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ABSTRACT

A lake-level record of Lake Ledro (northern Italy) spans the entire Holocene with a chronology derived from 51 radiocarbon dates. It is based on a specific sedimentological approach that combines data from five sediment profiles sampled in distinct locations in the littoral zone. On a millennial scale, the lake-level record shows two successive periods from 11,700 to 4500 cal yr BP and from 4500 cal yr BP to the present, characterized by lower and higher average lake levels, respectively. In addition to key seasonal and inter-hemispherical changes in insolation, the major hydrological change around 4500 cal yr BP may be related to a non-linear response of the climate system to orbitally-driven gradual decrease in insolation. The Ledro record questions the notion of an accentuated summer rain regime in the northern Mediterranean borderlands during the boreal insolation maximum. Moreover, the Ledro record highlights that the Holocene was punctuated by successive centennial-scale highstands. Correlations with the Preboreal oscillation and the 8.2 ka event, and comparison with the atmospheric ^{14}C residual record, suggest that short-lived lake-level fluctuations developed at Ledro in response to (1) final steps of the deglaciation in the North Atlantic area and (2) variations in solar activity.

Introduction

The reconstruction of past moisture conditions and availability is of crucial interest for the understanding of Holocene environmental changes and the trajectories of societies in the Mediterranean area. Lake-level records provide independent palaeohydrological data to specify those inferred from pollen studies. However, highly resolved studies aimed specifically at lake-level reconstruction are still scarce in the Mediterranean area (Harrison and Digerfeldt, 1993; Zolitschka et al., 2000; Reed et al., 2001; Giraudi et al., 2011). In addition, correlations and comparisons between records on an inter-regional scale require lake-level data based on a robust chronology and, preferably, obtained from similar proxies.

Recently, in a thorough review of outstanding issues on Mediterranean palaeoenvironmental conditions, P.C. Tzedakis (2007) has pointed out the increasingly complex paleohydrological/climatic scenarios outlined to reconcile conflicting data and/or interpretations, and he has questioned the notion of an accentuated summer rain regime in the northern Mediterranean borderlands during the boreal insolation maximum. At the same time, lake-level studies at Lake Accesa in north-central Italy have given evidence of a well-marked lake-level lowstand during the mid-Holocene (Magny et al., 2007). The Accesa lake-level record clearly contrasts with the maximal highstands of lake levels reconstructed at a more southerly latitude in the central Mediterranean (Sadori and Narcisi, 2001) and in the eastern Mediterranean (Digerfeldt et al., 2007; Eastwood et al., 2007). Such observations in the central Mediterranean seem to be in agreement with a tri-partition of western Europe as inferred from a comparison of palaeohydrological records with drier conditions over the mid-European latitudes between ca. 50° and 43°N, and wetter conditions over the northern and southern Europe (Magny et al., 2003, 2011).

As a further contribution to the reconstruction of Holocene hydro-climatic conditions in the central Mediterranean, this paper presents a high-resolution lake-level record established at Lake Ledro in northeastern Italy at the northern edge of the Mediterranean area. An earlier paper (Magny et al., 2009a) focused on the reconstruction of lake-level changes at Lake Ledro during the late Holocene (last 4000 yr), and on problems relative to the development of settlements in

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humid areas of northern Italy during the Bronze Age. This study (1) presents the results of supplementary cores and sediment profiles, and (2) combines these new data with earlier ones to establish a lake-level record for the entire Holocene at Lake Ledro.

Site and methods

Lake Ledro (45°87′N, 10°76′E, 652 m a.s.l.) is a relatively small lake (2.8 km long, 0.8 km wide, 38 m maximum depth) located on the southern slope of the Alps (Fig. 1). The lake surface is ca. 2.17 km^2. The outlet of Lake Ledro is the Ponale River, which is responsible for downcutting in a morainic dam (Beug, 1964). In 1929, the outlet was transformed for hydroelectricity and artificial regulation of the water table. Consequently, large parts of the original natural outlet area were disturbed and today the outlet itself is most often dry. The lake is surrounded by mountains culminating at ca. 1500–2200 m a.s.l. The catchment area covers ca. 131 km^2 and is characterized by relatively steep slopes, and by a carbonate substratum with Triassic (dolomite), Jurassic and Cretaceous limestone.

Lake Ledro is very close to the northern extremity of Lake Garda (65 m a.s.l.). Due to the influence of a large body of water, the region of Lake Garda (65 m a.s.l.) is famous for particularly mild climatic conditions which allow the presence of Mediterranean species (Fig. 1; Beug, 1964). However, due to higher altitude, the vegetation in the Ledro Valley is dominated by *Fagus sylvatica* (beech) mixed with *Abies alba* (silver fir), then *Picea abies* (spruce) in the higher part of the montane belt (650–1600 m), and by *Pinus mugo* (mountain pine), *Alnus viridis* (green alder), *Larix decidua* (larch) and *Picea* in the subalpine belt (1600–2000 m). Above 2000 m a.s.l. grasslands dominate (Beug, 1964; Reisigl, 2001). Generally speaking, mixed oak forests do not develop in the Ledro Valley. At Molina di Ledro, the mean temperature is ca. 0°C in the coldest month (January) and ca. 20°C in the warmest month (July). The annual precipitation ranges from ca. 750 to ca. 1000 mm, with seasonal maxima in spring and autumn.

In addition to previous lake-level data (Magny et al., 2009a) obtained from the stratigraphic section of site Ledro I and from core Ledro II-1 (Fig. 1), the present study examines three new sediment profiles recently sampled on the south-eastern shores of Lake Ledro (Fig. 1) and of particular interest for the reconstruction of Holocene lake-level fluctuations:

- Site Ledro II is located on the northeastern shore of the lake (Fig. 1, panel B). Core Ledro II-3 was taken with a Russian peat corer. It provides a ca. 8-m-long sediment sequence mainly composed of carbonate lake-marl. It continuously documents the early to mid-Holocene, and it completes the late Holocene data obtained from core Ledro II-1 (Magny et al., 2009a ; Fig. 1, panel C).
- Site San Carlo. Rescue archaeological excavations provoked by works for the reinforcement of building foundations close to Hotel San Carlo, offered the opportunity to sample a 1.6-m-high stratigraphic section above the present-day lowered water-level. Overlying morainic deposits and a pebble beach formation, the sediment sequence observed along a ca. 11-m section highlights an alternation of different layers composed of carbonate lake-marl, oncolites, and peaty sediments. It also includes an organic Bronze Age archaeological layer.
- Site Ponale. In 2008, we initiated the digging of a ca. 5-m-long trench across the past outlet of Lake Ledro, i.e. a key site for the reconstruction of Holocene lake-level changes. A 2.7-m-high stratigraphic section was recognised and sampled. It showed an alternation of carbonate lake marl, gyttja, and peat layers overlying late-glacial gravels and pebbles.

The absolute elevation (in metres a.s.l.) of the sediment profiles studied at Ledro was established in the field by reference to that of the daily water table furnished by the private company Hydro Dolomiti Enel.

Sedimentological analyses for lake-level reconstruction have been carried out on the three sediment profiles of San Carlo, Ponale, and core Ledro II-3, and palynological analyses only on the profile of Ponale. An additional high-resolution pollen record has been established from core LLO81 (Fig. 1) taken in the profundal zone of Lake Ledro where sediment accumulation is not affected by littoral erosion and sediment hiatuses. Pollen preparation followed standard methods using treatment with HCL, 10% KOH, HF, acetolysis and final mounting in glycerine. More than 450 terrestrial pollen grains were counted for each sample. Cyperaceae, palustrine taxa, aquatics and spores are systematically excluded from the pollen sum. All pollen types are defined according to Faegri and Iversen (1989), although some identification require the use of a pollen atlas (Reille, 1992–1998). A detailed reconstruction of the vegetation history is beyond the scope of the present study and will be developed in a further more specific paper.

The changes in lake level were reconstructed using a specific technique described in detail and validated elsewhere (Magny, 1992, 1998, 2004, 2006). It is based on a sedimentological approach that combines several markers as follows:

— The grain-size analysis : coarser deposits correspond to nearshore areas (shallower water and higher hydrodynamics). The grain-size analysis has been carried out by sieving. The percentages indicated on the diagrams of Figures 2, 3, and 4 refer to weight percentage.

— The lithology: silty carbonate lake-marl is deposited in lake water, whereas organic deposits (coarse gyttja, peat, anmoor) reflect nearshore areas (eulittoral zone, littoral mire).

— The macroscopic components of lake marl: it has been shown (Magny 1992, 1998, 2004, 2006) that, in carbonate lakes, the coarser fractions (larger than 0.2 mm) of lake marl are mainly composed of (1) carbonate concretions of biochemical origin, (2) mollusc tests, and (3) plant macro-remains. The concretions can be divided into several morphotypes. Modern analogue studies demonstrated that, in the fraction >0.5 mm, each morphotype shows a specific spatial distribution from the shore to the extremity of the littoral platform, with the successive domination of oncolites (nearshore areas with shallow water and a high-energy environment), cauliflower-like forms (littoral platform), plate-like concretions (encrustations of leaves from the Potamogetonion and Nymphaeion belts), and finally tube-like concretions (stem encrustations from the Characeae belt on the platform slope). In addition to variations in the assemblages of carbonate concretions, modern analogues studies also demonstrated that the relative frequency of plant macroremains and mollusc shells provide further information about the deposition environment. The abundance of mollusc shells increases towards the shore (Mouthon, 1984) as do vegetal remains partly inherited from littoral vegetation and mires (particularly lignosous vegetal remains and anmoor particles). After wet sieving, the macroscopic components of fraction >0.5 mm were identified and counted using a binocular microscope.

— Erosion surfaces (sediment hiatuses) marked by (1) pebble-beach accumulation (reduction horizon), (2) unconformities between sediment layers (Mitchum et al., 1977), and (3) abrupt changes in the sedimentological diagram point to a lowering of the limit of the sediment deposition associated with a lowering of the lake level. As extensively explained by Digerfeldt (1986, 1988), a raised limit of sediment accumulation gives evidence of a rise in lake level.

The chronology is based on 51 AMS radiocarbon dates (12 from site San Carlo, 13 from site Ponale, 12 from core Ledro II-3, 8 from site Ledro I, and 6 from core Ledro II-1; Table 1) from terrestrial plant macro-remains or from littoral peat deposits. Possible disturbances due to reworking material cannot be excluded in littoral areas marked by high hydrodynamics. However, the radiocarbon data set established for lake-level studies at Ledro offers a solid support to correlations between the analysed sediment profiles. The ages have been calibrated referring to Stuiver et al. (1998) and Reimer et al. (2004).

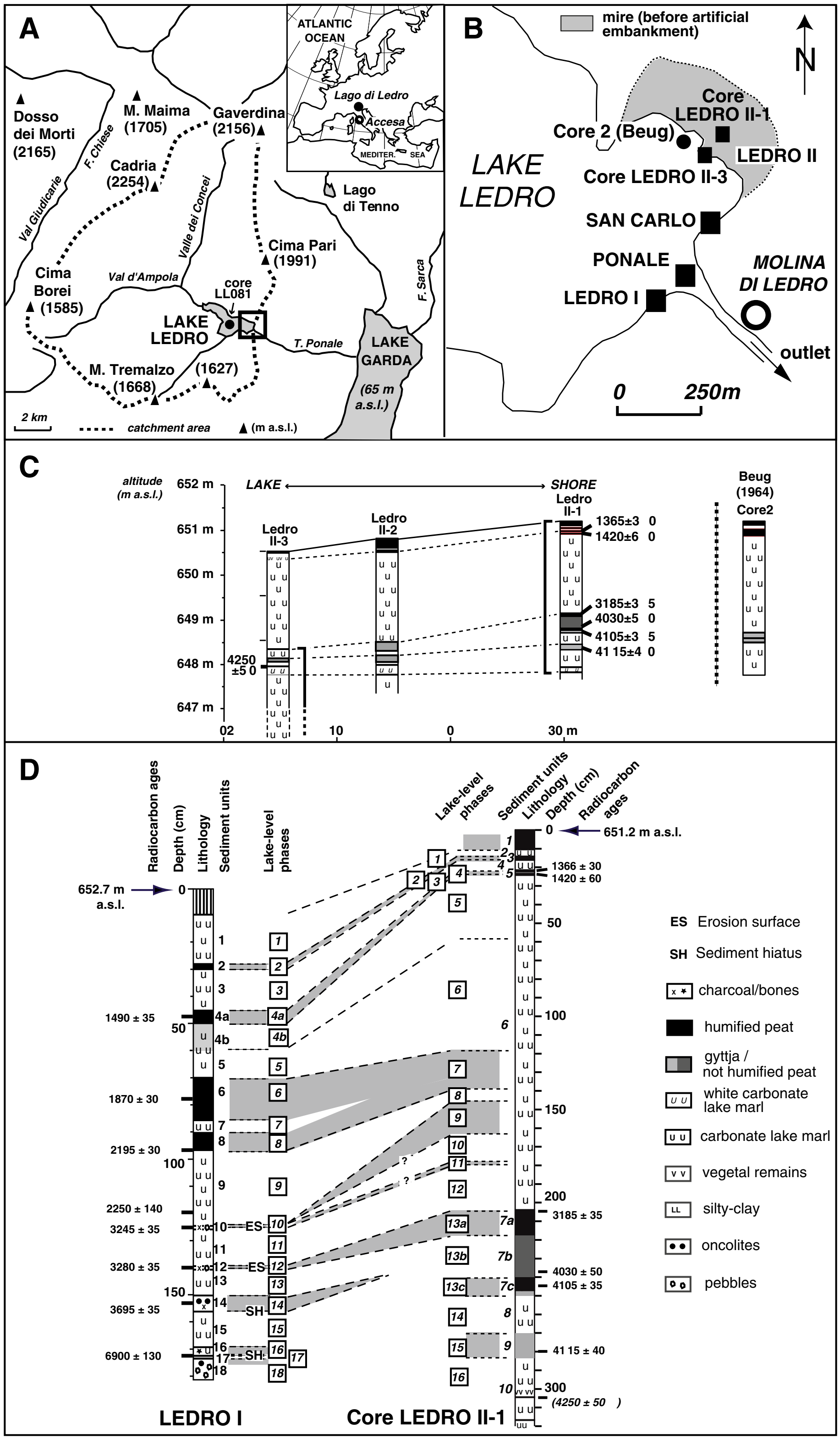

Figure 1. Panel A. Location and catchment area of Lake Ledro in northern Italy. Panel B. Location of sites studied on the southeastern shore of Lake Ledro for Holocene lake-level reconstruction. Note that the outline of the lake shore is that before the artificial regulation of the water table in 1929. Panel C. Lithostratigraphic correlations between cores examined at site Ledro II. Note (1) the revised altitude of cores Ledro II-1 and Ledro II-3 (by comparison with that published by Magny et al., 2009a), and (2) lateral variations of lithofacies illustrated by sediment profiles of cores Ledro II-1, Ledro II-3, and that of core 2 studied by Beug (1964). Two vertical brackets indicate the parts studied in cores Ledro II-1 and Ledro II-3, i.e. the late Holocene in core Ledro II-1 (above level 648 m a.s.l.) and the early to mid Holocene in core Ledro II-3 (below level 648.4 m a.s.l.). Panel D. Sediment profiles of site Ledro I and core Ledro II-1 with radiocarbon dates and reconstructed lake-level phases (Magny et al., 2009a). ES: erosion surface; SH: sediment hiatus. Note that all dates are reported as ^{14}C yr BP.

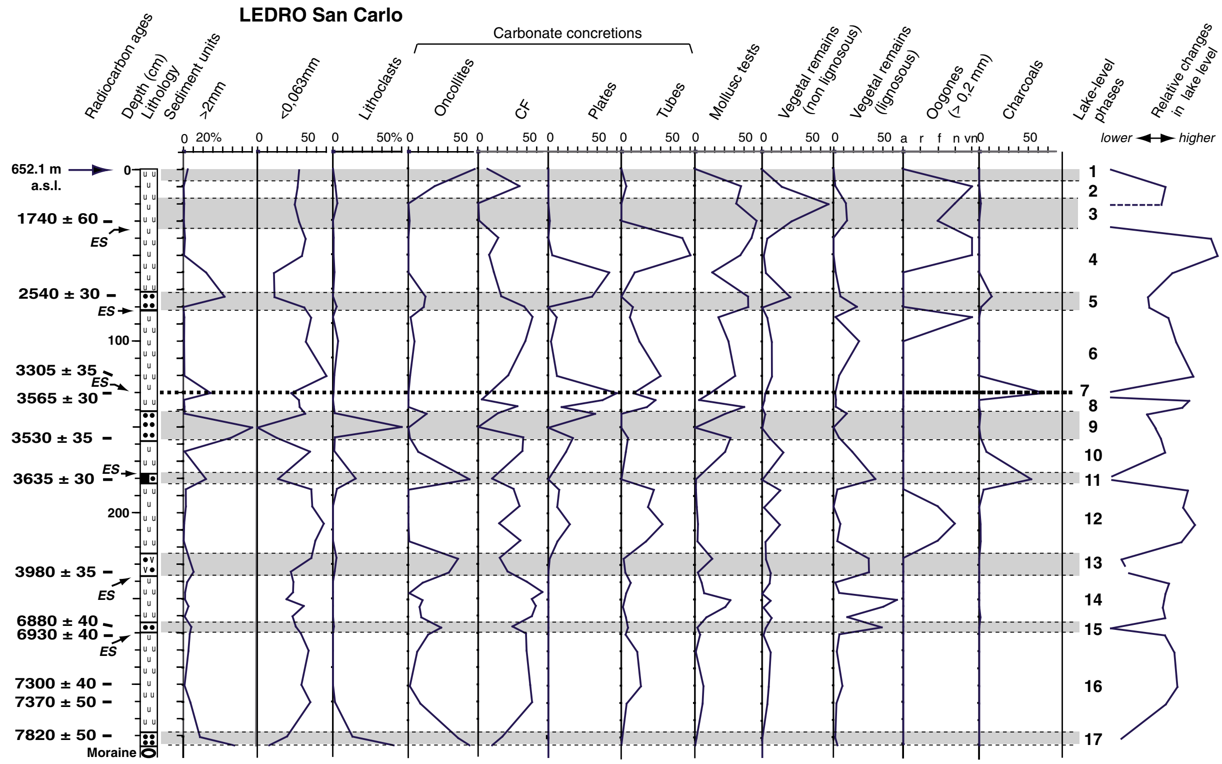

Figure 2. Sedimentological diagram established from site San Carlo. ES: erosion surface; SH: sediment hiatus. CF: cauliflower-like concretions. Grey bands marks low lake-level phases. The representation of the macroscopic components is indicated in percentages of the total number of elements counted in the fraction >0.5 mm. Note that all dates are reported as ^{14}C yr BP.

Results

In the following sections are presented lake-level data obtained from the sediment profiles of sites San Carlo, Ponale, and core Ledro II-3. The sediment diagrams in Figures 2, 3, and 4 show the representation of macroscopic components in fraction >0.5 mm; it is expressed in percentages by reference to the total number of elements counted per sample. On the right hand side of the sediment diagrams (Fig. 2, 3, and 4), a curve of relative changes in lake level indicates the ratio between the total scores (i.e., addition of percentages) of possible indicators marking low lake-level conditions (e.g., oncolites, cauliflower-type concretions, vegetal macro-remains), and those marking high lake-level conditions (e.g., plate and tube concretions; Magny, 1992, 1998, 2006). In a first approximation, the curves of relative changes in lake level provide qualitative data to distinguish successive phases of high and low water table registered by each sediment core. In a second phase (see below, section 'A synthetic lake-level curve'), a comparison of the lake-level data provided by these three sites and those obtained from site Ledro I and core Ledro II-1 (see Fig. 1, panel D) allows reconstruction of a quantitative synthetic lake-level curve at Ledro for the Holocene with absolute elevation of past lake levels.

Site San Carlo

Figure 2 shows the sediment diagram established from the stratigraphic section of site San Carlo. The chronology is based on 12 radiocarbon dates (Table 1, Fig. 2). This sediment sequence appears to have been affected by several sediment hiatuses and erosion surfaces because of (1) its relatively high elevation, which makes the site more sensitive to past lake-level lowstands (lowering of the sedimentation limit; Digerfeldt, 1988). The diagram gives evidence of 17 distinct successive phases of high and low water table, as follows (Fig. 2).

On top of the basal morainic deposits, a pebble beach layer with oncolites is observed and marks lake-shore sedimentation. This phase (17) developed around 7820 ± 50 ^{14}C yr BP (8764–8455 cal yr BP). A rise in lake level (phase 16) provoked the sedimentation of a first carbonate lake-marl layer, which overlies the morainic deposits. Afterwards, the sediment sequence San Carlo reveals 8 successive phases of low lake level marked by peaks of oncolites, lithoclasts (terrestrial inputs), and coarser texture (phases 15, 13, 11, 9, 7, 5, 3 and 1). Phase 11 also corresponds to the formation of an organic archaeological layer dated to the Early Bronze Age. Unconformities between sediment layers highlight the development of erosion surfaces during phases 15, 11, 7, 5, and 3, while the stratigraphic section gives evidence of important sediment hiatuses with an absence of Holocene sediments before 7820 ± 50 ^{14}C yr BP (8764–8455 cal yr BP) and an accumulation of less than 30-cm-thick sediment layer between 6880 ± 40 ^{14}C yr BP (7818–7621 cal yr BP) and 3980 ± 35 ^{14}C yr BP (4529–4300 cal yr BP). Intermediate phases 14, 12, 10, 8, 6, 4, and 2 correspond to higher lake-levels marked by the accumulation of carbonate lake-marl with a finer texture, the development of plate and tube concretions, and a decline of oncolites. The curve of charcoals shows two large peaks during phases 11 and 7, and a smaller one during phase 5, which confirm or suggest possible increases in wildfires and/or the proximity of human settlements, as marked by the archaeological layer of phase 11 dated to 3635 ± 30 ^{14}C yr BP (4081–3861 cal yr BP; Early and Middle Bronze Age). The upper part of the stratigraphic section was disturbed by anthropogenic embankment.

Site Ponale

Both pollen and sediment analyses (Fig. 3) have been carried out from the stratigraphic section Ponale, discovered by excavations in the past outlet of Lake Ledro (Ponale River). The Ponale sediment profile is located between 648.3 and 651 m a.s.l., i.e. at an elevation generally lower than that of the San Carlo sediment sequence (Fig. 2). The chronology is based on 13 radiocarbon dates (Table 1). The basal layer (sediment unit 25) is composed mainly of pebbles and oncolites. The radiocarbon date provided by vegetal macro-remains from level 648.28 m a.s.l. (11,050 ± 60 ^{14}C yr BP, 13,104–12,732 cal yr BP) as well as the high percentage of Non-Arboreal Pollen (NAP) and *Artemisia*

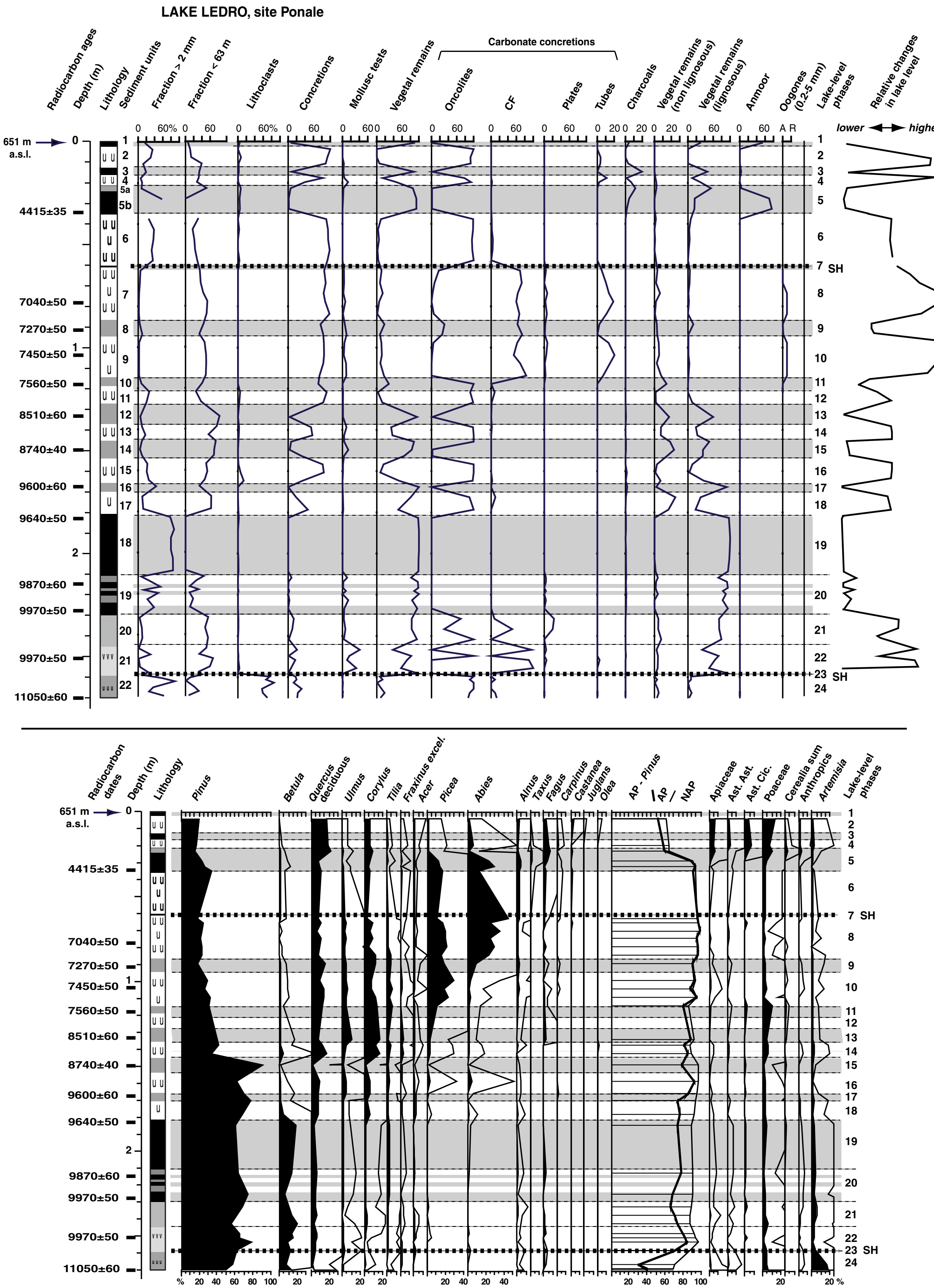

Figure 3. Upper panel. Sedimentological diagram established from site Ponale. SH: sediment hiatus. The representation of the macroscopic components is indicated in percentages of the total number of elements counted in the fraction > 0.5 mm. Lower panel. Simplified pollen diagram established from site Ponale. Note that all dates are reported as ^{14}C yr BP.

suggest Younger Dryas deposits (Beug, 1964). Abrupt jumps in the representation of lithoclasts, oncolites, CF concretions and vegetal remains at the transition between sediment units 22 and 21 point to a sediment hiatus (lake-level lowering, phase 23). It coincides with a rapid decrease in the curve of *Artemisia* (Younger Dryas/Holocene transition). Afterwards, the sediment units 21 to 17 show an alternation of carbonate

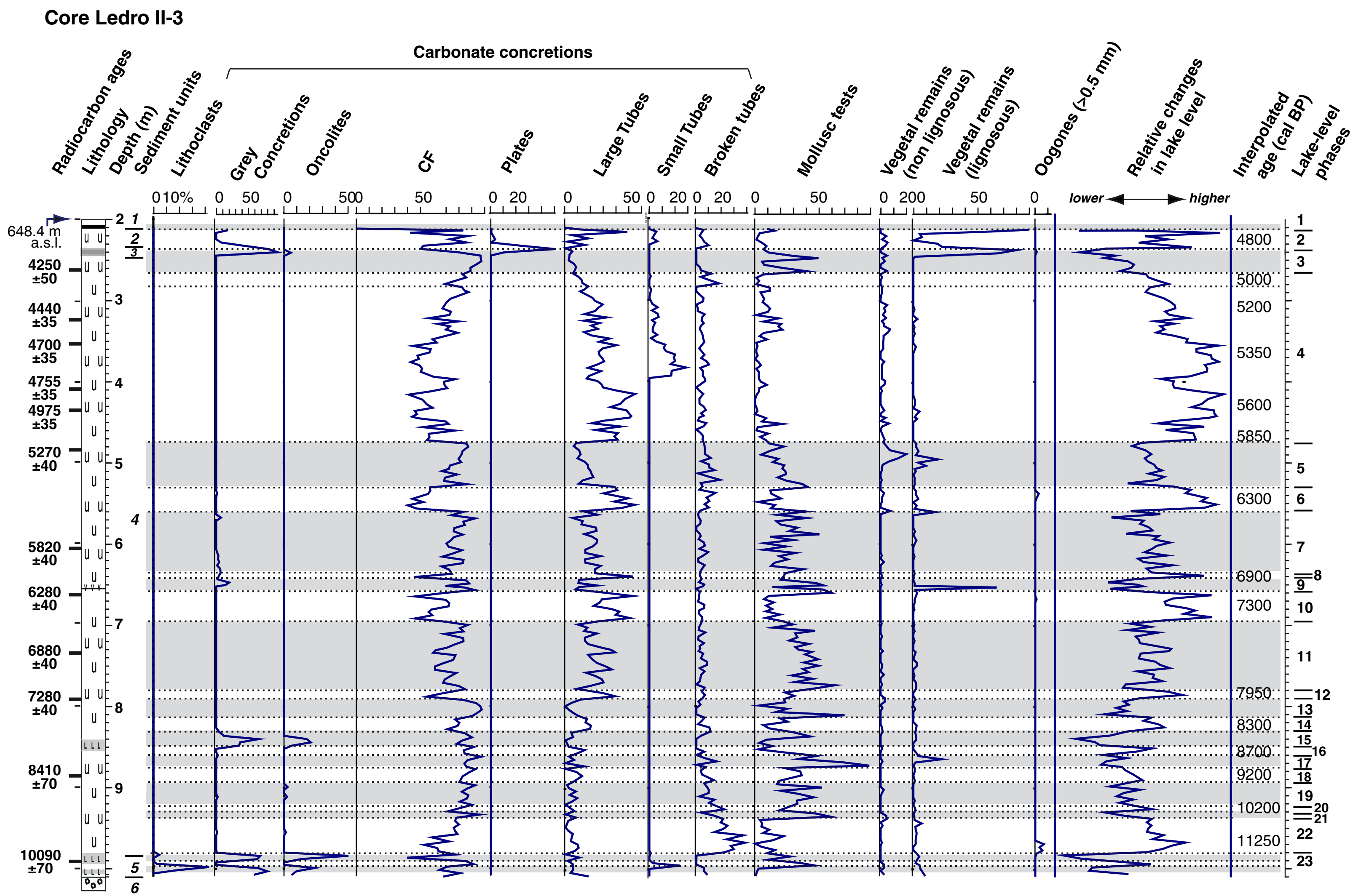

Figure 4. Sedimentological diagram established from core L3 of site Ledro II. The representation of the macroscopic components is indicated in percentages of the total number of elements counted in the fraction > 0.5 mm. Note that all dates are reported as ^{14}C yr BP.

Table 1
Radiocarbon dates obtained from the Ledro sediment profiles. Age calibration was done using the data sets by Stuiver et al. (1998) and Reimer et al. (2004).

Site and core	Depth in core (cm)	Radiocarbon date (^{14}C yr BP)	Calibrated age (2 sigmas)	Laboratory reference	Material	Number in Table 2
Ledro I	47–48	1490 ± 35	1509–1304 cal yr BP	Poz-11068	Charcoal + bark	1
	77–88	1870 ± 30	1877–1724 cal yr BP	Poz-11069	Wood fragments	2
	97–98	2195 ± 30	2317–2131 cal yr BP	Poz-11070	Wood fragments	3
	119–120	2250 ± 140	2707–1934 cal yr BP	Poz-13143	Charcoal	4
	125–126	3245 ± 35	3559–3392 cal yr BP	Poz-11893	Charcoal + bark	5
	140–142	3280 ± 35	3610–3406 cal yr BP	Poz-11894	Charcoal	6
	152–153	3695 ± 35	4149–3927 cal yr BP	Poz-11072	Charcoal	7
	172–173	6900 ± 130	7972–7514 cal yr BP	Poz-13144	Charcoal	8
Ledro II						
Core Ledro II-1	21–22	1365 ± 35	1339–1189 cal yr BP	Poz-17035	Peat	9
	23–24	1420 ± 60	1507–1184 cal yr BP	Poz-18588	Peat	10
	204–205	3185 ± 35	3470–3356 cal yr BP	Poz-17036	Twigs	11
	236–237	4030 ± 50	4805–4413 cal yr BP	Poz-18596	Peat	12
	244–245	4105 ± 35	4816–4453 cal yr BP	Poz-17038	Peat	13
	280–281	4115 ± 40	4822–4524 cal yr BP	Poz-17039	Twigs	14
Core Ledro II-3	264	4250 ± 50	4960–4590 cal yr BP	Poz-21190	Wood	15
	325	4440 ± 35	5282–4878 cal yr BP	Poz-21191	Wood	16
	366	4700 ± 35	5581–5321 cal yr BP	Poz-21193	Wood + leaves	17
	416	4755 ± 35	5588–5331 cal yr BP	Poz-21194	Wood	18
	444	4975 ± 35	5862–5608 cal yr BP	Poz-21195	Leaves	19
	512	5270 ± 40	6182–5935 cal yr BP	Poz-21197	Leaves	20
	622	5820 ± 40	6731–6504 cal yr BP	Poz-21198	Wood	21
	674	6280 ± 40	7309–7030 cal yr BP	Poz-21199	Wood	22
	758	6880 ± 40	7818–7621 cal yr BP	Poz-21200	Wood	23
	814	7280 ± 40	8175–8014 cal yr BP	Poz-21201	Wood	24
	915	8410 ± 70	9537–9267 cal yr BP	Poz-21202	Wood	25
	1019	10090 ± 70	11982–11342 cal yr BP	Poz-21204	Wood	26
Site San Carlo	15	1740 ± 60	1816–1534 cal yr BP	Poz-27896	Wood	27
	30	2540 ± 30	2747–2496 cal yr BP	Poz-27898	Charcoal	28
	60	3305 ± 35	3630–3463 cal yr BP	Poz-28965	Charcoal	29
	65	3565 ± 30	3970–3727 cal yr BP	Poz-27899	Charcoal	30
	78	3530 ± 35	3897–3702 cal yr BP	Poz-28966	Charcoal	31
	90	3635 ± 30	4081–3861 cal yr BP	Poz-27900	Charcoal	32
	117	3980 ± 35	4529–4300 cal yr BP	Poz-27901	Wood	33
	133	6880 ± 40	7818–7621 cal yr BP	Poz-27902	Wood	34
	135	6930 ± 40	7848–7676 cal yr BP	Poz-28967	Wood + charcoal	35
	148	7300 ± 40	8181–8020 cal yr BP	Poz-28969	Wood	36
	153	7370 ± 50	8308–8060 cal yr BP	Poz-27903	Wood	37
	163	7820 ± 50	8764–8455 cal yr BP	Poz-28970	Wood	38
Site Ponale	33	4415 ± 35	5280–4860 cal yr BP	Poz-32257	Wood	39
	74	7040 ± 50	7970–7750 cal yr BP	Poz-32258	Wood	40
	89	7270 ± 50	8180–7983 cal yr BP	Poz-30733	Wood	41
	104	7450 ± 50	8371–8183 cal yr BP	Poz-32259	Wood	42
	118	7560 ± 50	8450–8210 cal yr BP	Poz-32260	Wood	43
	134	8510 ± 60	9580–9415 cal yr BP	Poz-33877	Wood	44
	146	8740 ± 40	9890–9560 cal yr BP	Poz-32261	Charcoal	45
	168	9600 ± 60	11170–10747 cal yr BP	Poz-33878	Wood	46
	184	9640 ± 50	11192–10781 cal yr BP	Poz-30735	Wood	47
	216	9870 ± 60	11600–11183 cal yr BP	Poz-33880	Wood	48
	227	9970 ± 60	11700–11240 cal yr BP	Poz-32262	Charcoal	49
	250	9970 ± 60	11700–11240 cal yr BP	Poz-32263	Charcoal	50
	272	11050 ± 60	13104–12732 cal yr BP	Poz-30736	Wood	51

lake-marl, coarse gyttja and peaty layers, which mark an unstable water table and rapid successive changes in lake level between 9970 ± 50 ^{14}C yr BP (11,700-11,240 cal yr BP) and 9600 ± 60 ^{14}C yr BP (11,710-10,747 cal yr BP). The radiocarbon ages obtained from sediment units 21 to 16 suggest a relatively high sedimentation rate with an important accumulation of coarse gyttja–peaty deposits during the lowstands and carbonate lake-marl during highstands. Lake-level phase 21 appears to have been synchronous with a slight reinforcement of *Artemisia* values.

Sediment units 16 to 8 are characterized by an alternation of gyttja layers which accumulated during phases of lower lake level (phases 17, 15, 13, 11, and 9), and carbonate lake-marl layers which formed during phases of higher lake level (phases 16, 14, 12, and 10). It is worth noting that sediment units 9 and 7 show a strong development of CF and tube concretions, which clearly contrasts with the domination of oncolites in the underlying and overlying sediment units. This marks important rises in lake level during phases 10 and 8. In addition, both phases 10 and 8 coincided with the successive expansion of *Picea* and *Abies* respectively, while preceding less-pronounced highstands (phases 18, 16, and 14) were synchronous with small peaks of *Picea* and *Abies*.

The abrupt jump of the curves of CF and oncolites at the transition between the sediment units 7 to 6 in addition to the radiocarbon ages obtained from sediment units 8 (7270 ± 50 ^{14}C yr BP, 8180–7983 cal yr BP) and the base of sediment unit 5 (4415 ± 35 ^{14}C yr BP, 5280–4860 cal yr BP) suggests a sediment hiatus between lake-level phases 8 and 6. All together, sediment units 6 to 1 show an alternation of low lake levels (phases 5, 3, and 1) marked by the deposition of gyttja, peat and anmoor, and higher lake-levels (phases 6, 4, and 2) recorded by carbonate lake-marl where oncolites dominate. In a previous study (Shotton et al., 1968), sediment unit 3 (equivalent to lake-level phase 3) has been dated to 3656 ± 66 and 3642 ± 36 ^{14}C yr BP. In the pollen diagram, sediment unit 5a composed of gyttja corresponds to a development of *Cerealia* and anthropogenic indicators as well as a rapid decline of arboreal pollen (Early Bronze Age settlement).

Finally, the last 3500 yr are not documented at site Ponale probably because of disturbances due to past successive archaeological excavations in the outlet area (e.g., Battaglia, 1943).

Core Ledro II-3

Figure 4 shows the sediment diagram established from the middle and lower parts of core Ledro II-3. The upper part may be considered to be documented by core Ledro II-1 (Fig. 1; Magny et al., 2009). This sequence is composed of 6 sediment units. Above a basal pebble layer (sediment unit 6), a silty-clayish lake marl (sediment unit 5) is overlaid by a ca. 7.7-m-thick carbonate lake-marl layer which forms the relatively homogeneous sediment unit 4. The upper part of the profile displays a carbonate lake-marl layer (sediment unit 2) interbedded between a gyttja and a peat layer (sediment units 3 and 1 respectively). Lithostratigraphic correlations indicate that sediment units 3, 2, and 1 in core Ledro II-3 correspond to sediment units 9, 8, and 7 of core Ledro II-1 (Fig. 1; Magny et al., 2009a). The chronology is based on 12 radiocarbon dates in addition to two others inferred from lithostratigraphic correlations with the neighbouring core Ledro II-1 (Magny et al., 2009a).

On a millennial scale, the sedimentological indicators suggest a first period spanning the early Holocene until ca. 7280 ± 40 ^{14}C yr BP (8175–8014 cal yr BP), characterized by lower lake-level conditions with a strong domination of CF concretions and a weak representation of tube concretions. Afterwards, the second period until ca. 5900 cal yr BP shows the development of the tube concretions around an average value of ca. 20–30%, while the representation of CF concretions retreats from ca 80–90% to ca. 70%. This suggests a slight increase in the water table. A third period until ca. 5250 cal yr BP coincided with a marked rise in the lake level as indicated by a clear decline of CF concretions, an important development of the tube concretions, and a strong retreat of the mollusc tests. Finally, a fourth period until ca. 4700 cal yr BP corresponds to a trend towards lowering, with a clear reinforcement of the CF concretions and mollusc tests, a retreat of tube concretions, and the formation of littoral lithofacies (gyttja and peat deposits) of sediment units 3 and 1 respectively. This lowering period was interrupted around 4800 cal yr BP by a rise event marked by peaks of plate and tube concretions (lake-level phase 2, Fig. 4).

On a centennial scale, the curve of the relative changes in lake-level on the right hand of the diagram (Fig. 4) shows that the beginning of the Holocene coincided with low water-table conditions well marked by peaks of oncolites and grey concretions. Afterwards, the curve suggests that the Holocene was punctuated by successive highstands around 11,500-11,000, 10,200, 9200, 8700, 8300, 7950, 7300–7100, 6900, 6300, 5850, 5600, 5350, 5200, 5000, and 4800 cal yr BP. It is noteworthy that those dated to 11,400-11,300, 7300–7100, 6300, 5850–5300, and 4800 cal yr BP appear to be major events within these successive events.

A synthetic lake-level curve

A synthetic absolute curve of Holocene lake-level fluctuations for Lake Ledro was established using a two-step strategy (Magny et al., 2007). In the first step, curves of relative changes in lake level are constructed from the sediment diagrams as shown above by the curves on the right-hand side of the diagrams in Figures 2, 3, and 4, and in Panel D in Figure 1 (see also upper panel of Fig. 6). The second step has two aims:

(1) To establish a synthetic lake-level record for the Holocene at Lake Ledro. This curve presents a synthesis of all events distinguished from the 5 sediment profiles studied at Ledro. It is based on the correlations and radiocarbon dates presented in Table 2 and in the upper panel of Figure 6. Table 2 also gives evidence of how the age and duration of the important sediment hiatuses recognized in the Ponale, San Carlo and Ledro I sediment sequences have been inferred from available radiocarbon ages and correlations between sediment profiles.

(2) To quantify the magnitude of successive lake-level fluctuations. The estimation of the past positions of the water table (expressed in absolute elevation in meters a.s.l.; Fig. 6, lower panel) and, consequently, of the lake-level fluctuation magnitude were based on two references as follows:

First, the lithology and the composition of sediment: modern analogue studies in carbonate lakes (Magny, 1992, 1998, 2004, 2006) have shown that peat deposits correspond to overgrowing processes (shore area), while oncolites dominate more particularly in the shallow water of nearshore areas (ca. 0–0.5 m water depth), CF concretions correspond to at least ca. 0.5–1 m water depth, plate concretions ca. 1–1.5 m water depth, and tube concretions ca. 1.5–2 m water depth.

Secondly, the absolute elevation at which the main sedimentological and lithological markers have been observed in the sediment profiles. In addition, the sediment hiatuses and the erosion surfaces recognised in the different sites provide key indications about the elevation of the upper limit of sediment accumulation and, consequently, the possible position of the water table (Digerfeldt, 1986, 1988).

Of particular interest is the fact that the five sites studied in the littoral zone of Lake Ledro are located at different absolute elevations with different sensitivity to lake-level changes (Fig. 1, panel B; Fig. 5). Thus, they offer complementary lake-level data that either (1) overlap and

Table 2
Correlations between lake-level phases distinguished in the 5 sediment profiles studied at Lake Ledro. The numbers in bold type refer to lake-level phases (see Figs. 1, 2, 3, and 4; see also upper panel of Fig. 6), while the numbers in brackets refer to radiocarbon ages listed in Table 1. Asterisk: note that sediment unit 3 of the Ponale sediment sequence (equivalent to lake-level phase 3; Figs. 3 and 6) was dated to 3656 ± 66 and 3642 ± 42 ^{14}C yr BP in a previous study (Shotton et al., 1968).

high lake-level phases (cal yr BP)	Core Ledro II-3		Ponale		San Carlo		Ledro I		Core Ledro II-1	
lake-level →	low	high	low	high	low	high	low	high	low	high
400								**1**		**1**
							2		**2**	
1200								**3**		**3**
					1		**4a+b**(*1*)		**4+5**(*9-10*)	
1700						**2**		**5**		**6**
							6(*2*)			
					3(*27*)			**7**	**7**	
							8(*3*)			
2600						**4**		**9**(*4*)		**8**
					5(*28*)		**10?**(*5*)		**9**	
										10
3300						**6**(*29*)	**10?**(*5*)		**11**	
								11		**12**
			1		**7**(*30*)		**12**(*6*)		**13a** (*11*)	
						8				
3800				**2**	**9**(*31*)			**13**		**13b** (*12*)
						10				
			3(***)		**11**(*32*)		**14**(*7*)			
4300				**4**		**12**				
	1				**13**(*33*)				**13c**(*13*)	
4800		**2**	**5**(*39*)							**14**
	3(*15*)								**15**(*14*)	
5000/5800		**4** (*16to19*)		**6**	sediment hiatus		sediment hiatus			**16**
	5(*20*)		sediment hiatus							
6300		**6**								
	7(*21*)									
6900		**8**								
	9									
7300		**10**(*22*)		**8**(*40*)		**14**		**15**		
	11(*23*)				**15**(*34*)		**16**(*8*)			
7900		**12**(*24*)	**9**(41)			**16**(*35to37*)		**17**		
	13				**17**(*38*)		**18**			
8300		**14**		**10**(*42*)	MORAINE		MORAINE			
	15									
8750		**16**	**11**(*43*)							
	17									
9200		**18**(*25*)		**12**						
			13(*44*)							
9500	**19**			**14**						
			15(*45*)							
10200		**20**		**16**						
	21		**17**(*46*)							
				18						
11000/11500		**22**	**20-19** (*47to49*)	**22-21** (*50*)						
	23(*26*)		**23**							

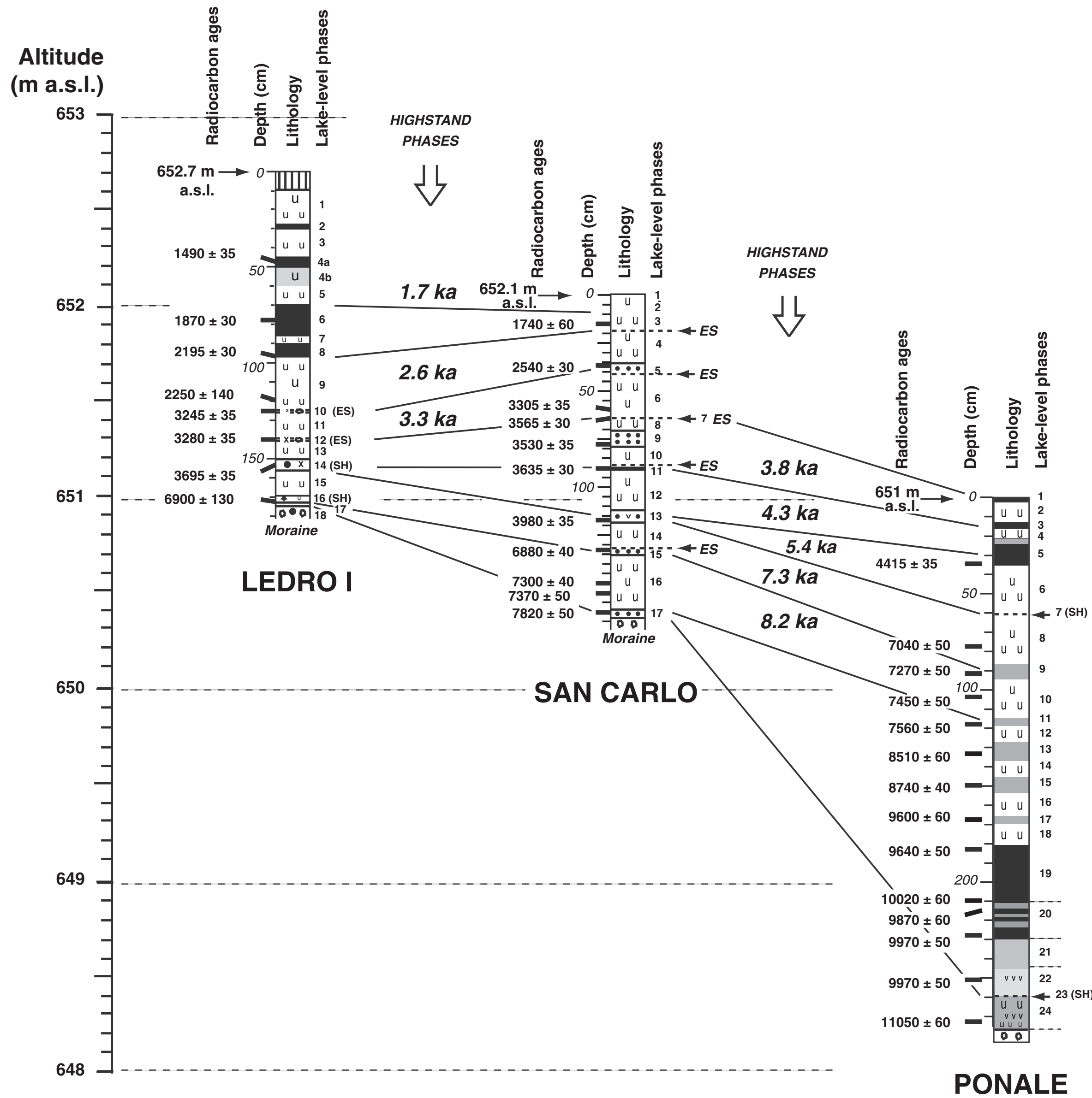

Figure 5. Stratigraphic correlations between the sediment profiles of sites Ponale, Ledro I and San Carlo. Note that all dates are reported as ^{14}C yr BP. The ages of highstand phases expressed in ka correspond to cal ka BP.

allow observation of lateral variations in the sediment facies, informative for the reconstruction of water depth in the past deposition environments, or (2) take over from each other when a period corresponding to a sediment hiatus in one profile is well-documented by deposits accumulated within another. This combination of five sediment profiles (Fig. 1, panel C; Fig. 5) also allows a better recognition of lateral variations in lithofacies and an absolute estimation of past lake-level fluctuations to be developed.

Thus, as illustrated by Figure 6, the synthetic lake-level curve is a composite record. The early Holocene from 11,700 to 8000 cal yr BP is best documented by site Ponale, the mid-Holocene from 8000 to 4700 cal yr BP by core Ledro II-3, and the late Holocene from 4700 to 2250 cal yr BP by site San Carlo, and from 2250 cal yr BP to present by site Ledro I. On the basis of this synthetic record, it is possible to recognise both millennial-scale trends and centennial-scale events within the Holocene history of Lake Ledro.

On a millennial scale, two major periods may be distinguished as follows:

The period 11,700–4500 cal yr BP was characterized by a relatively low mean water table, interrupted by two major rises around 8200 and 7300–7100 cal yr BP. The general lower lake-level average is clearly reflected by an absence of sedimentation and important sediment hiatuses affecting the sediment sequences of sites San Carlo and Ledro I. At site San Carlo, the basal morainic deposits are directly overlain by layers of carbonate lake-marl accumulated during the 8200 and 7300–7100 cal yr BP rise events (lake-level phases 16 and 14). At site Ledro I, located at an elevation slightly higher than that of the San Carlo profile (Fig. 5), the fingerprints of these two rise events appear to be less developed (phases 17 and 15), and they also directly overlie basal morainic deposits. The intermediate lowstand is marked by the deposition of a very thin sediment layer (only 2 cm) on the site of Ledro I (phase 16). This suggests that the water table was most often below 651 m a.s.l. during this lowstand phase.

The period from 4500 cal yr BP to the present corresponds to a higher lake-level average following an abrupt rise in the water table

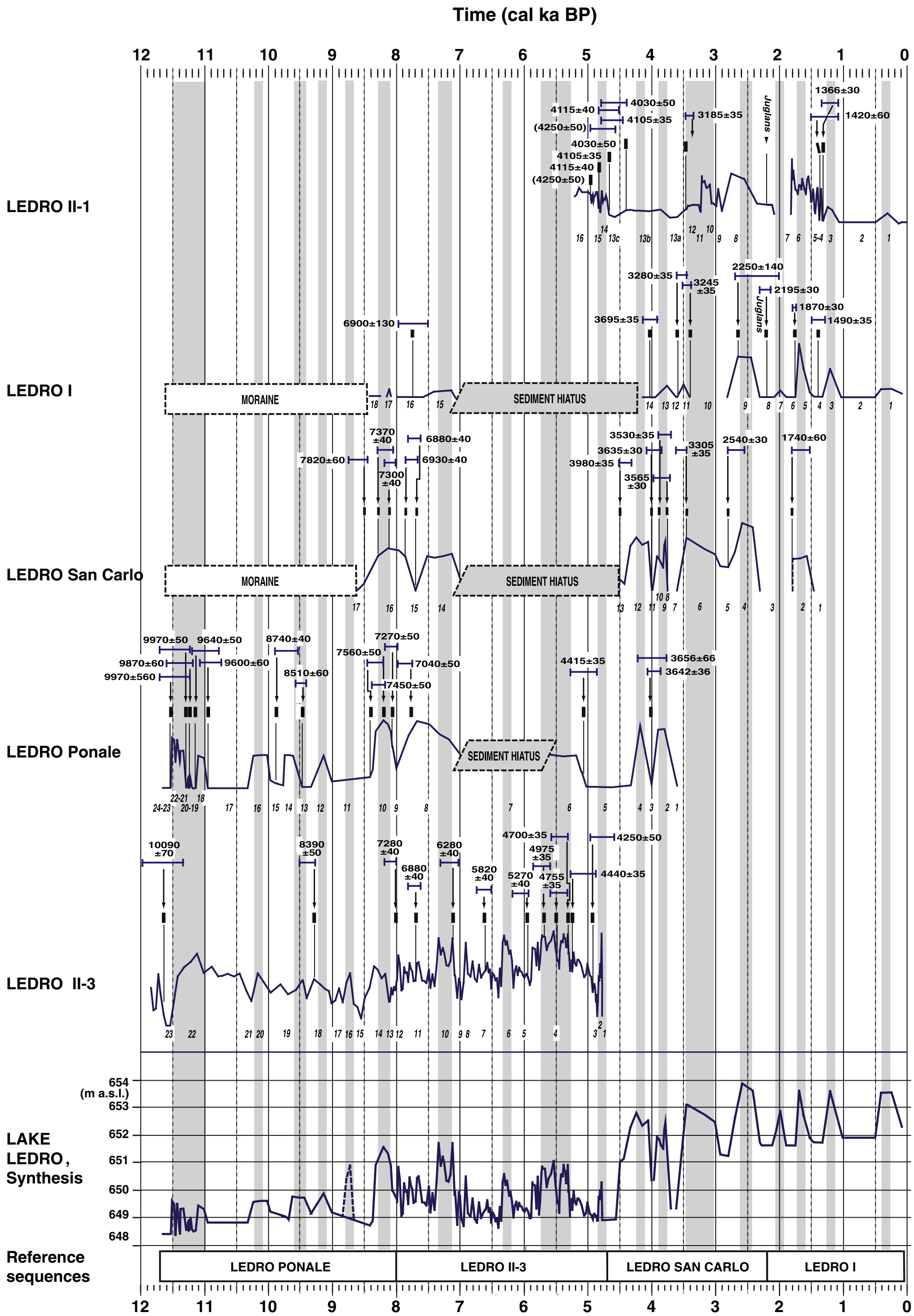

Figure 6. Upper panel: relative changes in lake level reconstructed from sites Ledro I, San Carlo, Ponale, and cores Ledro II-1 and Ledro II-3 (see Magny et al. (2009a) for the curves of site Ledro I and core Ledro II-1, and see Figs. 2 to 4 for the curves of sites San Carlo and Ponale, and of core Ledro II-3). Numbers in italics indicate lake-level phases illustrated in Figs. 1, 2, 3, and 4, and in Table 2. Lower panel: composite synthetic curve of lake-level fluctuations at Ledro (see text) expressed in absolute elevation in meter a.s.l. Reference sequences indicate the key lake-level records (i.e., Ledro Ponale, Ledro II-3, Ledro San Carlo, Ledro I) used for the reconstruction of the successive parts of the synthetic Ledro lake-level record. The radiocarbon dates are indicated in ^{14}C yr BP with their corresponding calibrated ages at two sigma.

around 4500 cal yr BP. While core Ledro II-1 (phase 13b) did not highlight such a marked event (probably due to lateral variations in lithofacies; Magny et al., 2009a), this event is well evidenced by a return to a continuous sediment accumulation above 651 m a.s.l. (Fig. 5) at site San Carlo around 4500 cal yr BP (phases 13 and 12) and at site Ledro I around 4000 cal yr BP (phases 14 and 13). As suggested by differences in pollen preservation observed at site Ledro I (Magny et al., 2009a), the range of lake-level fluctuations during the period 4600–2800 cal yr BP has reached a mean elevation lower than during the period from 2800 cal yr BP onwards. The age of phase 3 in the Ledro I and Ledro II-1 sediment sequences has been fixed at approximately 1200–1000 cal yr BP by reference to the radiocarbon ages obtained for the immediately preceding phases 4 and 4–5 (Fig. 6; Table 2). Finally, the most recent highstand shown by the Ledro I and Ledro II-1 sediment profiles (i. e., phase 1) is assumed to be contemporaneous with the Little Ice Age (around 400–200 cal yr BP), in agreement with other regional lake-level records (Magny et al., 2009a).

On a centennial scale, site Ponale offers a sediment sequence with high temporal resolution and marked changes in the lithofacies to recognise lake-level events punctuating the early Holocene. The interval 11,500–11,000 cal yr BP appears to have been particularly complex with multiple highstands interrupted by lowering episodes. Additional phases of higher lake level appear at ca. 10,200, 9500 and 9150 cal yr BP in general agreement with those observed from core Ledro II-3 (Fig. 4). However, this later site gives evidence of a well-marked rise event around 8700 cal yr BP, which has been added to the synthetic lake-level record (Fig. 6, dotted line). The rise events around 8200 and 7300–7100 cal yr BP are characterized by a sediment limit above 650 m a.s.l. as shown by the Ponale and San Carlo sediment profiles, and close to 651 m a.s.l. at Ledro I sediment profile (Fig. 5); this suggests a magnitude clearly larger than that of the events punctuating the preceding early Holocene and the following mid-Holocene periods. Core Ledro II-3 offers a high temporal resolution to document the mid-Holocene affected by sediment hiatuses at sites Ledro I, San Carlo, and also partly at site Ponale. It highlights major rises around 7300–7100 and 6300 cal yr BP, and around 5850–5350 cal yr BP, the latter also partly registered at site Ponale (phase 6). Finally, the sediment profiles of sites San Carlo and Ledro I allow the identification of major rise events at ca. 4300–3800, 3300, 2600, 1700, 1200, and 400 cal yr BP.

Discussion

Lake-level changes are driven by climatic parameters affecting both evaporation and precipitation, but they can also be induced by 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, Figure 7 presents a comparison between the Ledro lake-level record with that reconstructed at Lake Accesa in Tuscany, north-central Italy (Magny et al., 2007). Both the records benefit from good chronological control, and they are based on the same method of reconstruction. On a millennial scale, differences and similarities appear between the two lake-level records. Regarding the differences, the phase of relative high lake-level conditions at Accesa for the early Holocene from 11,600 to 9200 cal yr BP does not find any equivalent in the Ledro record. This may reflect (1) the influence of a rocky threshold formed by the substratum, and/or (2) the peculiar conditions of the outlet area of Lake Ledro, which was occupied by a morainic dam during the last glacial maximum (Castellarin et al., 2005). At the deglaciation, the dam was incised as a result of the lowering of the regional base level of erosion. In contrast, the Accesa region has never been glaciated. Regarding the similarities, both the Ledro and Accesa records give evidence of (1) an abrupt rise in lake level around 4500 cal yr BP, which resulted in a water table at an elevation never reached before during the Holocene, and (2) higher lake-level average from ca. 2800 cal yr BP onwards.

The general pattern of palaeohydrological changes observed at Lakes Accesa and Ledro for the Holocene fully supports the interrogation by Tzedakis (2007) concerning the notion of an accentuated summer rain regime in the northern Mediterranean borderlands during the boreal insolation maximum. Given that sedimentological markers (i.e., carbonate concretions) used for the lake-level reconstruction form during the summer season, the generally lower water table observed at Lake Ledro during the early and mid-Holocene periods suggests that relatively dry summer conditions prevailed over the first half of the Holocene in northern Italy. This is also in agreement with the tripartite palaeohydrological pattern observed for the Holocene in western Europe from Scandinavia to the Mediterranean (Magny et al., 2003). However, the interpretation of isotopic data obtained at Lake Frassino by Baroni et al. (2006) does not agree with this general reconstruction and suggests that the late Holocene was characterized in northern Italy by generally drier climate conditions than during the mid Holocene. Moreover, stalagmite data from Corchia in north-central Italy suggest enhanced rainfall in the western Mediterranean during the deposition of sapropel 1 (Zanchetta et al., 2007). Such apparent discrepancies between the lake-level and isotopic records (i.e., different proxies used for the reconstructions) may reflect processes linked to the seasonality as illustrated by Peyron et al. (2011) and Magny et al. (2011). Thus, questions remain open and further lake-level investigations are needed for a precise reconstruction of the Holocene palaeohydrological history in the central Mediterranean, while multi-proxy studies are clearly needed for a better reconstruction and understanding of seasonality.

In addition, both the Ledro and Accesa records emphasize the importance of the period around 4500 cal yr BP in the general climatic evolution of the Holocene. The millennial trend from generally low lake-level conditions during the early-mid Holocene towards a relatively high lake-level average during the late Holocene reconstructed at Lakes Ledro and Accesa reflects a common forcing factor, i.e. orbitally-driven induced changes in summer insolation. However, the abrupt rise in lake levels around 4500 cal yr BP points to the crucial impact of the climatic oscillation around 4500–4000 cal yr BP (Marchant and Hooghiemstra, 2004; Booth et al., 2005; Magny et al., 2009b; Giraudi et al., 2011) in the northwestern Mediterranean area. In the case of Lake Ledro, the marked rise in lake level around 4500 cal yr BP may have been accentuated by human impact due to early and middle Bronze age settlements. Thus, it is possible that wetter climatic conditions in combination with forest clearances have induced increasing erosion in the catchment area and, more particularly, may have been responsible for an accumulation of colluvial deposits in the outlet area with, as a result, an amplification of the response of the water table to the 4500 cal yr BP climate reversal. In south-central Italy, at Lakes Mezzano and Albano, marked environmental changes were also observed around 4000–3800 cal yr 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 Figure 7, the climatic oscillation around 4500–4000 cal yr 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. This orbital forcing was associated to a reorganisation of the general atmospheric circulation, with a southward shift of the ITCZ in the Tropics (Haug et al., 2001) and also possibly of westerlies affecting the mid-European latitudes and the northwestern Mediterranean. Figure 8 gives evidence of a strong impact of the climatic oscillation around 4500–4000 cal yr BP around the Mediterranean area and the contrasting palaeohydrological patterns associated to this event, with wetter conditions in the northwestern Mediterranean area as in west-central Europe (Magny et al., 2011), and drier conditions in the southwestern and eastern Mediterranean as in northern Tchad (Kröpelin et al., 2008).

On a centennial scale, Figure 7 shows a comparison of the successive highstands and lowstands which punctuated the entire Holocene period at Ledro with the same types of events recognised (1) in north-central Italy at Lake Accesa (Magny et al., 2007) and (2) in west-central Europe north of the Alps (Magny, 2004, 2006). Keeping in mind the radiocarbon-age uncertainty, the three lake-level records suggests generally similar patterns of changes with major highstands at ca. 11,200-11,100, 10,200, 9500–9000, 8200, 7300, 6200, 5700–5300, 4800, 4500–3800, 3300, 2600, 1200, and 400 cal yr BP.

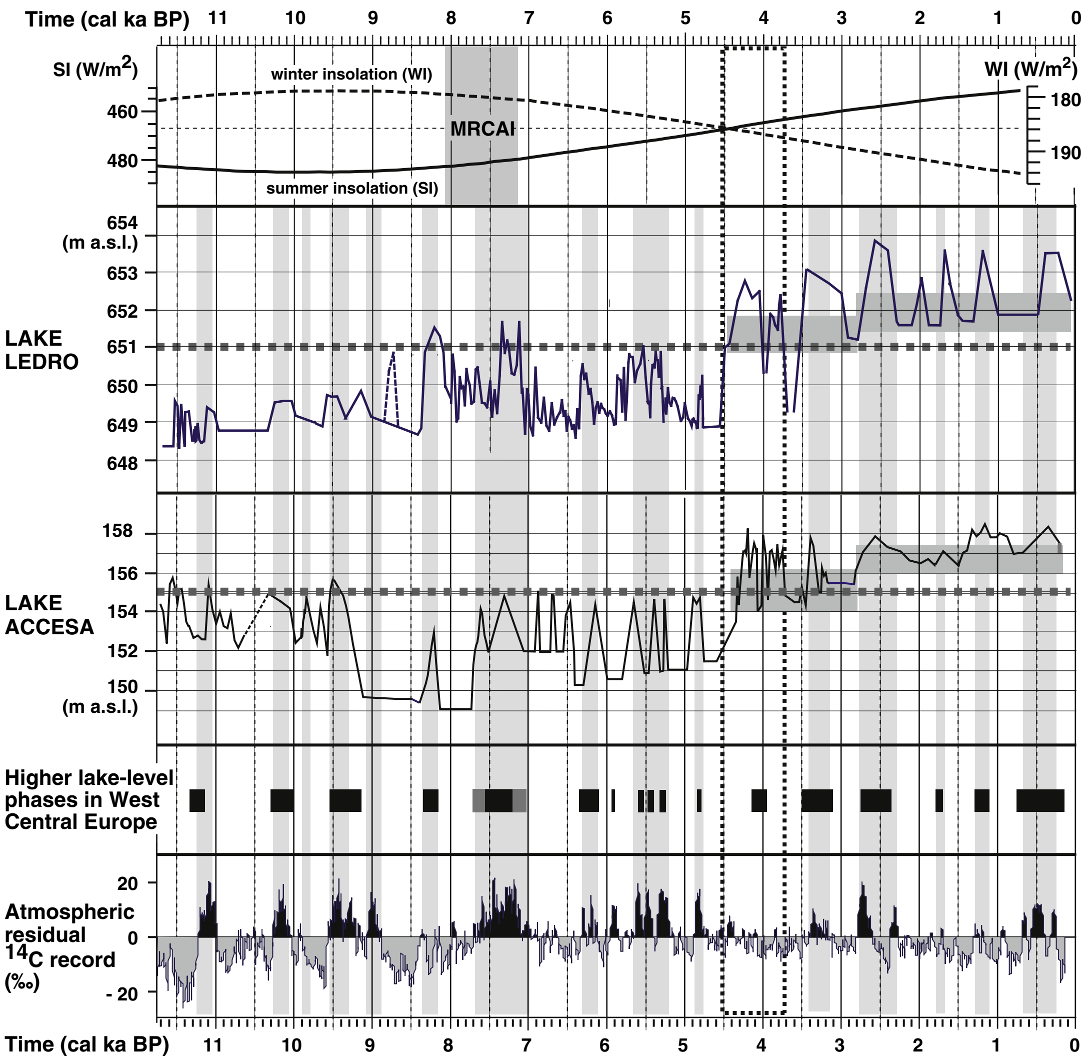

Figure 7. Comparison of the Ledro lake-level record (this study) with that of Lake Accesa, north-central Italy (Magny et al., 2007), the Holocene lake-level fluctuations recognised in west-central Europe (Magny, 2004, 2006), the annual insolation at 40°N (Berger and Loutre, 1991), and the atmospheric residual ^{14}C record (Stuiver et al., 1998). The two grey horizontal dotted lines point to the major differences in lake-level before and after 4500 cal yr BP for Lakes Ledro and Accesa. The vertical rectangle in dotted line gives evidence that the climatic oscillation around 4500–3800 cal yr BP does not coincide with any anomaly in the ^{14}C residual record, but with major changes in the insolation pattern (i.e., an important reorganisation in seasonality). MRCAI: Period of maximal rate of change in annual insolation (Zhao et al., 2010). SI: summer insolation, WI: winter insolation.

As shown in west-central Europe and illustrated by Figure 7 in comparison with the atmospheric ^{14}C residual record (Stuiver et al., 1998), the changes were probably responses to cooling events induced by (1) the final steps of the deglaciation in the North Atlantic area such as the Preboreal oscillation, the 9.3 ka and 8.2 ka events (Magny and Bégeot, 2004; Fleitman et al., 2008; Yu et al., 2010), and (2) variations in solar activity (Björck et al., 2001; Magny, 2004). The late Holocene at Ledro shows strong similarities with paleohydrological changes recognised at Lakes Fucino (Giraudi, 1998) and Mezzano (Giraudi, 2004) as well on the higher Apennine massifs (Giraudi, 2005) and in the Ombrone river delta (Bellotti et al., 2004). As an additional comment for this later period, it is worth noting that the Ledro record confirms the complexity of the tripartite climatic event around 4300–3800 cal yr BP in the central Mediterranean as discussed by Magny et al. (2009b).

Regarding the early Holocene, the Ledro record suggests another possible complex climatic oscillation around 11,500–11,000 cal yr BP, i.e. at the time of the Preboreal oscillation (Björck et al., 1997). This complexity echoes that observed for the same time window at Lake Accesa and, as a working hypothesis, may have resulted from different successive forcing factors (deglaciation and solar activity) as discussed by van der Plicht et al. (2004) and Bos et al. (2007).

The rises around 8200, 7300–7100, and 5800–5300 cal yr BP appear to be the most prominent events in the early to mid-Holocene at Lake Ledro. The lake-level and the pollen data collected at Ledro suggest that the 8.2 kyr event may have had a key impact on the regional vegetation. As pointed out in the Results section, Figure 3 shows how the rise events at ca. 11,100, 10,200, and 9500 cal yr BP coincided with successive small peaks of *Picea* and *Abies*. The rise event broadly synchronous with the 8.2 ka event corresponded to a strong expansion of *Picea* and to the starting expansion of *Abies*, probably favoured by increasing moisture. Finally, the strong development of *Abies* coincided with the rise event dated to 7300–7100 cal yr BP. This major event is also observed at Lake Accesa where it marks the end of the lake-level minimum dated to 9200–7700 cal yr BP (Magny et al., 2007). In marine core MD90-917 in the Adriatic Sea, Siani et al. (2010) have shown that the Holocene SST record was punctuated by two major negative anomalies at 8200 and around 7000 cal yr BP. This event may have had a more widespread significance as suggested by (1) a near cessation of the early to mid-Holocene sea-level rise (Bird

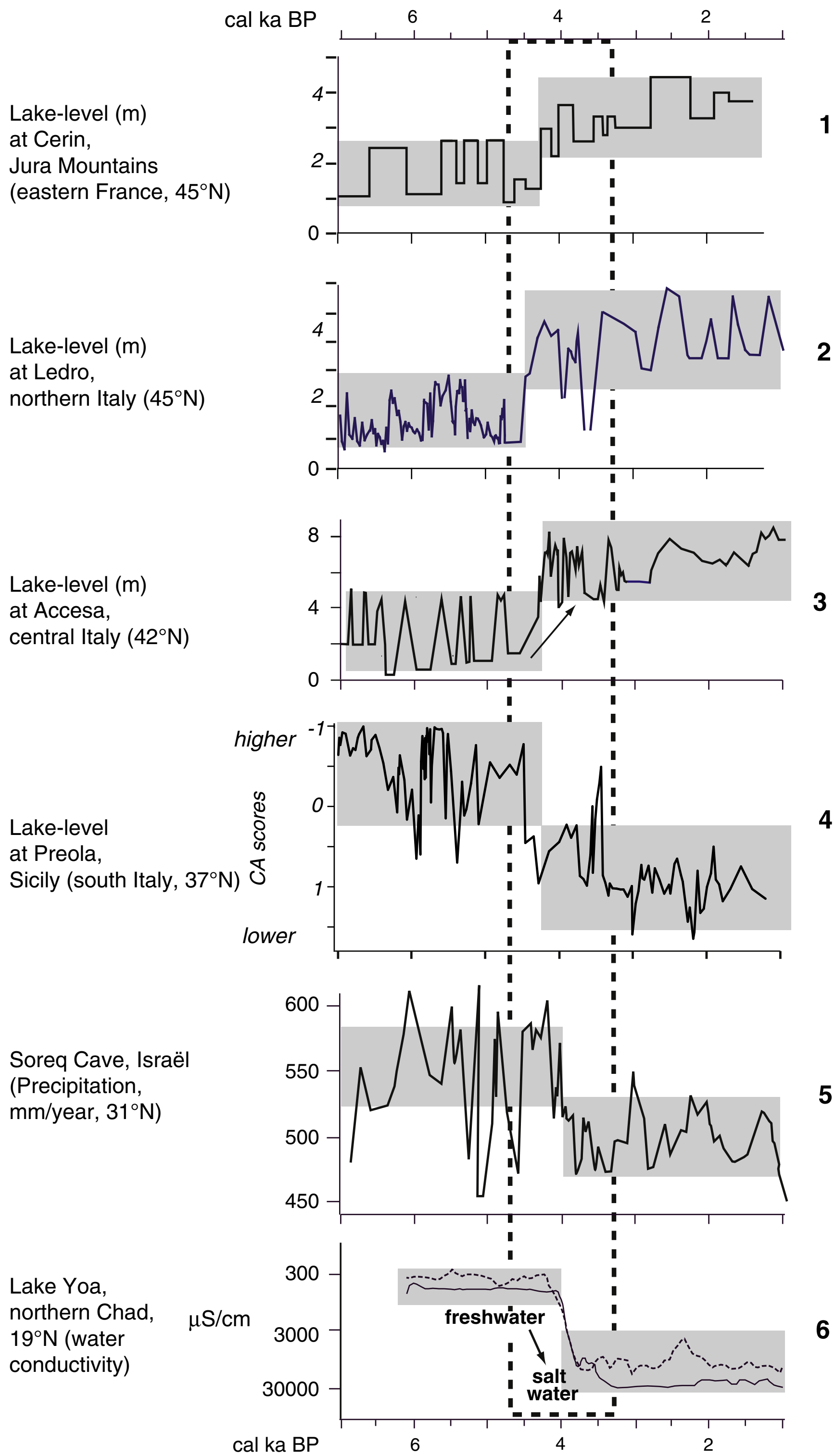

Figure 8. Comparison of paleohydrological records around 4500–3500 cal yr BP (vertical rectangle in dotted line) at the mid- to late Holocene transition from Lake Cerin (Magny et al., 2011a), Lake Ledro (this study), Lake Accesa (Magny et al., 2007), Lago Preola (Magny et al., 2011b), Soreq cave (Bar-Matthews et al., 1998) and Lake Yoa (Kröpelin et al., 2008). Note the opposite palaeohydrological signals provided by sites north and south of latitude ca. 40°N.

et al., 2010), (2) a major IRD peak in the North Atlantic (Bond et al., 2001), and (3) an expansion of polar water in the Nordic Seas (Rasmussen and Thompsen, 2010). The interval 8000–7000 cal yr BP also appears to be synchronous with the highest rate of change in annual insolation for the Holocene (Fig. 7; Zhao et al., 2010), while a prolonged period of decrease in the residual atmospheric radiocarbon developed between 8500 and 7200 cal yr BP (Fig. 7; Stuiver et al., 1998). Thus, the 7500–7000 cal yr BP event may have been driven by a combination of orbital forcing and change in solar activity. Finally, the rise event dated to 5850–5300 cal yr BP at Lake Ledro coincided with a major worldwide cooling event (Mayewski et al., 2004) at the beginning of the Neoglacial (Magny et al., 2004).

Conclusions

On the basis of a specific sedimentological approach, this paper aims at establishing a lake-level record for the Holocene at Lake Ledro (Trentino, northeastern Italy). The chronology is derived from 51 radiocarbon dates. The reconstruction of the lake-level record combines data from five sediment profiles sampled in distinct locations in the lake's littoral zone.

- On a millennial scale, two successive periods may be distinguished. The first, between 11,700 and 4500 cal yr BP, was characterized by lower average lake level, and the second by a higher mean water table. The first period was interrupted by two major rise events around 8200 and 7300–7100 cal yr BP.

— The major climatic oscillation marked, at Ledro by an abrupt rise at 4500 cal yr BP, may be related to (1) key seasonal and inter-hemispherical changes in insolation, and (2) to a non-linear response of the climate system to the orbitally-driven gradual decrease in insolation.

— In agreement with the lake-level record at Accesa in north-central Italy, the results obtained at Lake Ledro suggest that relatively dry summer conditions prevailed during the early to mid-Holocene periods in northern Italy. This questions the notion of an accentuated summer rain regime in the northern Mediterranean borderlands during the boreal insolation maximum.

— On a centennial scale, the Ledro record indicates that the entire Holocene was punctuated by century-scale highstands. Correlations with the Preboreal oscillation and the 8.2 ka event as well as comparisons with the atmospheric ^{14}C residual record suggest that these short-lived variations in lake-level developed at Ledro in response to (1) the final steps of the deglaciation in the North Atlantic area, and (2) variations in solar activity.

Finally, the expansion of *Picea* and *Abies* around 8200 and 7300 cal yr BP respectively may have been favoured by climatic changes towards wetter conditions.

Acknowledgments

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