic data from literature, Harrison and Digerfeldt (1993) have outlined Holocene patterns of lake-level changes for the Mediterranean region. They distinguished a western Mediterranean

* Corresponding author. Tel.: +33 3 81 66 64 39; fax: +33 3 81 66 65 68.
E-mail address: michel.magny@univ-fcomte.fr (M. Magny).

0277-3791/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.quascirev.2011.05.018

pattern characterised by conditions significantly wetter than today's remaining throughout the early to mid-Holocene, with an abrupt transition to drier conditions after ca 5700 cal BP. Conversely, for the eastern Mediterranean they suggested relatively arid conditions during the early Holocene, moister conditions for the mid-Holocene, and a gradual transition to drier conditions after ca 5700 cal BP. More recently, a thorough review by Tzedakis (2007) has pointed out the increasingly complex climatic scenarios invoked by authors, and attempted to reconcile conflicting interpretations. He specifically questioned the notion of an accentuated summer rain regime in the northern Mediterranean borderlands during the boreal insolation maximum. On the basis of lake isotope records, Roberts et al. (2008) suggest a possible NW/SE contrast in Mediterranean climate history during the Holocene. On the other hand, using mainly pollen data, Jalut et al. (2009) concluded that, in the circum-Mediterranean region, the Holocene can be divided into three periods: a humid early Holocene (11500–7000 cal BP), a transition phase (7000–5500 cal BP), and a dry late Holocene (5500 cal BP-present), which was characterised by drier conditions.

Recent research including oxygen-isotope analysis and climate modelling (see synthesis in Roberts et al., 2011a) emphasises the spatio-temporal complexity of Mediterranean paleo-environmental dynamics (e.g. Bar-Matthews and Ayalon, 2011; Brayshaw et al., 2011; Giraudi et al., 2011; Kuzucuoglu et al., 2011; Mercuri et al., 2011; Roberts et al., 2011b; Sadori et al., 2011). Multiproxy evidence from several sites suggests a wet period 6000–3000 cal. BP in the Western Mediterranean, while in the Eastern Mediterranean precipitation declined already after 6000 cal. BP (Roberts et al., 2011a). Latitudinal differences contributed to paleo-environmental complexity, suggesting a north–south partition around 40°N with almost inverse Mediterranean fire-activity patterns during the Holocene (Vannière et al., 2011). Such latitudinal differences seem in agreement with a spatial tri-partition of western Europe (including Scandinavia and the Mediterranean) as inferred from a comparison of palaeohydrological records: during the Holocene, mid-European latitudes between ca 50° and 43°N were characterised by wetter conditions, while drier climatic conditions prevailed in northern and southern Europe during cold events such as around 8200 cal. BP (Magny et al., 2003). Moreover, long-term seasonal effects emerged (e.g. Finsinger et al., 2010; Peyron et al., 2011), which may reconcile seeming contradictions among the different proxies.

As a contribution to the reconstruction of Holocene hydro-climatic conditions in the central Mediterranean, we first present a high-resolution lake-level record established at Lago Preola, a small lake in southern Sicily, using a specific sedimentological approach and summary pollen analysis. On the basis of a comparison with other palaeohydrological records recently reconstructed in the Mediterranean area and in west–central Europe, we then examine the palaeoclimatic significance of our results in regard to regional patterns of hydrological changes, seasonality, forcing factors and vegetation.

2. Site and methods

2.1. Study area

Lago Preola (37°37 N, 12°38 E, 4 m a.s.l., ca 33 ha) lies in south-western Sicily (Fig. 1), ca 2 km east of the Mediterranean Sea. Maximal water depth was 2 m in June 2008 during coring, but before the lake basin was transformed into a vegetated swamp after a sequence of dry years prior to 2004. It is of karstic origin and topographically closed with no major inlet or outlet, which makes the lake ideal for Holocene lake-level reconstructions. A calcareous ridge up to ca 30 m high separates the lake from the Mediterranean Sea. The catchment area of the lake covers ca 17 km^2 (Fig. 1) and is dominated by limestone and Pleistocene calcarenites. It is characterised by gentle slopes and relatively flat plateaus culminating at ca 70 m a.s.l. The climate of the area is Mediterranean with marked seasonal variations in precipitation. Mean annual precipitation reaches 505 mm at nearby Trapani/Mazara del Vallo, summer precipitation (June–August) 26 mm, and winter precipitation (December–January) 177 mm (AD 1961–1990 average; World Climate, 2008). Mean annual temperature is 17.6 °C, with 25.2 °C for August, and 11.7 °C for January. Preola is part of a nature reserve including the swamp Pantano Murana and the three small karstic depressions of Gorghi Tondi, i.e. the ponds Gorgo Alto, Gorgo Medio, and Gorgo Basso. Pollen and charcoal investigations have been carried out recently at Gorgo Basso to reconstruct Holocene vegetation and fire dynamics (Tinner et al., 2009).

2.2. Coring and dating

Two cores were taken in June 2008 with a modified Streif-Livingstone piston corer 4.8 cm in diameter (Lang, 1994) (Fig. 1). Core LPA was extracted in the littoral zone and core LPBC in the deeper part of the lake. The coring was stopped due to high friction in the sandy and clayey sediment at the base. Similarities observed in the sediment profiles allow lithostratigraphic correlations between the cores LPA and LPBC. The chronology is based on AMS radiocarbon dates (Table 1). Radiocarbon ages were calibrated using Calib 6 (Stuiver et al., 1998; Reimer et al., 2004). In addition to radiocarbon ages, pollen analyses carried out on core LPBC offer the support of correlations with the pollen-stratigraphy of Gorgo Basso, which was radiocarbon-dated from terrestrial plant macrofossils only (Tinner et al., 2009). The age-depth models were made using general addictive models (GAM, Heegaard et al., 2005) that take into account the 2s errors of the calibrated ^{14}C dates as well as the sampling depths of the dated material.

2.3. Tephra analyses

Core LPBC includes a mm-thick tephra layer at level 730 cm. Energy-dispersive spectrometry (EDS) analyses of glass shards and glasses from micro-pumice fragments were performed at the Dipartimento di Scienze della Terra (University of Pisa), with an EDAX-DX micro-analyser mounted on a Philips SEM 515 (operating conditions: 20 kV acceleration voltage, 100 s live time counting, 200–500 nm beam diameter, 2100–2400 shots per second, ZAF correction). The ZAF correction procedure does not include natural or synthetic standards for reference, and requires analysis normalisation at a given value (which is chosen at 100%). Analytical precision is 0.5% for abundances higher than 15 wt%, 1% for abundances around 5 wt%, 5% for abundances of 1 wt% and less than 20% for abundances close to the detection limit (around 0.5 wt%). Accuracy and analytical comparison have been extensively discussed elsewhere (Caron et al., 2010; Sulpizio et al., 2010; Vogel et al., 2010).

2.4. Sedimentological analyses

The lake-level fluctuations were reconstructed using a specific technique described in detail and validated elsewhere (Magny, 1992, 1998, 2004, 2006) and based on a sedimentological approach combining several markers as follows.

- Lithology: fine carbonate lake-marl is deposited in lake water, whereas peat and anmoor reflect marshland conditions. Sand accumulation corresponds to runoff (blunt shining quartz grains) or wind-transport (round-frosted quartz grains).
- Macroscopic components of lake-marl: it has been shown that, in carbonate lakes, the coarser fractions (larger than 0.2 mm) of

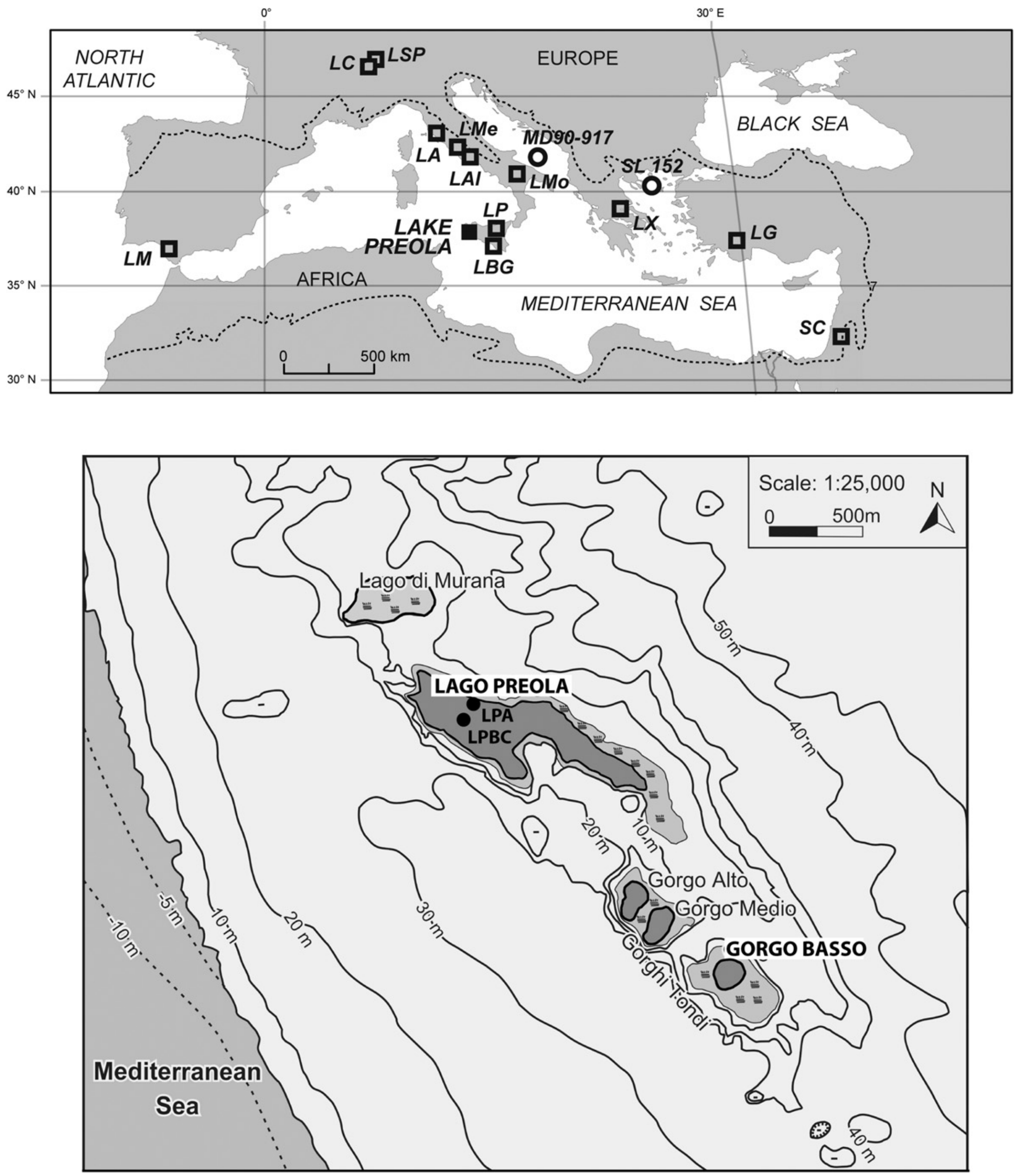

Fig. 1. Upper panel. Geographical location of Lago Preola and reference sites in the Mediterranean. LA: Lake Accesa, LAI: Lake Albano, LBG: Lake Biviere di Gela; LC: Lake Cerin; LG: Lake Gölhisar; LM: Lake Medina, LMe: Lake Mezzano, LMo: Lago Grande di Monticchio, LP: Lake Pergusa; LSP: Lake Saint Point; LX: Lake Xinias; SC: Soreq cave; MD90-917 and SL 152 are two marine cores. Lower panel. Detailed map of the Nature Reserve "Lago Preola e Gorghi Tondi" with the location of two cores LPA and LPBC in Lake Preola, and Gorgo Basso pollen record (Tinner et al., 2009).

lake-marl are mainly composed of (1) carbonate concretions of biochemical origin, (2) mollusc and ostracod tests, and (3) plant macro-remains. The concretions can be divided into several morphotypes. Modern analogues based on surface samples taken along transects perpendicular to the shore have revealed that oncolites and cauliflower-like forms correspond to shallower water than plate-like and tube-like forms. Moreover, grey-coloured concretions including detritic elements mark occasionally dried littoral areas. The macroscopic components were identified and counted using a binocular microscope. Two fractions (i.e. >0.5 mm, and 0.2/0.5 mm) have been studied. A contiguous dense subsampling of sediment sequences (generally 2 to 3 cm-thick samples) made recognition of short-lived palaeohydrological events possible (high temporal resolution).

- Visible to naked-eye geometric micro-unconformities resulting from erosion or non-deposition (lake-level lowering), or micro shrinkage cracks observed along core profiles offer additional information about conditions of sediment deposition.

In addition to markers mentioned above, the reconstruction of lake-level fluctuations relies on the comparative sediment analysis of two distinct cores (the littoral core LPA, and core LPBC from the lake centre). This strategy provides a more comprehensive view of

Table 1
Radiocarbon dates obtained from cores LPA and LPBC.

Core	Depth (cm)	Radiocarbon date	Calibrated age at 2 sigma range	Laboratory reference	Material
Core LPA	44–45	1600 ± 30 BP	1546–1410 cal BP	Poz-27885	peat
Core LPA	157–158	4120 ± 35 BP	4821–4527 cal BP	Poz-30094	peat
Core LPA	234–235	5140 ± 40 BP	5990–5751 cal BP	Poz-27886	Carex seeds and wood fragments
Core LPA	310–311	5340 ± 40 BP	6271–5998 cal BP	Poz-30095	peat
Core LPA	461–462	6220 ± 40 BP	7252–7007 cal BP	Poz-30096	peat
Core LPA	602–603	7940 ± 50 BP	8990–8634 cal BP	Poz-32423	peat
Core LPA	673–674	8930 ± 50 BP	10227–9906 cal BP	Poz-30097	peat
Core LPA	808–809	9360 ± 60 BP	11063–10265 cal BP	Poz-33875	peat
Core LPBC	131–132	2280 ± 40 BP	2353–2158 cal BP	Poz-33867	wood fragments
Core LPBC	401–402	4400 ± 40 BP	5267–4858 cal BP	Poz-33870	peat
Core LPBC	493–494	5160 ± 50 BP	6095–5748 cal BP	Poz-33871	peat
Core LPBC	735–736	7610 ± 50 BP	8538–8345 cal BP	Poz-33874	peat

the sediment sequence and also permits observation of lateral variations in the sediment facies, informative for the reconstruction of past deposition environments.

Finally, given the large amount of the stratigraphically ordered data combining various sedimentological markers from two fractions (more than 0.5 and 0.2/0.5 mm), an approach based on a correspondence analysis (CA) was used to summarise lake-level curves from cores LPA and LPBC. As discussed in detail by Ammann et al. (2000), preliminary Detrented Correspondence Analysis (DCA) were applied to the percentages matrix of sedimentological markers observed in cores LPA and LPBC in fractions more than 0.5 and 0.2/0.5 mm to assess the gradient length of the first axis. If the gradient length is less than two standard deviation units, the Principal Components Analysis (PCA) is the appropriate technique, whereas if the gradient length is more than two deviation standard units, CA is the relevant technique (Ter Braak and Prentice, 1988) to extract the major underlying gradient. For both records, the first DCA axis length was >2.5 SD units justifying the further use of a unimodal response model and hence of CA as the appropriate ordination method for the sedimentological markers (Birks, 1995). Stratigraphic plots of sample scores along the CA axis were used as a means to emphasising the main changes in sedimentological features in both cores. For the central core LPBC, the distribution of samples along axis 1 was governed by the particular features of basal sediment unit 6 compared to the rest of the core. To better explore the sedimentological variability from unit 5 to 1, sample scores were plotted and analysed using axis 2 of the CA. Axis 1 in the CA of core LPA and axis 2 in the CA of core LPBC explain 24% and 15% of the variance respectively. For each core, the percentages matrix composed of sedimentological markers observed in both fractions (more than 0.5 and 0.2/0.5 mm), excluding the percentages corresponding to columns labelled Lithoclasts, Concretions, Molluscs + Ostracods, and Vegetal remains in the diagrams of Figs. 5 and 6. These columns show totals of different types of markers.

3. Results and interpretation

3.1. Lithology and chronology

Considered as a whole, the sediment profiles of cores LPA and LPBC show six similar successive sediment units which allow first lithostratigraphic correlations between the littoral and the central cores (Fig. 2). Basal sediment unit 6 is composed of blue–grey abiotic sand. Sediment unit 5 consists of black humified peat (anmoor). Sediment units 4 and 2 correspond to silts with an alternation of peaty dark-coloured organic layers and light-coloured carbonate layers (sometimes laminated). Organic layers are more frequent in core LPBC and in the lower part of sediment unit 2 in core LPA. These two units are also marked by abundant mollusc shells. In both cores, unit 2 includes a thin layer of lithoclasts dated to 5340 ± 40 BP in core LPA. Sediment unit 3 interbedded between units 4 and 2 is made up of relatively homogeneous black–grey organic silts, where mollusc shells are nearly absent.

In core LPBC, unit 3 also includes one mm-thick tephra layer at level 730 cm which is dated to ca 7444–7136 cal BP (interpolated age from the age-depth model presented in Fig. 3) and corresponds to volcanic activity from neighbouring Pantelleria Island. This cryptotephra is composed by micropumices (Fig. 3) and aphyric glass shards with rhyolitic composition (Table 2, Fig. 3). Alkali ratio (K_2O/Na_2O) is below 1. In the FeO_{tot} vs. Al_2O_3 diagram the rhyolite plots into the field of pantellerites, which indicates the peralkaline volcano of Pantelleria as its source. At Pantelleria there is a documentation of an Early Holocene to Middle Holocene eruptive activity (Mahood and Hildreth, 1986; Civetta et al., 1988; Speranza et al., 2009), and our tephra should be related to the so-called VI cycle (Civetta et al., 1988) even if at this stage a detailed correlation with a specific eruptive event is not possible. It is interesting to note that this is the first identification of Pantelleria Holocene ash layer on land.

Finally, sediment unit 1 consists of organic and carbonate silty layers (sometimes laminated) with carbonate components dominating. Mollusc shells are scarce.

Fig. 4 presents the age–depth models of both cores LPA and LPBC. That of core LPA is based on 8 radiocarbon dates. The chronology of core LPBC relies (1) on 4 radiocarbon dates obtained from core LPBC, (2) on 3 radiocarbon ages induced by lithostratigraphic correlations with core LPA as illustrated in Fig. 2, and (3) on 9 radiocarbon ages inferred from correlations with the well-dated pollen-stratigraphy of the neighbouring Gorgo Basso record (Figs. 1 and 2; Tinner et al., 2009).

On the basis of these age–depth models, the mean temporal resolution of sedimentological analysis is 64 years/sample for core LPA and 58 years/sample for core LPBC. Moreover, the comparison of the two age–depth models gives evidence that the littoral core LPA offers a better resolution for the early to mid-Holocene than for the late Holocene. The central core LPBC displays a more regular temporal resolution.

3.2. Lake-level fluctuations

Figs. 5 and 6 show the sediment diagrams, and Fig. 7 the curves of relative changes in lake level established from cores LPA and LPBC. As illustrated by Fig. 7, the two lake-level curves display strong similarities which support the consistence of the reconstruction method and the robustness of the chronology, even if minor differences appear in the detail. Taken together, the sediment diagrams (Figs. 5 and 6) and the lake-level curves (Fig. 7) of cores LPA and LPBC allow three main successive periods to be distinguished as follows.

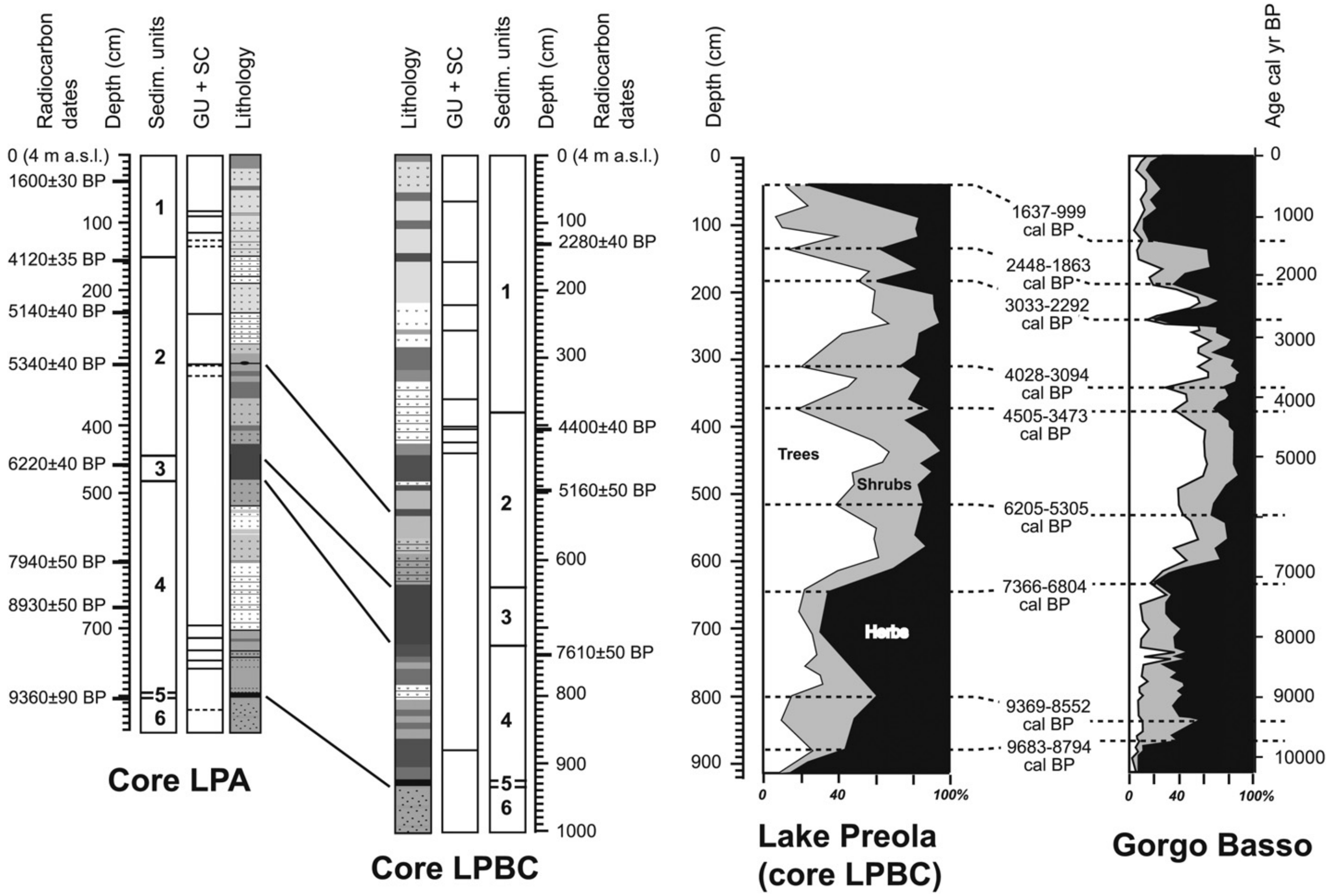

Fig. 2. Left panel. Sediment profiles of cores LPA and LPBC with lithostratigraphic correlations. Lower panel: Correlations of the pollen-stratigraphy of core LPBC with that of Gorgo Basso. The chronology of the Gorgo Basso pollen record is based on 10 radiocarbon dates (Tinner et al., 2009). The dotted lines mark (1) the correlations between the pollen stratigraphies of Gorgo Basso and core LPBC of Lake Preola, and (2) the corresponding ages interpolated from the age–depth model of Gorgo Basso pollen record (Tinner et al., 2009). GU + SC: geometric unconformities and shrinkage cracks. Note that the lithostratigraphic correlations between the littoral core LPA and the central core LPBC suggest a relatively small depth of the Preola lacustrine basin. The difference in absolute altitude reaches ca 1.3 m for the sediment unit 5, 2.5 for the base of sediment unit 3, 2.2 m for the lithoclast layer dated to 5340 ± 40 BP in sediment unit 2, and 2.1 m for the sediment unit 2/1 transition.

- The first phase of the early Holocene ca 11500–10600 cal BP is characterised by very dry conditions, and corresponds to the deposition of sediment unit 6. The sediment diagrams of core LPBC show that the sand of basal unit 6 contains a large proportion of round-frosted quartz grains, which reflect wind-transport (Fig. 6). Dry conditions are also suggested by the complete absence of aquatic biotic remains such as mollusc and ostracod tests. This points to the absence of a lake in the Preola basin. Shortly after 10600 cal BP, the formation of sediment unit 5 marks a transition towards more humid conditions. Unit

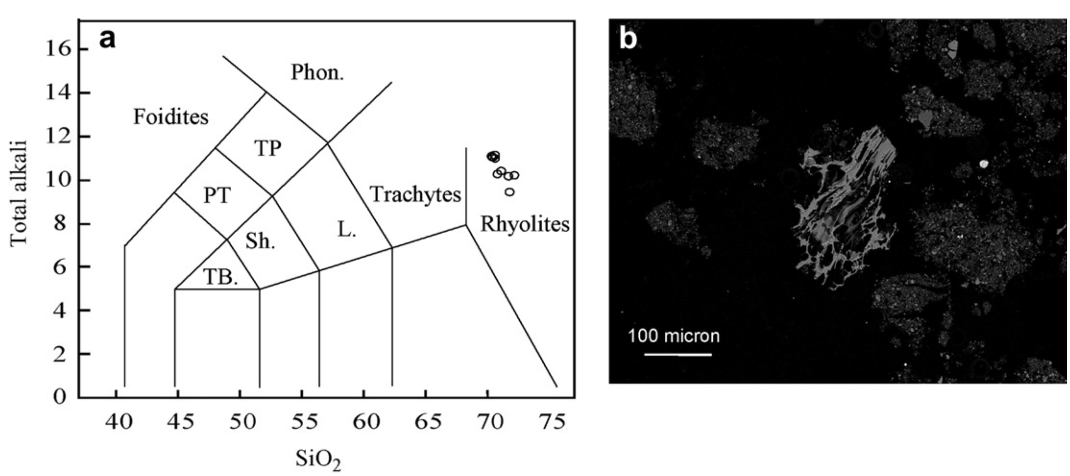

Fig. 3. (a) Total alkali vs. silica diagram (Le Bas et al., 1986) of glass compositions of the recognised tephra layer of level 730 cm in core LPBC. (b): Micropumices of the studied tephra.

Table 2
Analytical data for the Preola tephra layer of level 730 cm in core LPBC.

	1	2	3	4	5	6	7	8	9	Mean	stdev
SiO2	70.44	70.37	71.74	72.15	71.82	71.12	70.87	70.65	70.64	71.09	0.62
TiO2	0.38	0.4	0.34	0.16	0.29	0.37	0.44	0.41	0.39	0.35	0.08
Al2O3	8.31	7.99	8.23	8.28	8.94	8.59	8.37	8.25	7.84	8.31	0.30
FeOtot	8.36	8.4	7.91	7.8	7.95	7.88	8.48	8.13	8.42	8.15	0.25
MnO	0.4	0.38	0.23	0.15	0.37	0.32	0.51	0.44	0.35	0.35	0.10
MgO	0.09	0.06	0	0	0	0	0	0	0.08	0.03	0.04
CaO	0.39	0.6	0.5	0.62	0.53	0.67	0.39	0.42	0.43	0.51	0.10
Na2O	6.62	6.6	5.84	5.76	5.02	5.98	5.75	6.51	6.62	6.08	0.52
K2O	4.37	4.43	4.28	4.4	4.37	4.37	4.46	4.44	4.46	4.40	0.05
P2O5	0	0	0.09	0	0	0	0	0	0	0.01	0.03
ClO	0.65	0.75	0.85	0.69	0.72	0.7	0.74	0.74	0.78	0.74	0.05
Total	100.01	99.98	100.01	100.01	100.01	100	100.01	99.99	100.01	100.00	
Total alkali	10.99	11.03	10.12	10.16	9.39	10.35	10.21	10.95	11.08	10.5	
Alkali ratio	0.66	0.67	0.73	0.76	0.87	0.73	0.78	0.68	0.67	0.72	

5 composes of humified peat (anmoor) including remains of aquatic fauna. This type of deposit indicates moister conditions which led to the formation of a mire, and/or of a shallow body of water intermittently drying (unstable water table during a transitional phase), before the formation of a lake at ca 10300 cal BP (transition between sediment units 5 and 4). A small peak of anmoor in the sediment diagrams of core LPBC at ca 9800 cal BP (Fig. 6) probably marks the occurrence of a pronounced lowering after 10300 cal BP. The relatively abrupt transition from unit 6 to unit 5 suggests a rapid climate change provoking a stop in sand accumulation.

- The period 10300–4500 cal BP corresponds to a phase of high lake-levels (sediment units 4 and 2). The deposition of silty lake-marl including abundant remains of freshwater molluscs clearly marks the formation of a permanent lake. Geometric unconformities, shrinkage cracks and anmoor material (Figs. 2, 5 and 6) are still frequent in core LPA (littoral zone) until ca 10000 cal BP, but they then disappear between 10000 and 6300 cal BP, pointing to increasing water depths also close to the shore. In the centre of the lake (core LPBC), there is only one geometric unconformity observed at ca 9300 cal BP, and this type of feature did not reappear before ca 5500 cal BP (Fig. 6). Comparison of the sediment diagrams of cores LPA and LPBC (Figs. 5 and 6) reveals that the littoral zone was characterised by a stronger development of carbonate concretions than in the central zone marked by less abundant concretions. In fact, given the shallow depth of Preola lacustrine basin, aquatic vegetation developed and survived more particularly in the zones of permanent water, i.e. in the centre of the basin, whereas it was less abundant in the littoral zones more sensitive to seasonal water-level lowering (see lithostratigraphic correlations between the sediment profiles of cores LPA and LPBC in Fig. 2).

This phase of high lake level was interrupted by a temporary return to dry conditions marked by the deposition of sediment unit 3 between 8300 and 7000 cal BP. Both cores LPA and LPBC show a maximal dryness around 7400–7300 cal BP. The mollusc shells nearly disappear whereas the accumulation of fine eolian sand resumes. The deposition of a tephra layer from Pantelleria at ca 7300 cal BP (7434–7136 cal BP) offers a potential key time-marker for this dry period. The preservation of this tephra in core LPBC in contrast to core LPA where it is lacking is an additional indication that the water remained in the central part of the Preola basin while the littoral zone probably partly dried up during this phase. Taken together, the lake-level record (Fig. 7) shows larger fluctuations from 10300 to 9000 cal BP and from 6400 to 4500 cal BP, i.e. at the beginning and the end of the period 10300–4500 cal BP. This suggests transitional phases with more unstable lake-level (climate) conditions as reflected by occurrences of geometric unconformities and shrinkage cracks in cores LPA and LPBC (Fig. 2).

- The period from 4500 cal BP to present coincides with a lowering of the lake-levels. The deposition of sediment unit 1 shows a strong retreat of freshwater molluscs. Only small aquatic fauna such as ostracods maintained well. Geometric unconformities and shrinkage cracks affect even the central zone of the basin, where carbonate concretions and Characae oogones, rare before ca 5500 cal BP, show a large development as in the littoral zone. The grey colour of the carbonate encrustations (concretions, ostracod tests, oogones) reflects the invasion of terrestrial detritism into the centre of the Preola basin. The lake-level lowering is also marked by the successive development of the tube-like, plate-like concretions and oncolites in core LPA after 4500 cal BP. However, the lake-level record reconstructed from littoral core LPA suggests a rise for the last two millennia in contrast to that of central core LPBC which shows persistent lowstands. This may reflect a bias due to the marked development of vegetal remains. In fact, sediment diagrams in Fig. 5 indicate that this development from ca 2000 cal BP onwards is limited to coarse fraction (more than 0.5 mm) and probably results from overgrowing processes which affect the littoral core LPA more strongly than the central core LPBC located in deeper water. This interpretation is supported by the fact that the development of vegetal remains since 2000 cal BP in core LPA is not associated with maxima of mollusc tests, in contrast to the period of high lake-levels between 10300 and 4500 cal BP (Fig. 5) where maxima of vegetal remains and mollusc tests are coupled.

4. Discussion

4.1. Lake-level fluctuations and vegetation history of Sicily

The Preola lake-level record offers new insights into the possible linkages between climate, lake-levels and vegetation history in Sicily. Water resources (through soil moisture and precipitation) are a crucial factor for the development of forests in the Mediterranean region. Fig. 8 presents a comparison between the lake-level record of Preola and three Sicilian pollen records from Gorgo Basso (Tinner et al., 2009), Biviere di Gela (Noti et al., 2009), and Pergusa (Sadori and Narcisi, 2001; Sadori et al., 2011). Depending on the period, it suggests moderate to pronounced correlations between

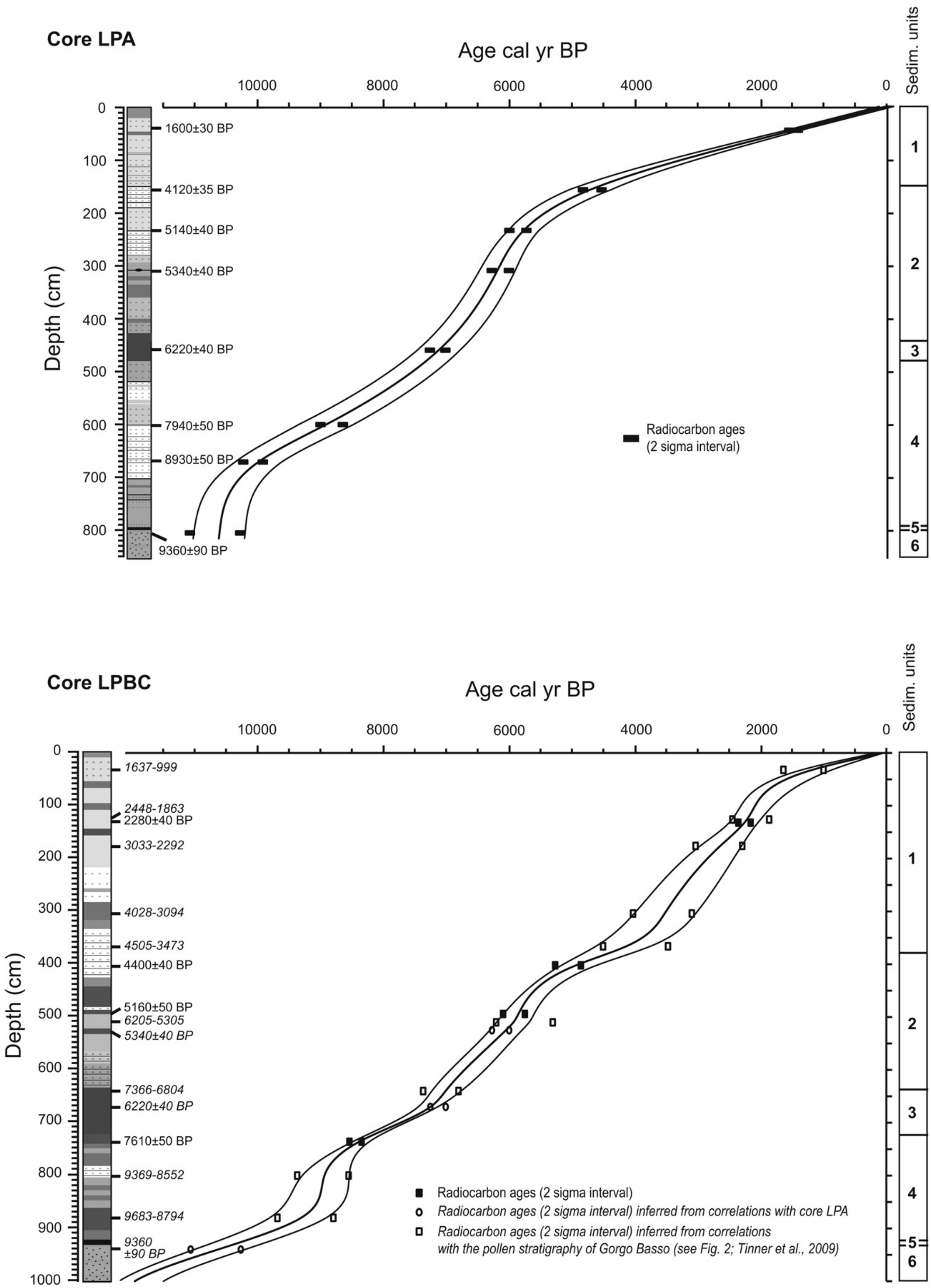

Fig. 4. Age–depth models of cores LPA and LPBC based on GAM (Heegaard et al., 2005).

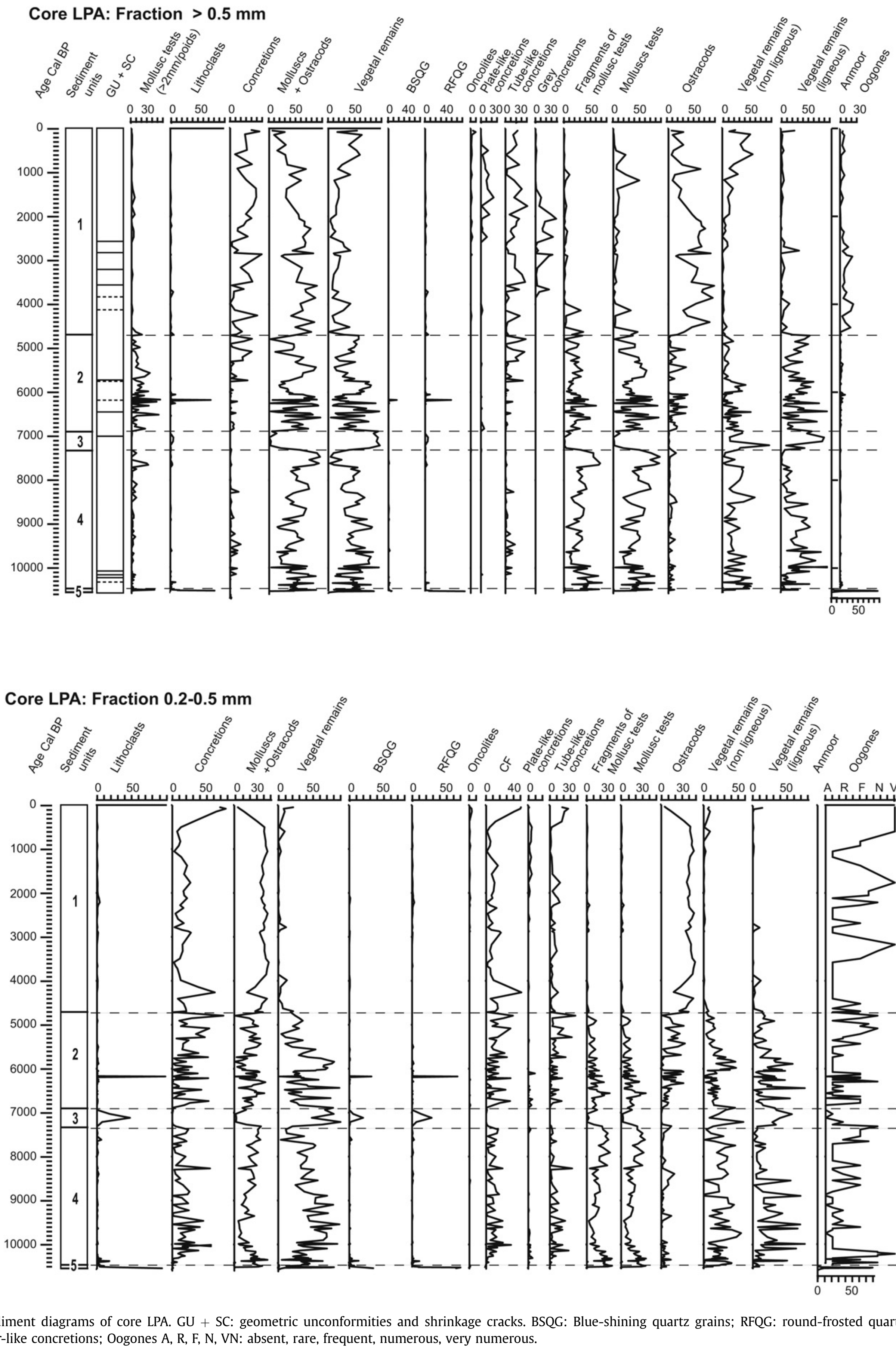

Fig. 5. Sediment diagrams of core LPA. GU + SC: geometric unconformities and shrinkage cracks. BSQG: Blue-shining quartz grains; RFQG: round-frosted quartz grains. CF: cauliflower-like concretions; Oogones A, R, F, N, VN: absent, rare, frequent, numerous, very numerous.

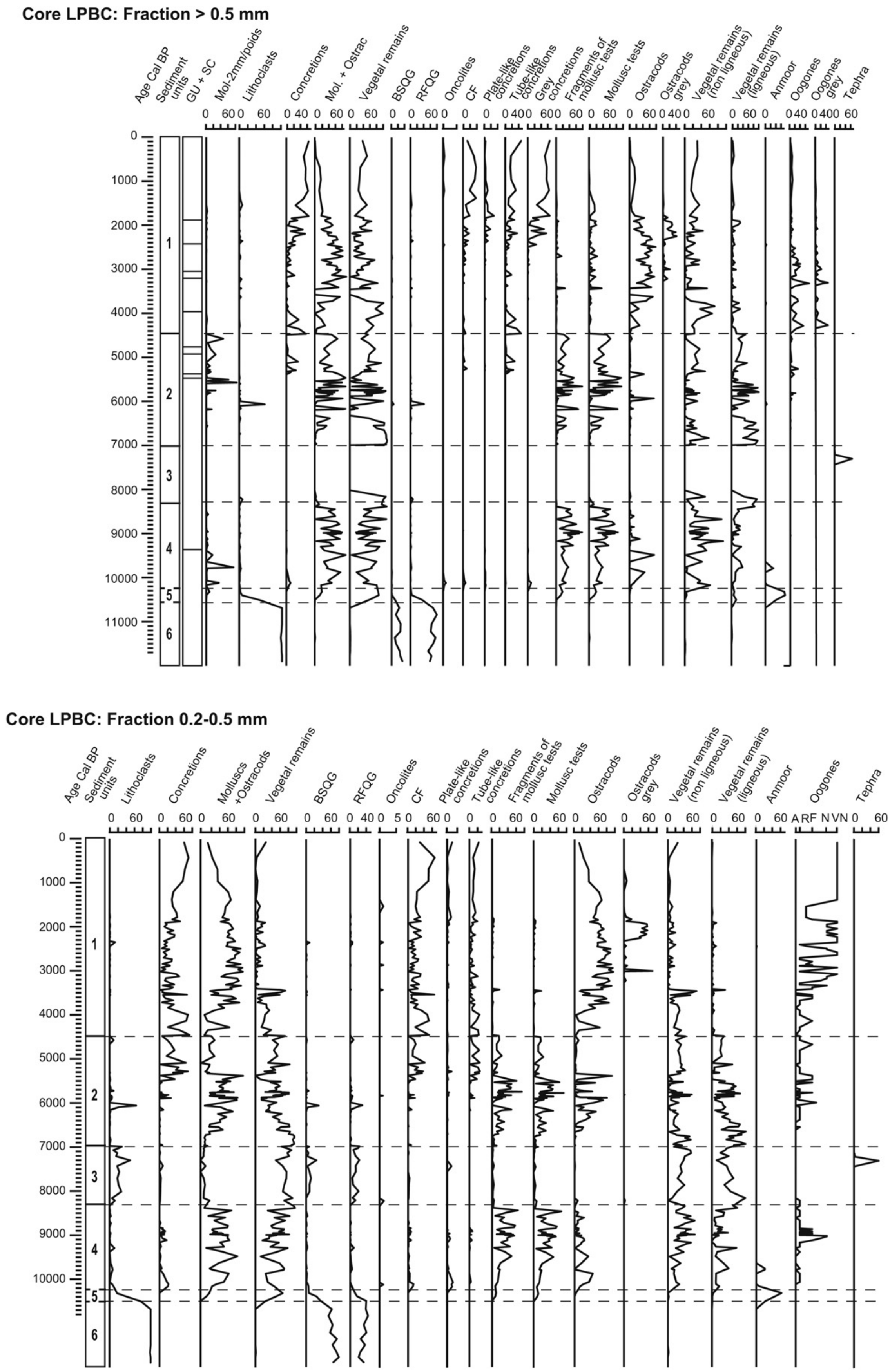

Fig. 6. Sediment diagrams of core LPBC. GU + SC: geometric unconformities and shrinkage cracks. BSQG: Blue-shining quartz grains; RFQG: round-frosted quartz grains. CF: cauliflower-like concretions; Oogones A, R, F, N, VN: absent, rare, frequent, numerous, very numerous.

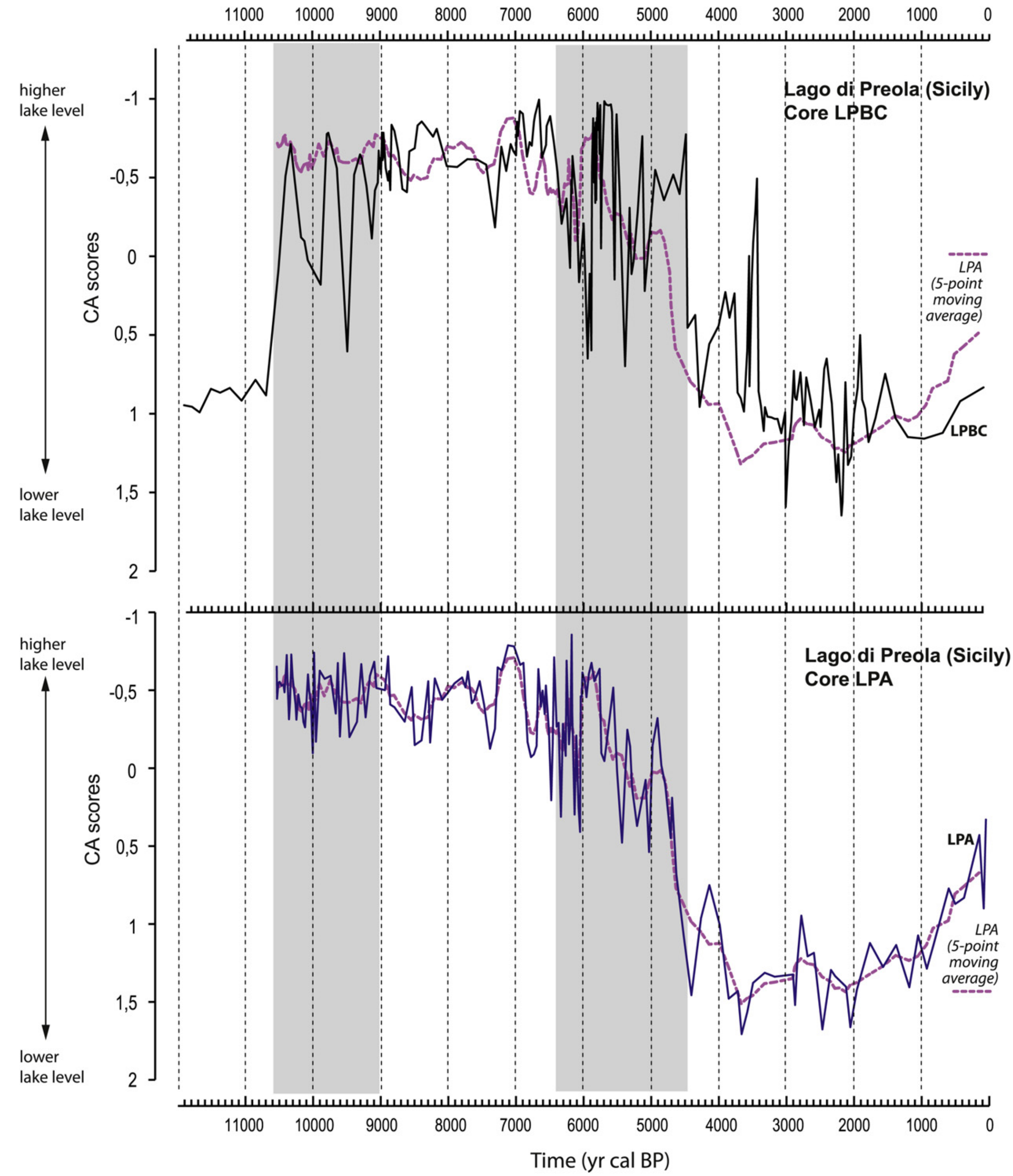

Fig. 7. Relative changes in lake-level reconstructed from cores LPA and LPBC.

lake-levels and vegetation dynamics during the Holocene. The presence of a mire or of low lake-levels during the early Holocene at Preola coincides with the persistence of a fire-prone open grassland until ca 10000 cal BP at Lago Preola and Gorgo Basso (Figs. 2 and 8). The abrupt rise in lake level around 10300 cal BP preceded the rapid expansion of oak forests and *Fagus* in the high-elevation inland site of Pergusa (667 m a.s.l.), and shrubs in the low-elevation coastal site of Gorgo Basso, by about 100–300 years. The delayed expansion of evergreen forests on the coast at ca 7000 cal BP, i.e. almost three millennia later than in the Sicilian uplands, probably resulted from lower moisture availability at the warmer coastal sites (Tinner et al., 2009). Percentage distortions (e.g. masking of the woodland vegetation by local vegetation such as Poaceae growing at the lake shore) can be excluded since the interpretation of Gorgo Basso is based on agreeing percentage, concentration and influx changes (Tinner et al., 2009).

It is intriguing that the lake-level proxies suggest rather high average lake-levels when drought-adapted shrublands (*Pistacia* mainly evergreen *P. lentiscus*, see Tinner et al., 2009) were abundant, but no moisture-requiring evergreen oak forests existed

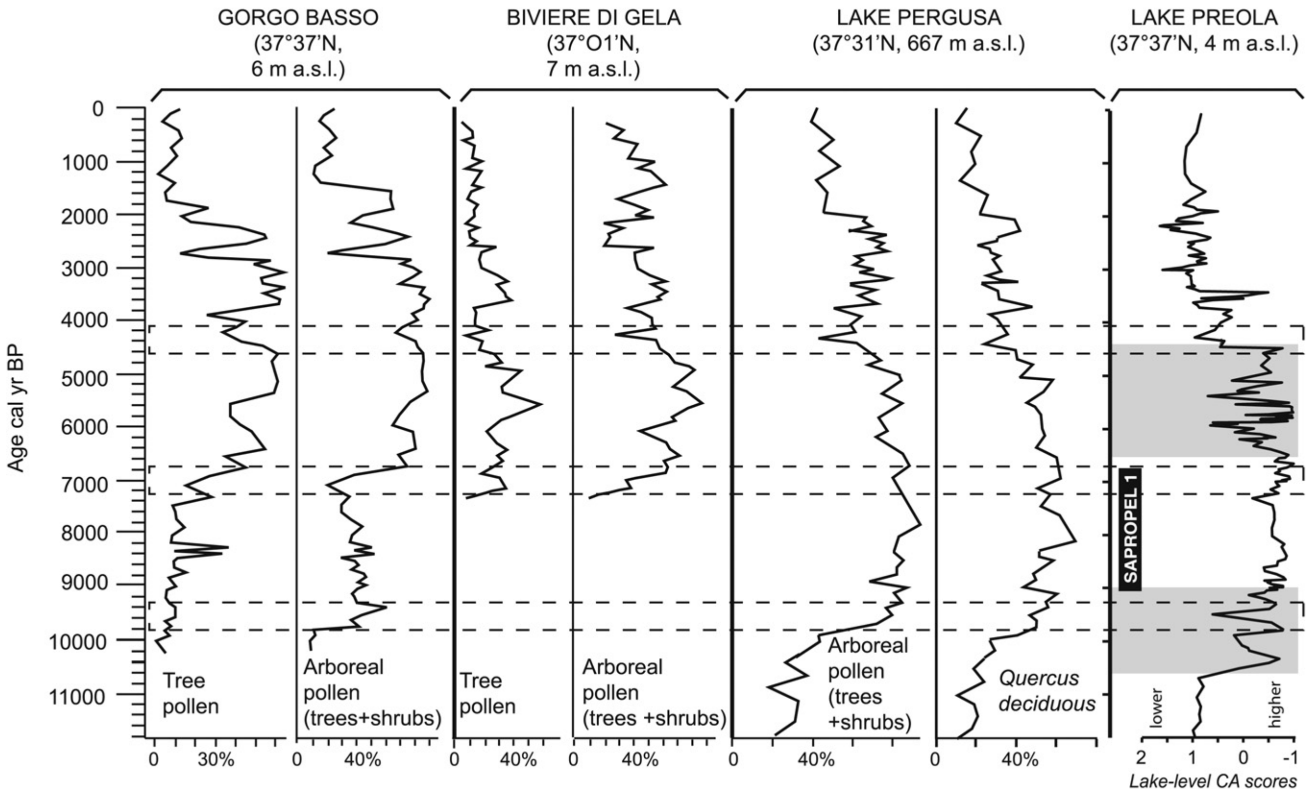

Fig. 8. Comparison of the LPBC lake-level record from Lago Preola with pollen records from Gorgo Basso (Tinner et al., 2009), Biviere di Gela (Noti et al., 2009), and Lake Pergusa (Sadori and Narcisi, 2001). The grey bands mark periods characterised by relatively unstable climatic conditions (large lake-level fluctuations).

(Fig. 8). The absence of evergreen forests may also have originated from more pronounced seasonal and interannual variability of drought between 10300 and 7000 cal BP. This might apply especially for the dry period between 8300 and 7000 cal BP. Indeed this latter event coincided with a stop in the expansion of *Olea* woodlands and an increase in fire activity at Gorgo Basso (Tinner et al., 2009). In the Eastern Mediterranean similar early Holocene discrepancies exist between oxygen-isotope records suggesting high precipitation amounts and pollen records reflecting unforested conditions (Roberts et al., 2011a). This seeming contradiction is best explained with seasonal effects, since the absence of forests is mainly controlled by insufficient summer moisture availability, whereas in the Mediterranean the oxygen-isotope records may mainly reflect winter precipitation (Zanchetta et al., 2007; Tzedakis et al., 2009).

At Lago Preola, discrepancies between lake-level reconstructions and vegetational dynamics are particularly pronounced during the period 4000–3000 and 2600–2200 cal BP when forests were dense (inferred from pollen percentages and influx), but lake-levels very low. Similar discrepancies between lake-level conditions and pollen data have been observed by Eastwood et al. (2007) at Lake Gölhisar in southwest Turkey and probably point to other factors than precipitation controlling vegetation during this period (land-use, human impact, fire). At Preola, the low lake-levels occurred during a general trend to drier conditions observed at several sites in the Mediterranean region. On the other hand, the abrupt fall in lake level registered at Preola at 4500 cal BP coincided with a marked retreat of *Quercus deciduous* at Pergusa, which is synchronous with the onset of tree and shrub decline at Biviere and with a transient and minor retreat of trees and shrubs at Gorgo Basso. However, Noti et al. (2009) concluded that the deforestation trend during the late Holocene at Lago di Biviere (a low-elevation site on the southeast coast of Sicily, Fig. 8) was not the consequence of increasing drought, but of increasing land-use activities as unambiguously recorded by pollen of crops and weeds.

Evidence of climatic influence on the vegetation has been reconstructed in the Segura Mountains of southern Spain, with a mid-Holocene maximum forest development at the time of highest lake-levels (Carrion, 2002) which corresponds well with our coastal Sicilian lake-level and vegetation records. However, detailed investigations in recent years have revealed that human impact strongly affected vegetational dynamics and especially triggered late-Holocene forest declines in Mediterranean Spain (Carrion et al., 2010), as was the case in Sicily. Indeed the Gorgo Basso pollen record suggests that the impact of climate on late Holocene vegetation was relatively limited until strong anthropogenic activities such as fire, pasture and crop production suddenly increased at the beginning of the Greek colonisation and later Roman occupation. On the basis of the Gorgo Basso and Biviere pollen evidence, we suggest that drier conditions during the late Holocene may have exacerbated the effects of human impact, favouring the forest decline during the late Holocene. However, the maquis and garrigue vegetation of today, where forest was present during the mid-Holocene, in Sicily (Noti et al., 2009; Tinner et al., 2009) and elsewhere in Italy (Colombaroli et al., 2007, 2008), primarily resulted from intensive land-use and anthropogenic fire over the last millennia (for further details see Noti et al., 2009; Tinner et al., 2009).

4.2. Opposite Holocene palaeohydrological patterns in the Mediterranean area

Lake-level changes are driven by climatic parameters affecting both evaporation and precipitation, but they can also be induced by

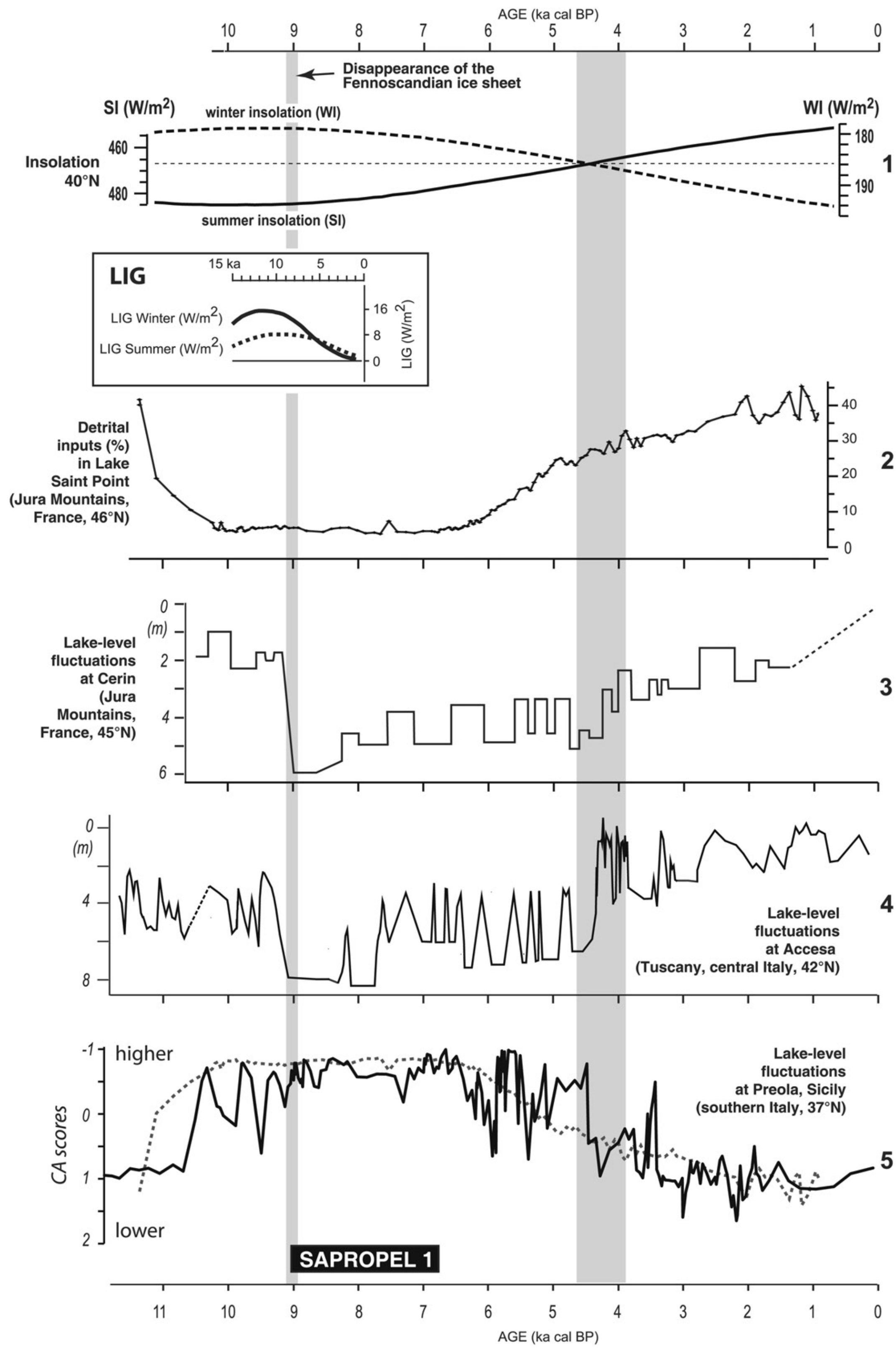

Fig. 9. Comparison of the Preola record (1) with the curve of summer insolation at 65°N (Berger, 1978), and (2) with other lake-level/palaeohydrological records along a north—south transect, i.e. Lake Accesa (Magny et al., 2007), Lake Cerin (Magny et al., 2011) and Lake Saint Point (Leroux et al., 2008). The chronology of Sapropel event 1 is based on Ariztegui et al. (2000). In panel 5, the curve with dotted line is that of Lake Saint Point (panel 2) inverted for direct comparison with the Preola lake-level record. Inset: Latitudinal Insolation Gradient (LIG) from Davis and Brewer (2009). Note that the insolation curves at 40°N (Berger and Loutre, 1991) give evidence that the general late-Holocene decline of the annual insolation also coincided with an important reorganisation in seasonality around 4500–4000 cal BP.

a variety of local non-climatic factors including geomorphological phenomena, as well as human impact on the vegetation cover and the hydrology of the catchment. However, the comparison of lake-level records may give evidence of synchronous lake-level changes within an area assumed to be climatically driven (Digerfeldt, 1988; Harrison and Digerfeldt, 1993; Magny, 1998, 2004). To assess this, Fig. 9 presents a first comparison with other lake-level records along a north–south transect, i.e. Lake Accesa in central Italy (Magny et al., 2007), and Cerin (Magny et al., 2011) in the Jura Mountains (eastern France, north of the Alps). These three records have been established using the same sedimentological approach making the comparison easier. Also in the Jura Mountains, Lake Saint Point offers for comparison an additional record of palaeohydrological variations based on the estimation of detrital inputs into the lake using the ratio authigenic carbonate deposits/silicate input. This ratio, informative of the hydrological activity of lake inlets (Leroux et al., 2008), reflects combined effects of both precipitation (silicate inputs) and temperature (authigenic carbonate). It is noteworthy that, in the Mediterranean area, the lake-level maximum observed at Lago Preola during the mid-Holocene shows an opposite palaeohydrological pattern to the lake-level minimum reconstructed for this period at Lake Accesa. Small lakes such as Accesa are good archives of lake-level changes since they are complementary to large lakes that may be more affected by tectonic changes (Giraudi et al., 2011). Clearly, the Accesa record in the northwestern Mediterranean belongs to the same palaeohydrological pattern as those established at Lakes Cerin and Saint Point in the Jura Mountains north of the Alps, with a mid-Holocene characterised by a lake-level minimum (Lakes Accesa and Cerin), or a minimal hydrological activity (Lake Saint Point). The direct comparison of Lakes Saint Point and Preola records in panel 5 of Fig. 9 gives a more striking illustration of the opposition between the Holocene palaeohydrological patterns that characterise two distinct zones, i.e. the southwest Mediterranean and the northwest Mediterranean/west–central Europe. This supports a previous palaeohydrological pattern outlined for the central Mediterranean (Magny et al., 2007).

On the other hand, in the southern Mediterranean region, the Preola record finds equivalents along a west–east Mediterranean transect as illustrated by the lake-level records reconstructed at Laguna de Medina (latitude 36°N in southern Spain; Reed et al., 2001), at Lake Xinias in Greece (latitude 38°N; Digerfeldt et al., 2007), and at Lake Gölhisar in southwest Turkey (latitude 37°N; Eastwood et al., 2007). The Medina record is based on various (biotic and abiotic) palaeolimonological data (Reed et al., 2001), the Pergusa and Xinias records on pollen data and lithofacies observation (Sadori and Narcisi, 2001; Digerfeldt et al., 2007; Sadori et al., 2008, 2011), and the Gölhisar record on oxygen-isotope data from authigenic calcite (Eastwood et al., 2007). In addition, the chronology of the Xinias record is based only on reference to a regional pollen-stratigraphy established by Bottema in 1979, while, at Lake Gölhisar, the interval 5700–3600 cal BP is dated only by ages interpolated between two radiocarbon-dated horizons (Eastwood et al., 2007). Keeping in mind the uncertainties in dating, in the differences in the methods used for reconstruction and also in the resolution of analyses, all these lakes along a west–east transect give evidence of a tri-partite pattern, with a lake-level maximum during the mid-Holocene period, preceded by a minimum during the early Holocene, and followed by a trend towards lower lake-levels during the late Holocene.

The synchronicity between the lake-level/palaeohydrological changes presented in Fig. 9, even if contrasting, suggests a common forcing factor, i.e. orbitally-induced changes in summer insolation. Moreover, the abrupt lake-level lowering observed around 9000 cal BP at both Lake Accesa in the northwest Mediterranean and Lake Cerin in west–central Europe appears to be synchronous with the disappearance of the Fennoscandian ice sheet. This may reflect a strong influence of deglaciation in the reorganisation of the general atmospheric circulation in Europe at that time (Magny et al., 2011; Shuman and Plank, 2011). Furthermore, the contrasting palaeohydrological patterns observed along a north–south versus a west–east transect highlight two distinct zones characterised by two different climatic evolutions in response to forcing factors. This observation confirms the importance of the latitude around 40°/43°N for Holocene palaeoenvironments and climates, as pointed out by previous studies based on palaeohydrological data (Magny et al., 2003), or fire history (Vannière et al., 2011). Davis and Brewer (2009) observed similar features for the mid-Holocene from pollen data, with negative temperature anomalies (climate cooling) to the south of 40°N, and positive (or nearly zero) values for temperature anomalies to the north.

4.3. Contrasting seasonality patterns

In a first approximation, given the warm-season development of the carbonate concretions used as sedimentological markers to reconstruct past lake-level changes at Lakes Cerin, Accesa and Preola, the lake-level records reflect changes in summer moisture availability. At Lake Accesa, in the northwest Mediterranean area, in agreement with the lake-level record (Magny et al., 2007), pollen-based quantitative reconstruction of precipitation suggest that the mid-Holocene period coincided with minimal summer precipitation but also maximal winter precipitation (Finsinger et al., 2010; Peyron et al., 2011). This points to a seasonal contrast stronger than today's and which is in agreement with the forcing evolution by the Latitudinal Insolation Gradient (LIG, see inset in Fig. 9; Davis and Brewer, 2009). This winter precipitation maximum may be related to the influence of warmer SST in the eastern North Atlantic and the western Mediterranean during the Holocene climate optimum (Marchal et al., 2002). Such a winter precipitation maximum north of ca 40°N is also supported by a pollen-based quantitative reconstruction of seasonal precipitation from marine core SL 152, which documents environmental and climatic changes in the northern borderlands of the Aegean Sea (Kotthoff et al., 2008).

South of 40°N, high Preola lake-level stands suggest a mid-Holocene precipitation maximum. A similar pattern is also recorded at Monticchio in southern Italy with a moisture maximum around 8000–3000 cal BP (Allen et al., 2002; De Beaulieu et al., 2005) and at Fucino east of Rome with high levels between ca 6000 and 2000 cal BP (Giraudi et al., 2011). As pointed out by Tinner et al. (2009), the mid-Holocene moisture increase observed in coastal Sicily at ca 7000 cal BP, which allowed evergreen forests to expand into Mediterranean shrublands, probably relates to a decrease in the Hadley circulation (trade winds) and monsoonal activity after the boreal insolation maximum. A similar forcing has been suggested for other areas of the Mediterranean (Tzedakis et al., 2009). Gaetani et al. (2006) have shown how an intense African monsoon reinforces the Hadley circulation, and consecutively strengthens the North Atlantic anticyclone and its blocking effect for the western moist airflow towards the Mediterranean. Taken together, this new (palaeo)climatic evidence suggests that more humid conditions developed in the southern Mediterranean only when the Hadley circulation maximum started to decline, i.e. after the early Holocene insolation maximum. Such an evolution of the orbital forcing may explain the general early Holocene dryness observed in the Mediterranean area south of ca 40°N and illustrated by the lake-level records in Fig. 10.

4.4. Centennial-scale events

On a multi-centennial scale, one of the most salient features of the Preola lake-level record is the dry episode registered by sediment unit 3 in both the cores LPA and LPBC. In core LPBC, this dry event spans the period 8300–6900 cal BP with a maximal lowering at ca 7300 cal BP. For the same time window, littoral core LPA shows a slightly different pattern with two distinct events, the first peaking at 8400–8200 cal BP, and the second at 7400 cal BP. While the first one may be related to the 8.2 ka event (Alley et al., 1997; Wick and Tinner, 1997; Ariztegui et al., 2000) which has linked to an arid phase in the southernmost parts of western Europe (Magny et al., 2003), the second deserves more specific attention. Stable isotope data from a cave in northern Sicily indicate two successive cool and dry events which interrupted the wet mid-Holocene at ca 8200 and 7500 cal BP (Frisia et al., 2006). The arid episode around 7500 cal BP reconstructed at Preola may also find an equivalent in the well-dated Medina and Gölhisar records and, taking into account the dating uncertainty, in the Xinias record (Fig. 10). At Lake Accesa (latitude 42°N), this climatic oscillation coincided with a marked rise in lake level (Fig. 9; Magny et al., 2007). Furthermore, in marine core MD90-917 in the Adriatic Sea (Fig. 1), Siani et al. (2010) have recognised that the Holocene SST record was punctuated by two major negative anomalies at 8200 and 7000 cal BP. This climatic reversal ca 7500–7000 cal BP is well documented in the west–central Europe lake-level record (Magny, 2004, 2006) as well as in Alpine and Central European palaeoclimatic series, e.g. glaciers, treelines, chironomids (Haas et al., 1998; Heiri et al., 2004). Its range may have exceeded the European continent as suggested by a near cessation of the early to mid-Holocene sea-level rise (Bird et al., 2010), as well as by a major IRD peak in the North Atlantic (Bond et al., 2001) and an expansion of polar water in the Nordic Seas (Rasmussen and Thomsen, 2010). It coincided with the highest rate of change in annual insolation during the interval 8000–7000 cal BP (Zhao et al., 2010) and with a prolonged period of decrease in the residual atmospheric radiocarbon between 8500 and 7000 cal BP (Stuiver et al., 1998). Thus, this event may have resulted from the combined effects of both orbital forcing and variations in solar activity.

Finally, despite contrasting Holocene patterns of palaeohydrological changes, the lake-level records established at Lakes Preola and Accesa in the Mediterranean area and at Lake Cerin in

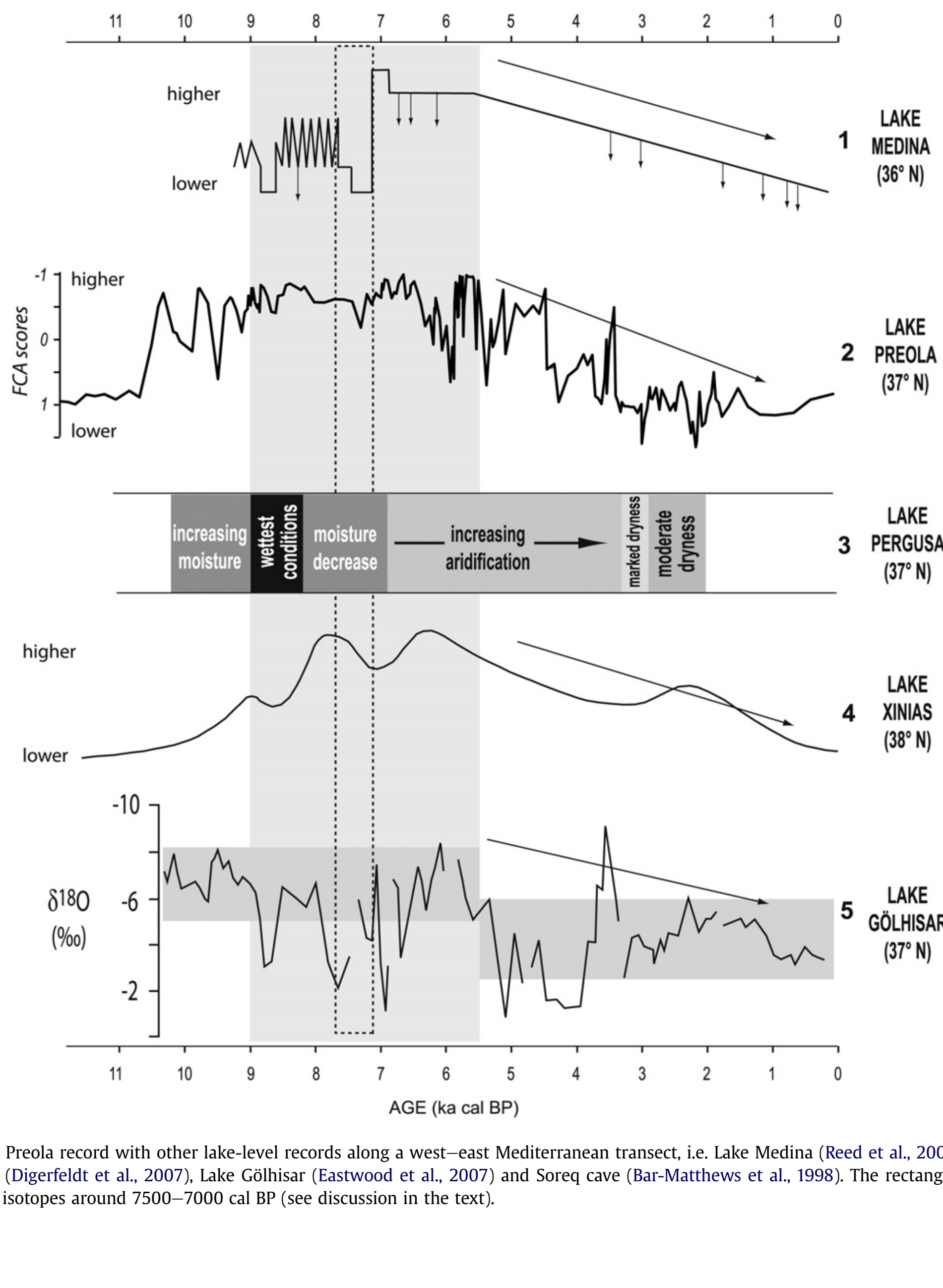

Fig. 10. Comparison of the Preola record with other lake-level records along a west–east Mediterranean transect, i.e. Lake Medina (Reed et al., 2001), Lake Pergusa (Sadori and Narcisi, 2001), Lake Xinias (Digerfeldt et al., 2007), Lake Gölhisar (Eastwood et al., 2007) and Soreq cave (Bar-Matthews et al., 1998). The rectangle with dotted line points to changes in lake-levels and isotopes around 7500–7000 cal BP (see discussion in the text).

west–central Europe, and presented in Fig. 9 give evidence of a strong impact of the climatic oscillation around 4500–4000 cal BP (Marchant and Hooghiemstra, 2004; Booth et al., 2005). In the northwestern Mediterranean area as in west–central Europe, it coincided with a marked increase in humidity well recorded at Lake Cerin in the Jura Mountains (Magny et al., 2011), at Lake Accesa in central Italy (Magny et al., 2007), and at Lake Maliq in Albania (Magny et al., 2009). This is in agreement with an advance of the Calderone glacier in the Gran Sasso massif in central Italy (Giraudi et al., 2011), as well as with an abrupt decline of the treeline in the Austrian Alps (Nicolussi et al., 2005). In more southern areas, the period 4500–4000 cal BP corresponds to a strong aridification well observed by a lake-level fall in the south-western Mediterranean at Lago Preola (this study) and at Lake Pergusa (Sadori et al., 2008, 2011), a decrease in precipitation at Soreq Cave in the eastern Mediterranean (Bar-Matthews et al., 1998) and an increasing salinity at Lake Yoa, northern Tchad (Kröpelin et al., 2008). In south-central Italy, at Lakes Mezzano and Albano, marked environmental changes were also observed around 4000–3800 cal BP in pollen and diatom assemblages (Ramrath et al., 2000; Sadori et al., 2004) as well as in sediment markers (Ramrath et al., 1999; Ariztegui et al., 2001). As discussed by Zhao et al. (2010) and illustrated by Fig. 9, the climatic oscillation around 4500–4000 cal BP may reflect a non-linear response of the climate system to the gradual decrease of insolation, in addition to key seasonal and inter-hemispherical changes in insolation (Fig. 9, panel 1; see also inset in Fig. 9). This orbital forcing was associated with a reorganisation of the general atmospheric circulation with a further southward shift of the ITCZ in the Tropics (Haug et al., 2001), which may have led to a southward shift of the westerlies bringing more humidity to the mid-European latitudes and the northwest Mediterranean. By contrast, an orbitally-driven SST cooling (Marchal et al., 2002) may have contributed to moderately drier conditions over the south-western and eastern Mediterranean, south of latitude 40°N corresponding to today's climatic conditions.

5. Conclusions

Using a specific sedimentological approach, the reconstruction of a high-resolution lake-level record for the Holocene at Lago Preola allows to conclude that:

- The Preola lake-level record gives evidence of three major successive palaeohydrological periods, with (1) the absence of a lake or a pronounced lowstand during the early Holocene until ca 10300 cal BP, (2) a highstand from 10300 to 4500 cal BP, and (3) a lowstand from 4500 cal BP to present. Period 2 was interrupted between 8300 and 7000 cal BP by a dry phase punctuated by the deposition of a tephra layer from Pantelleria Island around 7300 cal BP.
- The comparison of the Preola lake-level record with Sicilian pollen records shows a strong influence of the moisture availability on the vegetation development in Sicily. Very dry to dry early Holocene conditions may explain the delayed expansion of the forests, and low moisture availability during the late Holocene may have exacerbated the effects of intensive land-use (e.g. deforestations, fire increase).
- Comparison of the Preola record with other palaeohydrological records along north–south and west–east transects shows contrasting patterns of hydrological changes: north of latitude ca 40°N, the records give evidence of a mid-Holocene period characterised by a lake-level minima; south of it, the same period corresponded to lake-level maxima. We hypothesise that maximum humidity during the mid-Holocene may have concerned the winter season north of 40°N, and the summer season to the south. In addition, the early Holocene corresponded to very dry conditions south of ca 40°N both in the western and eastern Mediterranean.
- On a multi-centennial scale, the high-resolution palaeohydrological records reconstructed in the central Mediterranean area as well as in west–central Europe highlight a strong climate reversal around 4500–4000 cal BP. This major oscillation may be related to a non-linear response of the climatic system to the gradual decrease in insolation, in addition to seasonal and inter-hemispherical changes in insolation. Another major climate oscillation around 7500–7000 cal BP may have resulted from combined effects of a strong rate of change in insolation and of variations in solar activity.
- Finally, from a methodological point of view, additional well-dated high-resolution records are needed to reconstruct both the timing and the seasonality of the Holocene precipitation changes in the Mediterranean area. The present study also suggests the interest of establishing records based on similar approaches and homogeneous data to facilitate inter-regional comparisons and to get a more comprehensive view of regional palaeohydrological trajectories.

Acknowledgements

Financial support for this study was provided by the French ANR (project LAMA), as well as the Ecole Française de Rome and the Swiss National Science Foundation (grant PPOOP2-114886 to W. Tinner). We are grateful to the people of the Nature Reserve "Lago Preola e Gorghi Tondi" and specially to S. D'Angelo and S. Pasta for their support in the field and fruitful discussions. The authors also express their sincere thanks to J. Olsen for his help with the English language.

References

Allen, J.R.M., Watts, W.A., McGee, E., Huntley, B., 2002. Holocene environmental variability-the record from Lago Grande di Monicchio, Italy. Quaternary International 88, 69–80.

Alley, R.B., Mayewski, P.A., Sowers, T., Stuiver, M., Taylor, K.C., Clark, P.U., 1997. Holocene climatic instability: a prominent, widespread event 8200 yr ago. Geology 25, 483–486.

Ammann, B., Birks, H.J.B., Brooks, S.J., Eicher, U., von Grafenstein, U., Hofmann, W., Lemdahl, G., Schwander, J., Tobolski, K., 2000. Quantification of biotic responses to rapid climatic changes around the Younger Dryas – a synthesis. Palaeogeography, Palaeoclimatology, Palaeoecology 159, 313–347.

Ariztegui, D., Chondrogianni, C., Lami, A., Guilizzoni, P., Lafargue, E., 2001. Lacustrine organic matter and the Holocene paleoenvironmental record of Lake Albano (central Italy). Journal of Paleolimnology 26, 283–292.

Ariztegui, D., Asioli, A., Lowe, J.J., 2000. Palaeoclimate and the formation of sapropel S1: inferences from Late Quaternary lacustrine and marines sequences in the central Mediterranean region. Palaeogeography, Palaeoclimatology, Palaeoecology 158, 215–240.

Bar-Matthews, M., Ayalon, A., 2011. Mid-Holocene climate variations revealed by high-resolution speleotheùm records from Soreq Cave, Israel and their correlations with cultural changes. The Holocene 21, 163–172.

Bar-Matthews, M., Ayalon, A., Kaufman, A., 1998. Middle to Late Holocene (6500 yr period) paleoclimate in the eastern Mediterranean region from stable isotopic composition of speleothems from Soreq Cave, Israël. In: Issar, A., Brown, N. (Eds.), Environment and Society in Times of Climate Change. Kluwer Academic, Dordrecht, pp. 203–214.

Berger, A., 1978. Long-term variations of caloric insolation resulting from the earth's orbital elements. Quaternary Research 9, 139–167.

Berger, A., Loutre, M.F., 1991. Insolation values for the climate of the last 10 miollion of years. Quaternary Science Reviews 10, 297–317.

Bird, M., Austin, W.E.N., Wurster, C.M., Fifield, L.K., Mojtahid, M., Sargeant, C., 2010. Punctuated eustatic sea-level rise in the early mid-Holocene. Geology 38, 803–806.

Birks, H.J.B., 1995. Quantitative palaeoenvironmental reconstructions. In: Maddy, D., Brew, J.S. (Eds.), Statistical Modelling of Quaternary Science Data, Technical Guide, vol. 5. Quaternary Research Association, Cambridge, pp. 161–254.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., Bonani, G., 2001. Persistent solar influence on North Atlantic climate during the Holocene. Science 294, 2130–2136.

Booth, R., Jackson, S.T., Forman, S.L., Kutzbach, J.E., Bettis, E.E., Kreig, J., Wright, D.K., 2005. A severe centennial-scale drought in mid-continental North America 4200 years ago and apparent global linkages. The Holocene 15, 321–328.
Brayshaw, D.J., Rambeau, C.M.C., Smith, S.J., 2011. Changes in Mediterranean climate during the Holocene: insights from global and régional climate modeling. The Holocene 21, 15–32.
Caron, B., Sulpizio, R., Zanchetta, G., Santacroce, R., 2010. The late Holocene to Pleistocene tephrostratigraphic record of Lake Ohrid (Albania). Comptes Rendus Geoscience 342, 453–466.
Carrión, J.S., 2002. Patterns and processes of Late Quaternary environmental change in a montane region of southwestern Europe. Quaternary Science Reviews 21, 2047–2066.
Carrion, J.S., Fernandez, S., Jimenez-Moreno, G., Fauquette, S., Gil-Romera, G., Gonzalez-Samperiz, P., Finlayson, C., 2010. The historical origins of aridity and vegetation degradation in southeastern Spain. Journal of Arid Environments 74, 731–736.
Civetta, L., Corenette, Y., Gillot, P.Y., Orsi, G., 1988. The eruptive history of Pantelleria (Sicily Channel) in the last 50 ka. Bulletin of Volcanology 50, 47–57.
Colombaroli, D., Marchetto, A., Tinner, W., 2007. Long-term interactions between Mediterranean climate, vegetation and fire regime at Lago di Massaciuccoli (Tuscany, Italy). Journal of Ecology 95, 755–770.
Colombaroli, D., Vannière, B., Emmanuel, C., Magny, M., Tinner, W., 2008. Fire-vegetation interactions during the Mesolithic-Neolithic transition at Lago dell'Accesa, Tuscany, Italy. Holocene 18, 679–692.
Davis, B.A.S., Brewer, S., 2009. Orbital forcing and role of the latitudinal insolation/temperature gradient. Climate Dynamics 32, 143–165.
De Beaulieu, J.L., Miras, Y., Andrieu-Ponel, V., Guiter, F., 2005. Vegetation dynamics in north-western Mediterranean regions: instability of the Mediterranean bioclimate. Plant Biosystems 139, 114–126.
Digerfeldt, G., 1988. Reconstruction and regional correlation of Holocene lake-level fluctuations in lake Bysjön, South Sweden. Boreas 17, 165–182.
Digerfeldt, G., Sandgren, P., Olsson, S., 2007. Reconstruction of Holocene lake-level changes at Lake Xinias, central Greece. The Holocene 17, 361–367.
Eastwood, W.J., Leng, M.J., Roberts, N., Davis, B., 2007. Holocene climate change in the eastern Mediterranean region: a comparison of stable isotope and pollen data from Lake Gölhisar, southwest Turkey. Journal of Quaternary Science 22, 327–341.
Finsinger, W., Colombaroli, D., de Beaulieu, J.L., Valsecchi, V., Vannière, B., Vescovi, E., Chapron, E., Lotter, A.F., Magny, M., Tinner, W., 2010. Early to mid-Holocene climate change at Lago dell'Accesa (central Italy): climate signal or anthropogenic bias? Journal of Quaternary Science 25, 1239–1247.
Frisia, S., Borsato, A., Mangini, A., Spötl, C., Madonia, G., Sauro, U., 2006. Holocene climate variability in Sicily from a discontinuous stalagmite record and the Mesolithic to Neolithic transition. Quaternary Research 66, 388–400.
Gaetani, M., Baldi, M., Dalu, G.A., Maracchi, G., 2006. Connessioni tra il clima della regione Mediterranea e l'Africa occidentale attraverso la circolazione meridiana di Hadley. In: Carli, B., Cavarretta, G., Colacino, M., Fuzzi, S. (Eds.), Clima e cambiamenti climatici. Consiglio Nazionale delle Ricerche, Roma, pp. 23–26.
Giraudi, C., Magny, M., Zanchetta, G., Drysdale, R.N., 2011. The Holocene climatic evolution of the Medtirreanean Italy: a review of the geological continental data. The Holocene 21, 105–115.
Haas, J.N., Richoz, I., Tinner, W., Wick, L., 1998. Synchronous Holocene climatic oscillations recorded on the Swiss Plateau and at timberline in the Alps. The Holocene 8, 301–309.
Harrison, S.P., Digerfeldt, G., 1993. European lakes as palaeohydrological and palaeoclimatic indicators. Quaternary Science Reviews 12, 233–248.
Haug, G.H., Hughen, K.A., Sigman, D.M., Peterson, L.C., Röhl, U., 2001. Southward migration of the Intertropical Convergence zone through the Holocene. Science 293, 1304–1308.
Heegaard, E., Birks, H.J.B., Telford, R.J., 2005. Relationships between calibrated ages and depth in stratigraphical sequences: an estimation procedure by mixed-effect regression. The Holocene 15, 612–618.
Heiri, O., Tinner, W., Lotter, A.F., 2004. Evidence for cooler European summers during periods of changing meltwater flux to the North Atlantic. Proceedings of the National Academy of Sciences of the United States of America 101, 15285–15288.
Jalut, G., Deboubat, J.J., Fontugne, M., Otto, T., 2009. Holocene circum-Mediterranean vegetation changes: climate forcing and human impact. Quaternary International 200, 4–18.
Kotthoff, U., Pross, J., Müller, U.C., Peyron, O., Schmiedl, G., Schulz, H., Bordon, A., 2008. Climate dynamics in the borderlands of the Aegean Sea during formation of sapropel 1 deduced from amarine pollen record. Quaternary Science Reviews 27, 832–845.
Kröpelin, S., Verschuren, D., Lézine, A.M., Eggermont, H., Cocquyt, C., Francus, P., Cazet, J.P., Fagot, M., Rumes, B., Russell, J.M., Darius, F., Conley, D.J., Schuster, M., von Suchodoletz, H., Engstrom, D.R., 2008. Climate-driven ecosystem succession in the Sahara: the past 6000 years. Science 320, 765–768.
Kuzucuoglu, C., Dörfler, W., Kunesh, S., Goupille, F., 2011. Mid- to late-Holocene climate change in central Turkey: the Tecer Lake record. The Holocene 21, 173–188.
Lang, G., 1994. Quartäre Vegetationsgeschichte Europas. Methoden und Eregebnisse. G. Fischer, Jena, p. 462.
Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., Zanettin, B., 1986. A chemical classification of volcanic rocks based on the total alkali–silica diagram. Journal of Petrology 27, 745–750.
Leroux, A., Bichet, V., Walter-Simonnet, A.V., Magny, M., Adatte, T., Gauthier, E., Richard, H., Baltzer, A., 2008. Late-Glacial Holocene sequence of Lake Saint-Point (Jura Mountains, France): detrital inputs as records of climate change and anthropic impact. Compte-Rendus Geosciences 340, 883–892.
Magny, M., 1992. Holocene lake-level fluctuations in Jura and the northern subalpine ranges, France: regional pattern and climatic implications. Boreas 21, 319–334.
Magny, M., 1998. Reconstruction of Holocene lake-level changes in the Jura (France): methods and results. Paläoklimaforschung 25, 67–85.
Magny, M., 2004. Holocene climatic variability as reflected by mid-European lake-level fluctuations, and its probable impact on prehistoric human settlements. Quaternary International 113, 65–79.
Magny, M., 2006. Holocene Fluctuations of Lake Levels in West–central Europe: Methods of Reconstruction, Regional Pattern, Palaeoclimatic Significance and Forcing Factors. Encyclopedia of Quaternary Geology. Elsevier, pp. 1389–1399.
Magny, M., de Beaulieu, J.L., Drescher-Schneider, R., Vannière, B., Walter-Simonnet, A.V., Miras, Y., Millet, L., Bossuet, G., Peyron, O., Brugiapaglia, E., Leroux, A., 2007. Holocene climate changes in the central Mediterranean as recorded by lake-level fluctuations at Lake Accesa (Tuscany, Italy). Quaternary Science Reviews 26, 1736–1758.
Magny, M., Bégeot, C., Guiot, J., Peyron, O., 2003. Contrasting patterns of hydrological changes in Europe in response to Holocene climate cooling phases. Quaternary Science Reviews 22, 1589–1596.
Magny, M., Bossuet, G., Ruffaldi, P., Leroux, A., Mouthon, J., 2011. Orbital imprint on Holocene palaeohydrological variations in west-central Europe as reflected by lake-level changes at Cerin (Jura Mountains, eastern France). Journal of Quaternary Science 26 (2), 171–177.
Magny, M., Vannière, B., Zanchetta, G., Fouache, E., Touchais, G., Petrika, L., Coussot, C., Walter-Simonnet, A.V., Arnaud, F., 2009. Possible complexity of the climatic event around 4300–3800 cal BP in the central and western Mediterranean. The Holocene 19, 823–833.
Mahood, G.A., Hildreth, W., 1986. Geology of the peralkaline volcano at Pantelleria, Strait of Sicily. Bulletin Volcanology 48, 143–172.
Marchal, O., Cacho, I., Stocker, T., Grimalt, J., Calvo, E., Martrat, B., Shackleton, N., Vautravers, M., Cortijo, E., van Kreveld, S., Andersson, C., Koç, N., Chapman, M., Sbaffi, L., Duplessy, J.C., Sarnthein, M., Turon, J.L., 2002. Apparent long-term cooling of the sea surface in the northeast Atlantic and Mediterranean during the Holocene. Quaternary Science Reviews 21, 455–483.
Marchant, R., Hooghiemstra, H., 2004. Rapid environmental change in African and South American tropics around 4000 years before present: a review. Earth Science Reviews 66, 217–260.
Mercuri, A.M., Sadori, L., Ollero, P.U., 2011. Mediterranean and north-African cultural adaptations to mid-Holocene environmental and climatic changes. The Holocene 21, 189–206.
Nicolussi, K., Kaufmann, M., Patzelt, G., van der Plicht, J., Thurner, A., 2005. Holocene tree-line varioability in the Kauner Valley, Central Eastern Alps, indicated by dendrochronological analysis of living trees and subfossil logs. Vegetation History and Archaeobotany 14, 221–234.
Noti, R., Leeuwen, J.F.N., Colombaroli, D., Vescovi, E., Pasta, S., La Mantia, T., Tinner, W., 2009. Mid- and Late-Holocene vegetation and fire history of Biviere di Gela, a coastal lake in southern Sicily. Vegetation History and Archaeobotany 18, 371–387.
Peyron, O., Goring, S., Dormoy, I., Kotthoff, U., Pross, J., de Bealieu, J.L., Drescher-Schneider, R., Magny, M., 2011. Holocene seasonality changes in the central Mediterranean region reconstructed from the pôllen sequences of Lake Accesa (Italy) and Tenaghi Philippon (Greece). The Holocene 21, 131–146.
Ramrath, A., Nowaczyk, N., Negendank, J., 1999. Sedimentological evidence for environmental changes since 34,000 years BP from Lago di Mezzano, central Italy. Journal of Paleolimnology 21, 423–435.
Ramrath, A., Sadori, L., Negendank, J., 2000. Sediment from Lago di Mezzano, central Italy: a record of Lateglacial/Holocene climatic variations and anthropogenic impact. The Holocene 10, 87–95.
Rasmussen, T.L., Thomsen, E., 2010. Holocene temperature and salinity variability of the Atlantic Water inflow to the Nordic seas. The Holocene 8, 1223–1234.
Reed, J.M., Stevenson, A.C., Juggins, S., 2001. A multi-proxy record of Holocene climatic change in southwestern Spain: the Laguna di Medina, Cadiz. The Holocene 11, 707–719.
Reimer, P.J., Baillie, M.G.L., Bard, E., 2004. IntCal04 terrestrial radiocarbon age calibration, 26-0 ka BP. Radiocarbon 46, 1029–1058.
Roberts, N., Brayshaw, D., Kuzucuoglu, C., Perez, R., Sadori, L., 2011a. The mid-Holocene climatic transition in the Mediterranean: causes and conséquences. The Holocene 21, 3–14.
Roberts, N., Eastwood, W.J., Kuzucuoglu, C., Fiorentino, G., Caracuta, V., 2011b. Clmatic, végétation and cultural changes in the eastern Mediterranean during the mid-Holocene environmental transition. The Holocene 21, 147–162.
Roberts, N., Jones, M.D., Benkaddour, A., Eastwood, W.J., Filippi, M.L., Frogley, M.R., Lamb, H.F., Leng, M.J., Reed, J.M., Stein, M., Stevens, L., Valero-Garces, B., Zanchetta, G., 2008. Stable isotope records of Late Quaternary climate and hydrology from Mediterranean lakes: the ISOMED synthesis. Quaternary Science Reviews 27, 2426–2441.
Sadori, L., Narcisi, B., 2001. The postglacial record of environmental history from Lago di Pergusa, Sicily. The Holocene 11, 655–671.
Sadori, L., Giraudi, C., Petitti, P., Ramrath, A., 2004. Human impact at Lago di Mezzano (central Italy) during the Bronze Age: a multidisciplinary approach. Quaternary International 113, 5–17.
Sadori, L., Jahns, S., Peyron, O., 2011. Mid-Holocene vegetation history in the central Mediterranean. The Holocene 21, 117–129.

Sadori, L., Zanchetta, G., Giardini, M., 2008. Last Glacial to Holocene palaeoenvironmental evolution at Lago di Pergussa (Sicily, Southern Italy) as inferred by pollen, microcharcoal, and stable isotopes. Quaternary International 181, 4–14.

Shuman, B., Plank, C., 2011. Orbital, ice sheet, and possible solar controls in Holocene moisture trends in the North Atlantic drainage basin. Geology 39, 151–154.

Siani, G., Paterne, M., Colin, C., 2010. Late Glacial to Holocene planktic foraminifera bioevents and climatic record in the South Adriatic Sea. Journal of Quaternary Science 25 (5), 808–821.

Speranza, F., Landi, P., Caracciolo, F.D.A., Pignatelli, A., 2009. Paleomagnetic dating of the most recent silicic eruptive activity at Pantelleria (Strait of Sicily). Bulletin of Volcanology doi:10.1007/s00445-010-0368-5.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, G., van der Plicht, J., Spurk, M., 1998. Intcal98 radiocarbon age calibration, 24,000-0 cal BP. Radiocarbon 40, 1041–1083.

Sulpizio, R., van Welden, A., Caron, B., Zanchetta, G., 2010. The Holocene tephrostratigraphic record of Lake Shkodra (Albania and Montenegro). Journal of Quaternary Science 25, 633–650.

Ter Braak, C.J.F., Prentice, I.C., 1988. A theory of gradient analysis. Advances Ecological Research 18, 271–317.

Tinner, W., van Leeuwen, J.F.N., Colombaroli, D., Vescovi, E., van der Knaap, W.O., Henne, P.H., Pasta, S., D'Angelo, S., La Mantia, T., 2009. Holocene environmental and climatic changes at Gorgo Basso, a coastal lake in southern Sicily, Italy. Quaternary Science Reviews 28, 1498–1510.

Tzedakis, P.C., 2007. Seven ambiguities in the Mediterranean palaeoenvironmental narrative. Quaternary Science Reviews 26, 2042–2066.

Tzedakis, P.C., Palike, H., Roucoux, K.H., de Abreu, L., 2009. Atmospheric methane, southern European vegetation and low-mid latitude links on orbital and millennial timescales. Earth and Planetary Science Letters 277, 307–317.

Vannière, B., Power, M.J., Roberts, N., Tinner, W., Carrion, J., Magny, M., Bartlein, P., Contributors, Data, 2011. Circum-Mediterranean fire activity and climate changes during the mid Holocene environmental transition (8500–2500 cal yr BP). The Holocene 21, 53–73.

Vogel, H., Zanchetta, G., Sulpizio, R., Wagner, B., Nowaczyk, N., 2010. A tephrostratigraphic record for the last glacial-interglacial cycle from Lake Ohird, Albania and Macedonia. Journal of Quaternary Science 25, 320–338.

Wick, L., Tinner, W., 1997. Vegetation changes and timberline fluctuations in the Central Alps as indicator of Holocene climatic oscillations. Arctic and Alpine Research 29, 445–458.

World Climate, 2008. http://www.worldclimate.com/.

Zanchetta, G., Drysdale, R.N., Hellstrom, J.C., Fallick, A.E., Isola, I., Gagan, M.K., Pareschi, M.T., 2007. Enhanced rainfall in the western Mediterranean during deposition of sapropel 1: stalagmite evidence from Corchia cave (Central Italy). Quaternary Science Reviews 26, 279–286.

Zhao, C., Yu, Z., Zhao, Y., 2010. Holocene climate trend, variability, and shift documented by lacustrine stable-isotope record in the northeastern United States. Quaternary Science Reviews 29, 1831–1843.