Revealing the last 13,500 years of environmental history from the multiproxy record of a mountain lake (Lago Enol, northern Iberian Peninsula)

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Abstract

We present the Holocene sequence from Lago Enol (43°16′ N, 4°59′ W, 1070 m a.s.l.), Cantabrian Mountains, northern Spain. A multiproxy analysis provided comprehensive information about regional humidity and temperature changes. The analysis included sedimentological descriptions, physical properties, carbon and carbonate content, mineralogy and geochemical composition together with biological proxies including diatom and ostracod assemblages. A detailed pollen study enabled reconstruction of variations in vegetation cover, which were interpreted in the context of climate changes and human impact. Four distinct stages were recognized for the last 13,500 years: (i) a cold and dry episode that includes the Younger Dryas event (13,500–11,600 cal. yr BP); (ii) a humid and warmer period characterizing the onset of the Holocene (11,600–8700 cal. yr BP); (iii) a tendency toward a drier climate during the Middle Holocene (8700–4650 cal. yr BP); and (iv) a return to humid conditions following landscape modification by human activity (pastoral activities, deforestation) in the Late Holocene (4650–2200 cal. yr BP). Superimposed on relatively stable landscape conditions (e.g. maintenance of well established forests), the typical environmental variability of the southern European region is observed at this site.

Keywords: Holocene, northern Iberian Peninsula, lake sediments, scanning XRF, pollen, ostracods, diatoms

1. Introduction

The Holocene (encompassing the last 11,600 yr) has traditionally been considered a stable period in terms of climate conditions, especially when compared with the abrupt climate changes of the last glacial cycle, including the Heinrich events and the Dansgaard/Oeschger cycles (e.g. Dansgaard et al. 1993). Orbitally-induced differences in seasonal insolation have determined the long-term climatic evolution of the Holocene in Europe, which involved a transition from a warm climate optimum during the Early Holocene to colder and/or drier conditions around 5 kya (COHMAP 1988; Magny et al. 2002). However, an increasing number of studies, based on terrestrial and marine archives, point to the presence of important variations, termed rapid climate change (RCC; Mayewski et al. 2004) events, superimposed on the orbital pattern. In spite of the increasing evidence of their occurrences, the climatic mechanisms behind RCC events remain unknown. However, several hypotheses have been proposed including solar flux variability (Bond et al. 2001; O'Brien et al. 1995) and oscillation in production rates of the North Atlantic deep water (NADW) (Bianchi and McCave 1999; Denton and Broecker 2008). Attempts to unravel climate variability throughout the Holocene are further complicated by interactions between human activity and natural environmental changes, especially those that have occurred from the Middle Holocene to the present day (Carrión et al. 2000a). Therefore, multiproxy studies are required to disentangle the various influences merged in the paleorecords.

As cores from the Mediterranean Sea and Atlantic Ocean show low sedimentation rates during the Holocene, the most detailed climate reconstructions are based on peat bog and lake records including, for example, those from Lake Accesa in northern Italy (Magny et al. 2007), Lago Grande di Monticchio in southern Italy (Allen et al. 2002), Capestang in southeastern France (Jalut et al. 2000), Lake Le Bourget, northwestern Alps, France (Chapron et al. 2005), Laguna de la Roya in northwestern Spain (Allen et al 1996), Lago de Estanya in northeastern Spain (Morellón et al. 2008), and Siles Lake in southern Spain (Carrión 2002). Some exceptions are marine records from Menorca, offshore from northeastern Spain (Frigola et al. 2007), Biscaye in northwestern France (Naughton et al. 2007), and the Alborán Sea, southern Spain (Fletcher and Sánchez Goñi 2008), where higher sedimentation rates have occurred due to their particular settings. Additionally, several recent studies carried out on speleothems have provided high resolution paleohydrological variations in central Italy during the Early Holocene (Zanchetta et al. 2007) and at the southern foothills of the Cantabrian Range in the Late Holocene (Domínguez-Villar et al. 2008). The general pattern in these records is an evolution from wetter to drier climatic conditions between the Early and Late Holocene throughout southern Europe, consistent with changes in orbitally-induced insolation values, and hence seasonality (Wanner et al. 2008). With respect to the identification of abrupt climate change events during the Holocene, it seems clear from the study of lake levels (Magny 2004; Magny et al. 2003; Magny et al. 2002) that North Atlantic Holocene cooling events (the so-called 'Bond events' that appeared with a periodicity of 1500-yr) were periods characterized by increased moisture in central Europe. However, insufficient data are available from southern Europe to assess the response of terrestrial ecosystems, especially vegetation cover, to variations in water availability due to short-term climate change during the Holocene.

In the Cantabrian Mountains in northern Spain we recovered a lake sequence that proved to be a very sensitive record of climate and environmental change since the last glacial period (Moreno et al. in press). The first pollen analyses were carried out in this area in the 1970s at locations including Ercina Lake (Menéndez Amor 1975), Los Azules cave (López 1981), Tito Bustillo cave (Boyer-Klein 1976), La Riera (Leroi-Gourhan 1986), and Cueva Oscura (Leroi-Gourhan and Renault-Miskovsky 1977). More recently, several paleoclimate studies have been reported in the area in relation to Comeya Hollow (Ruiz Zapata et al. 2001a, Jiménez Sánchez at al. 2003), Tarna Pass (Ruiz Zapata et al. 2000, Jiménez Sánchez et al. 2003) and Cortegero Range (Ruiz Zapata et al. 2001b, Jiménez Sánchez et al. 2003). However, continuous and accurately dated records based on multiproxy analyses are needed to reconstruct the effective climate history of the region, and to identify any anthropogenic impact during the Holocene. In this study we reconstructed past hydrological and vegetation cover variations throughout the Holocene, based on a multiproxy study (sedimentology, geochemistry, diatoms, ostracods and palynology) of the Lago Enol sequence, from the Picos de Europa Mountains (eastern Cantabrian Mountain Range, northern Spain).

2. Present-day climate and geographical setting

The Picos de Europa Mountains are located in the eastern Cantabrian Mountain Range (northern Spain). The present-day landscape results from a structural relief created during the Alpine orogeny by a monoclinal flexure and associated reverse faults with an east–west trend (Alonso et al. 1996). Glacial features are preserved in the highest part of this relief, and have been described many times since the beginning of last century (Obermaier 1914; Hernández Pacheco 1914), and more recently (Moreno et al. in press). Lago Enol (43°16′ N, 4°59′ W, 1070 m a.s.l.; Fig.1) is located in the western massif of the Picos de Europa Mountains, and is bounded to the north by calcareous outcrops of Valdeteja limestone. A fault trending east–west with a 200 m high scarp separates the Lago Enol area from the Comeya depression, a hollow of smooth topography with a surface area of 1.2 km^2 (Farias et al. 1990, 1996) (Fig. 1).

The study area is located within the Atlantic climate domain, which is characterized by high annual precipitation (> 1000 mm) due to the proximity to the ocean. Winters are mild and summers are cool, and there is a very small annual temperature range (approximately 13° C). Precipitation mostly occurs in winter, associated with mid-latitude Atlantic Ocean storms. As in other areas of northern Spain, much of the present-day decadal timescale climate variability in this region has been linked to a natural mode of atmospheric pressure variation, the North Atlantic oscillation (NAO; Trigo et al. 2004).

The study area is located within the Eurosiberian biogeographical region. The mildly humid climatic characteristics favor the development of dense deciduous forests, mainly on slopes facing oceanic winds, where peatlands are abundant. The forested areas are dominated by deciduous *Quercus* species (mostly *Q. robur*), with *Betula alba, Corylus avellana, Fraxinus excelsior, Alnus glutinosa* or *Acer* sp., together with Ericaceae and Fabaceae scrub extensions within a Poaceae herbaceous composition. In more humid locations *Fagus sylvatica* is the dominant tree species. Evergreen sclerophyllous formations of *Q. ilex* spp. *ballota, Laurus nobilis, Rhamnus alaternus, Arbutus unedo, Ruscus aculeatus, Ligustrum vulgare*, *Phillyrea media, Rubia peregrina* and *Smilax aspera* are developed on sunny, exposed calcareous ridges (Peinado-Lorca and Rivas-Martínez 1987; Blanco Castro et al. 1992). These sclerophyllous and thermophilous taxa are interpreted as relicts from the warmer and drier periods that occurred during the Pleistocene, and are now restricted to sites with favorable topographic or edaphic conditions (Costa Tenorio et al. 2001; García Antón et al. 2006). The Lago Enol margins are occupied by a vegetation belt of Poaceae, Fabaceae, Asteraceae and Cyperaceae species. During historical times the hydrological catchment and the entire region have been subjected to intense human activity for animal grazing, leading to deforestation and resulting landscape of alpine grassland and meadows.

Lago Enol has a water surface area of 12.2 ha and a maximum depth of 22 m. The small watershed (1.5 km^2) is located over carboniferous formations: limestone on the northern and southern borders (Valdeteja and Picos de Europa formations) and lutite and sandstone (Amieva series) elsewhere. The Picos de Europa formation is the most important karstic aquifer in the area (Meléndez Asensio et al. 2002), which was glaciated with a predominantly north to northeastward ice flow (Marquínez and Adrados 2000). Thus, Lago Enol was excavated by a glacier flowing from the southwest, although previous karstic processes may have been involved in the origin of the basin. The present-day bathymetry is the result of glacial erosion of the bedrock, and deposition of the basal till and moraine (Moreno et al. in press).

The lake is fed by surface runoff and groundwater and there is no permanent inlet. An outlet at the northeast border drains water northwards to the Comeya hollow (Fig. 1). Groundwater discharge and recharge, and evaporation, are key factors in the hydrological balance of Lago Enol. Although there are no available groundwater and lake level data to calculate the hydrological balance of the lake, the response of the system to precipitation is relatively rapid (Meléndez Asensio et al. 2002). Vertical profiling in May 2004 revealed thermal stratification, with a thermocline located at 10 m depth, but no significant changes were observed in electrical conductivity or pH (pH = 7.7–8.2) throughout the water column. Water surveys, in July 2007 and February 2008, enabled the lake waters to be characterized as oligotrophic (total phosphorus 8 μg l^{-1} (Velasco et al. 1999), moderately hard (alkalinity 2.4 meq l^{-1}; 29 mg Ca l^{-1}) and carbonate and calcium rich ($[HCO_3^{2-}] > [Ca^{2+}] > [SO_4^{2-}]$), with a conductivity of 202 μS cm^{-1} (Table 1).

3. Materials and methods

Six cores were retrieved from Lago Enol in spring 2004, using a modified Kullenberg piston corer operated from a platform provided by the Limnological Research Center (LRC), University of Minnesota (USA). Core ENO04-1D-1K, obtained from the deepest central area of the basin (21.5 m water depth at the time of coring), was selected for analysis in this study (Fig. 1). The physical properties of the core were measured at 1 cm intervals at the LacCore facility at LRC using a GEOTEK® multi-sensor core logger. The core was then split, imaged with a DMT® CoreScan, and analyzed for magnetic susceptibility at 0.5 cm intervals, using a high resolution point sensor (MS2E) mounted on a GEOTEK® XYZ-MSCL. The lightness parameter (L*) was obtained from digital images of the core lithologies following the LRC procedure (http://lrc.geo.umn.edu). The core was analyzed at 5 cm intervals for whole sediment mineralogy using X-ray diffraction with a Bruker® D8-Advance diffractometer, and for organic matter and carbonate content at the LRC using a UIC® model 5011 CO_2 coulometer. Additionally, major and minor elements (Si, K, Ca, Ti, V, Cr, Mn, Fe, Rb, Sr, Y, Zr, Ba and Pb) were measured at 1 cm intervals using an ITRAX® XRF core scanner (Large Lakes Observatory, the University of Minnesota, Duluth, USA) with a 30 s count time, 30 kV X-ray voltage and an X-ray current of 20 mA. Although elemental concentrations were not directly available from the XRF measurements and the installed processing software, the values obtained could be used as relative concentrations (see the high correlation between Inductively Coupled Plasma-Optical Emission Spectrometry and X-ray fluorescence scanner data for some elements, in Moreno et al. (in press)). X-radiographs were also obtained using the ITRAX® core scanner with a 60 kV X-ray voltage and 60 mA current intensity.

The core was also sampled for palynological analyses. A total of 33 samples were prepared, taken at approximately 5 cm intervals from the upper 165 cm. The chemical method used for the extraction of pollen and spores, and for nonpollen palynomorphs (NPPs; microfossils other than pollen and spores present in palynological preparations) has been described by Faegri and Iversen (1989) and Moore et al. (1991). A heavy liquid (Thoulet's solution; specific gravity = 2) (Goeury and Beaulieu 1979) was used to concentrate pollen, and *Lycopodium* spore tablets were added to calculate pollen concentrations (Strockmarr 1971). About 400−500 pollen grains were counted per sample, excluding aquatic taxa, fern spores and NPPs. Taxonomic identification followed Faegri and Iversen (1989) and Moore et al. (1991). To distinguish the morphology of *Plantago* we followed Ubera et al. (1988) while Renault-Miskovsky et al. (1976) was used for the Oleaceae family. Differenciation of the morphotype *Pinus pinaster* was based on Arobba (1979) and Carrión et al. (2000b). Most of the NPPs observed were identified, and their nomenclature conforms to that established by van Geel (2001). Pollen diagrams were prepared using Tilia and TGView (Grimm 1992, 2004).

A total of 33 samples were taken from the core at approximately 5 cm intervals and processed for diatom analysis. Diatom slides were prepared using 30% H_2O_2 and 10% HCl, following standard procedures (Renberg 1990), and aliquots of evaporated suspensions were embedded in Naphrax (refractive index = 1.74). At least 300 diatom valves were counted per slide, when diatom abundance and preservation were sufficient. Counting was performed on random transects, and taxonomic identification followed standard flora classification and other floristic works (Krammer and Lange-Bertalot 1986, 1991; Lange-Bertalot and Metzeltin 1996). Diatom stratigraphical diagrams were prepared using the computer software package C2, version 4 (Juggins 2003).

For ostracod analysis the core was sampled at 10 cm intervals, and the samples were passed through 63 µm and 150 µm sieves. Ostracods shells were picked using a stereo microscope and identified according to Meisch (2000). Relative abundance of species were calculated and a stratigraphical diagram was constructed using the program C2, version 1.5.1.

4. Chronological model of the Lago Enol sequence

Although the entire Lago Enol sequence (585 cm) covers 38,000 cal. yr BP (Moreno et al. in press), we focus here on the results for the 0–165 cm depth interval covering last 13,500 cal. yr BP. The chronology for this period was constructed using seven AMS ^{14}C dates obtained from terrestrial plant remains and charcoal samples (marked 'M' in Fig. 2), and from bulk sediment where there were no other terrestrial remains available for dating (Table 2, Fig. 2). As some of the plant fragments come from flood layers, the possibility of dates older than sediment matrix can not be totally discounted. The date of 2590 cal. yr BP at 3 cm depth indicates that the uppermost sediment was lost during the coring process. A separate short core that preserved sediment water interface gave a modern age (not shown).

The AMS ^{14}C dates were calibrated using CALIB 5.0.2 and the IntCal04 curve (Reimer et al. 2004). The median of the 1σ probability interval was selected for these dates, resulting in errors of ± 70 yr (average) in the calendar ages derived. The chronology was constructed by interpolating the radiocarbon dates listed in Table 2 using a generalized mixed-effect regression (Heegaard et al. 2005). As can be seen in Fig. 2, the chronology obtained using the entire set of dates (combining bulk samples and plant remains) would be almost identical to that obtained using only the dates from terrestrial plants and charcoal ('M' in Fig. 2). Thus, although a reservoir effect is possible, particularly considering that the catchment area is made of limestone, it is likely to be small and constant.

Having constructed the chronological model we analyzed the Lago Enol sequence for variability in sedimentation rates (Fig. 2). Unit 2, which corresponds to the Younger Dryas, showed a very low sedimentation rate (3.2 cm/kyr). Unit 1, which corresponds to the Holocene, showed a relatively high and constant sedimentation rate (17 cm/kyr); the exception was the uppermost interval (top 20 cm), where the rate decreased to 7.7 cm/kyr.

5. Results

5.1. Sedimentological and geochemical description

Three sedimentary facies were identified following smear slides description, visual assessment, and integration of mineralogical and grain size data, magnetic susceptibility and bulk density properties, and the elemental composition. Facies 1 and 2 are massive to banded calcite-rich silt to coarse silt (> 60% silt) sediment with high percentages of terrestrial organic matter. Facies 2 appears as mm-thick layers mostly composed of terrestrial and aquatic macrophyte remains, which are clearly indicated by the light colors in the X-ray radiograph (Fig. 3). Facies 1 represents deposition in offshore areas of the lake, where clastic and some endogenic (carbonate from the littoral platform) particles accumulated. Facies 2 marks periods of higher energy (floods), when macrophytes growing in the littoral areas were reworked and transported to deeper environments. Facies 3 consists of dark gray silty clays, massive or slightly banded, with low organic matter. The clay fraction contains filosilicates (illite, muscovite), quartz and feldspars, while the coarser particles are mainly quartz.

Total inorganic carbon (TIC) was used as an indicator of calcite content, due to the absence of other carbon-rich minerals in the XRD analyses and its high correlation to Ca content and calcite percentage (Fig. 3). Organic matter was evident as large fragments of terrestrial and littoral plant remains in mm-thick layers (Facies 2). TIC percentages were very low at the base of the studied interval, increased sharply at about 160 cm (6% for TIC) to a maximum at about 90 cm (8% for TIC) and then decreased toward the top concurrently with an increase in clay and quartz percentages (Fig. 3).

The high resolution record of the dominant geochemical elements obtained using the ITRAX® XRF core scanner is shown in Figure 3. An opposite pattern was detected between Ca and the other elements (Si, K, Fe) along the entire core. Ca levels peaked in the uppermost 155 cm and decreased downwards, while Si, K and Fe were higher where the clay and quartz content increased. The amount of Ca, as indicated by the correlation with TIC and calcite percentages, is related in this record to the amount of carbonate accumulated in the sediments; this was derived from dissolution of surrounding limestone or, to a lesser extent, from endogenic processes in the lake. The potential for preservation of carbonates in deeper areas of Lago Enol would increase if (1) the concentration of dissolved soil CO_2 increased and dissolved more limestone resulting in higher alkalinity content, and (2) higher temperatures led to the saturated state of calcite being attained (Moreno et al. in press). The only element that did not show any significant correlation with those two groups (Ca and siliciclastics) was Mn, which is often related to changes in redox conditions (Aguilar and Nealson 1998). In the upper 2 m of the Lago Enol sequence, Mn peaks appear to be associated with deposition of Facies 2, pointing to changes in the oxygen concentration, and thus in the position of the redox front related to the accumulation of organic matter. However, the absence of Mn-rich minerals in the XRD analyses prevents more detailed interpretation.

Analysis of the sedimentary facies, magnetic susceptibility and color lightness values, and TIC and total organic carbon (TOC) percentages, together with major and trace elements, enabled delineation of two units in the upper 165 cm of Lago Enol sediments:

Unit 2 (165–157 cm), ~13,500–11,600 cal. yr BP: This unit is characterized by slightly higher magnetic susceptibility (MS) and density than Unit 1, and was formed from the massive, non-carbonate, low organic matter Facies 3 (Fig. 3). The low sedimentation rate along this unit (3.2 cm/kyr) prevents any further interpretation of abrupt climate changes during the deglaciation. Of particular significance in this unit is the low percentage of carbonate, which begins to increase at the start of Unit 1, and the high values for elements related to clay minerals (Fe, K) and quartz (Si). Similarly, the TOC is very low, indicative of a barren landscape with sparse vegetation and low productivity in the lake. Consistent with the lithologic description, the grain size analysis of this unit indicated dominance of the clay fraction (Fig. 3).

Unit 1 (157–0 cm), 11,600–2,200 cal. yr BP: This unit comprises Holocene sediments and is composed of an alternating sequence of Facies 1 and 2. The dominance of Facies 1 indicates a continuous supply of detrital calcite punctuated by flooding episodes responsible of deposition of Facies 2. Unit 1 is characterized by high but variable MS and low density values, generally high TOC and TIC percentages, high values of Ca, and low levels of the siliciclastic elements (Fe, K, Si). Four subunits could be differentiated, based largely on chemical composition.

Subunit 1d (157–140 cm), 11,600–9,750 cal. yr BP: This subunit is characterized by a high concentration of Ca and a low concentration of elements associated with clay minerals and quartz (Fe, K, Si). TOC content is low and there is no Facies 2 sediment in this subunit suggesting the absence of flood events transporting macrophyte remains to the lake sediments. This may have been a consequence of a relatively open landscape in the catchment area. This subunit is also characterized by high density, suggesting still significant involvement of clay-containing sediments. Thus, although this unit represents the onset of the Holocene, some of the postglacial sedimentary properties are not yet present.

Subunit 1c (140–92 cm), 9750–8600 cal. yr BP: This subunit is distinguished by high TOC values, related to the presence of Facies 2. Ca, calcite and TIC values are maximum at the top of this subunit (together with the lightness values), while K, Si and Fe percentages, together with clay and quartz, follow a clear trend of decrease toward the top of the subunit.

Subunit 1b (92–20 cm), 8600–4650 cal. yr BP: This subunit is mostly composed of Facies 1, with Facies 2 present only in two isolated layers toward the top of the subunit. The characteristics of subunit 1b are largely the opposite of those of subunit 1c; although still high, Ca, calcite and TIC values decrease in this subunit, while Fe, K and Si values (together with clay and quartz percentages) increase slightly, probably due to a general shift to less humid conditions. Density and lightness values are stable, while MS is high but very variable, indicating rapid changes in the redox condition of the lake bottom water.

Subunit 1a (20–0 cm), 4650–2200 cal. yr BP: This subunit is characterized by high MS and density, consistent with increasing clay and quartz mineral content and TOC, and decreasing carbonate, Ca and TIC. The increase in TOC and decrease in the carbonate content associated with an organic-rich layer (Facies 2), is also marked by the decrease in density, and is probably the consequence of an intensification of surface runoff (sheet wash) processes related to a change to a more open landscape.

5.2. Biological proxies

5.2.1. Palynological results

The Lago Enol pollen sequence reflects a rapid and intense development of mesophilous forests beginning at the onset of the Holocene, probably due to the proximity to refuge areas during glacial conditions. Similar observations have been made for other mountain areas in northern Spain including Laguna Lucenza in Sierra del Courel (Santos et al. 2000), the Lago de Sanabria area in Montes de León (Muñoz Sobrino et al. 2004), and in the El Portalet and Tramacastilla sequences in the central Spanish Pyrenees (González-Sampériz et al. 2006; Montserrat 1992). In addition, while most of the sequence investigated in this study reflects a relatively stable and well developed mixed forest, it nevertheless records some of the climate trends visible in the sedimentological features. Two principal zones were identified in the ENO04-1D-1K core, based largely on the arboreal pollen (AP) percentages, and four subzones were identified in pollen zone 1 (the Holocene), corresponding to the sedimentary subunits (Fig. 4).

Pollen Zone 2 (PZ-2, 165–157 cm), 13,500–11,600 cal. yr BP: The pollen zone 2 interval reflects a landscape characterized by open vegetation consisting mainly of grassland (Poaceae represents 30–35%). Other herbaceous taxa detected in this zone include *Artemisia*, Fabaceae, Compositae, *Rumex acetosella* type, Chenopodiaceae/Amaranthaceae and *Plantago* sp. AP values are the lowest in the sequence (30–50%), with *Pinus* sp. (mainly *Pinus sylvestris* type but also minor percentages of *Pinus pinaster*) and *Betula* dominating. Other tree taxa include deciduous *Quercus*, *Corylus* and *Salix*, and *Fagus*. Shrub taxa are represented by *Juniperus* type and *Cytisus/Ulex* type. *Anabaena* and types 16C and 207 (*Glomus* cf. *fasciculatum*) are the most important NPPs in this zone, which shows the highest values for *Anabaena* in the whole sequence. This pollen zone is consistent with the occurrence of cool and relatively arid conditions associated with the Younger Dryas period, which is in agreement with the chronological model.

Pollen Zone 1 (PZ-1, 157–0 cm), 11,500–2200 cal. yr BP: In this zone there is evidence of a well developed forest, with AP values reaching 70–90%. Mesophyte pollen dominates but the continuous presence of *Pinus* sp. is also evident. Based on the variations in the mesophilous taxa dominating the forests, we were able to identify four pollen subzones, similar to the sedimentary subunits described above.

Subzone 1d (PZ-1d, 157–140 cm), 11,600–9750 cal. yr BP: AP values increase markedly to approximately 85% at the top of this subzone, dominated by a rapid increase of deciduous *Quercus* (45%). *Betula* and *Pinus* sp., together with *Corylus*, constitute the typical AP assemblage at the onset of the Holocene in northern mountain areas of Iberia (González-Sampériz et al. 2005; Muñoz Sobrino et al. 2004; Peñalba et al. 1997; Pérez-Obiol and Julià 1994; Santos et al. 2000). Evergreen *Quercus* is also present in subzone 1d, and in the entire sequence. Other mesophytes (Fig. 4) appear at the onset of this subzone and increase in relative abundance. Herbaceous taxa values decline from 65% in PZ-2 to 15% in PZ-1d, and shrubs are almost absent. Fern spores increase in relative abundance, with the most important NPP being *Botryococcus*, as is typically found in Early Holocene Spanish lacustrine sequences such as the Siles Lake in southern Spain (Carrión 2002). Thus, an improvement in both the regional (rapid forest expansion) and local (increase in hydro-hygrophytes and NPPs such as *Botryococcus*, which are associated with higher lake levels) climate conditions are inferred, with an increase in temperature and a decrease in aridity commonly associated with the onset of the Holocene in northern Iberian Peninsula.

Subzone 1c (PZ-1c, 140–92 cm), 9750–8600 cal. yr BP: AP values in this subzone are the highest in the entire sequence (80–90%). A deciduous forest was established in the area, with *Corylus*, deciduous *Quercus*, *Betula* and other mesophytes dominating the arboreal taxa. *Pinus* sp. and evergreen *Quercus* were also present and first evidence was found for the presence of *Olea europaea* in the sequence. Shrubs are poorly represented, and the herbaceous component is similar to subzone 1d, dominated by grassland taxa, but in lower percentages. The relative abundance of ferns is higher and *Botryococcus* abundance is similar to subzone 1d, indicating the continuation of humid conditions.

Subzone 1b (PZ-1b, 92–20 cm), 8600–4650 cal. yr BP: AP continues to dominate (70–80%), indicating the presence of well established deciduous forests, although the values fluctuate slightly throughout the subzone. Dominant taxa are the same as for subzone 1c, but with more abundant *Fraxinus, Salix* and *Fagus*, and the occurrence of *Alnus* appears to be continuous from previous subzones. *Cytisus/Ulex* type and *Juniperus* type are the main shrubs. Hydro-hygrophytes are well represented, with an increase of Ranunculaceae, the appearance of Cyperaceae around the basin, and an increase of ferns (Filicales trilete and monolete spores), including *Asplenium* type. The percentage of NPPs increases, mainly in the proportions of *Anabaena* and *Pediastrum*, in addition to fluctuations in *Botryococcus*. This pattern may indicate a general decrease in humidity.

Subzone 1a (PZ-1a, 20–0 cm), 4650–2200 cal. yr BP: The AP group is still dominant in this subzone, but there is a small increase in the proportion of shrub taxa, mainly Ericaceae and *Cytisus/Ulex* type. A major change was observed in the arboreal composition, with increases in *Alnus*, *Castanea* and *Fagus*, the appearance of *Juglans*, a decrease in deciduous *Quercus*, *Corylus* and *Fraxinus* towards the top of the subzone, and almost complete disappearance of *Pinus* sp. These changes, in association with the expansion of *Plantago* sp. and *Rumex acetosella* type, and the presence of *Urtica dioica* type, *Artemisia*, Compositae, Caryophyllaceae, Chenopodiaceae/Amaranthaceae, and Fabaceae, indicate anthropogenic influence. The decreased percentages of *Botryococcus* toward the top of the subzone, as well as the disappearance of *Anabaena* and *Pediastrum,* are probably related to the expansion of Cyperaceae, which in this subzone reach the maximum values found in the entire record.

5.2.2. Diatom stratigraphy

The diatom content in the analyzed sediments of Lago Enol is low throughout most of the record, and diatom remains are absent or poorly preserved. Only 11 samples from the top 56 cm (subunits 1b and 1a) had enough diatoms for a full analysis. Forty-one taxa were identified, involving 13 genera. Only 16 taxa were present at an abundance of at least 1% in more than one sample (Fig. 5). The most significant features of the diatom stratigraphy are the high percentages of *Amphora* species, and an increase in *Cyclotella ocellata* Pantocsek toward the top of the sequence (subunit 1a).

Diatom assemblages in subunit 1b are characterized by the dominance of benthic species including *Amphora pediculus* (Kutzing) Grunow, particularly *A. inaeriensis* Krammer and *Navicula scutelloides* (W. Smith); *Fragilaria* species are also present. The dominance of benthic assemblages suggests a relatively low lake level or a very transparent water. At 20 cm depth in the core, coinciding with the beginning of subunit

1a, the diatom record shows rapid and limnologically significant changes: planktonic *Cyclotella* species increased abruptly and rose in abundance, reaching their highest values at 6 cm depth (2900 cal. years BP), whereas benthic *A. pediculus* and *Fragilaria* species decreased then disappeared. This indicates major palaeohydrological changes in the study area, related to an increase in temperature and humidity, discussed below.

5.2.3 Ostracod assemblage

Six ostracod species were identified from unit 1 (150–0 cm depth), while none were found in unit 2. The sequence was characterized by the continuous presence of *Cypria ophtalmica* (Jurine 1820) and periodic appearance of *Candona neglecta* (Sars, 1887), *Potamocypris villosa* (Jurine 1820), *Candona* cf. *candida*, *Bradleystrandensia* spp. and *Cypria* sp. in lower abundances (Fig. 6). *C. ophtalmica*, a common ostracod, is considered a true nektonic species (i.e. a swimmer rather than a scrambler, which is the norm in continental ostracods; R.M. Forester, pers. comm.). *C. ophtalmica* has been found with *Physocypria* as subfossils in anoxic sediments of Elk Lake, USA, suggesting they were originally present in the epilimnetic waters above the core site. No indicators of transport of the shells to the core site were evident (R.M. Forester, pers. comm.). *C. ophtalmica* lives in permanent or temporary stagnant or flowing waters and tolerates a range of dissolved oxygen, salinity and pH conditions (Meisch 2000). *Candona neglecta* is a benthic ostracod that tolerates variable conditions (strong seasonality including desiccation, oxic to hypoxic environment). It may tolerate a greater salinity range than *C. ophtalmica*, as it is common in brackish waters of the Baltic Sea (Meisch 2000), and occurs in Tibetan lakes with specific conductivity above 3 mS cm^{-1} (Mischke et al. 2007). Meisch (2000) cites studies reporting that *C. ophtalmica* and *Candona neglecta* appear to be most tolerant of low oxygen conditions. *Potamocypris villosa* appears to prefer flowing waters that are rich in aquatic macrophytes (Meisch 2000). It is similar to *C. ophtalmica* in its preference for permanent water bodies and tolerance of eutrophic conditions, but differs in being restricted to dilute waters. *Candona candida* is a benthic ostracod that prefers relatively fresh cool to cold water and tolerates some seasonal variation (Forester et al. 2005). A diversity of *Bradleystrandensia* species occur in springs and wetlands, and may indicate groundwater discharge which does occur at Lago Enol.

The relative abundances of *C. ophtalmica* and *Candona neglecta* in Lago Enol were negatively correlated, thus allowing periods with higher water levels to be discriminated from drier periods. Thus, subunit 1b (92−20 cm; 8600−4650 cal. yr BP), which had the highest values of *Candona neglecta* and low values for *Potamocypris villosa* and *Candona candida*, is interpreted as having been deposited in a drier period than subunits 1c (10−92 cm; 9750−8600 cal. yr BP) and 1a (20−0 cm; 4650−2200 cal. yr BP), where the relative abundances of these ostracods were reversed (Fig. 6).

6. Climatic versus anthropogenic forcing in the Picos de Europa mountains through the Younger Dryas and the Holocene

Based on the multiproxy analyses of the Lago Enol sequence, four stages of environmental evolution since 13,500 ca. yr. BP were identified, and compared with regional and global reconstructions (Table 3).

6.1. Pleistocene/Holocene transition (13,500–11,600 cal. yr BP)

The Younger Dryas (YD; 12,700–11,600 cal. yr BP) is one of the most abrupt cooling events in North Atlantic paleoclimate records (McManus et al. 2004). An intensification of westerly winds associated with this event has recently been postulated as the cause of cold and dry climates in central Europe (Brauer et al. 2008). In addition, the pollen-based climate inferred from many southern European pollen records (e.g. Allen et al 1996; Watts et al 1996) generally points to seasonal drought and probably cooler conditions during the YD.

The sediments recovered from the Lago Enol that correspond to the YD are gray, massive siliciclastic silty-clay (Facies 3), with low organic carbon and calcite contents, and high percentages of quartz and clay minerals. We interpret these as being the result of sedimentation in a cold environment characterized by a barren landscape with little vegetation and very low in-lake productivity (no ostracods or diatoms were found for this interval) (Table 3). In addition, the pollen record of Lago Enol during this period was dominated by grassland taxa with high proportions of steppe taxa (e.g. *Artemisia*, Compositae, Caryophyllaceae, Chenopodiaceae/Amaranthaceae or *Juniperus* type), whereas the relative abundance of arboreal taxa was low, rarely exceeding 30%. The tree component was dominated by *Pinus* and *Betula*, but deciduous *Quercus* was also present, as were *Corylus, Fagus* and other mesophytes, pointing to the presence of refuge areas in the region, as has been suggested in analyses of other Iberian sequences (Martínez Atienza and Morla Juaristi 1992; Costa Tenorio et al. 1990, 2001; Ramil-Rego et al. 2000; Valero-Garcés et al. 2000; (González-Sampériz et al. 2003). Rapid reforestation occurred at the beginning of the Holocene, and the presence of evergreen *Quercus* throughout the entire sequence, including the YD period, confirms that the mesothermophilous refuge areas were close to the Cantabrian Mountains. The most significant component of these vegetation refuges is the sclerophyllous taxon *Quercus ilex*, which still occurs in coastal 'refuges' and in south and southwest facing areas on calcareous substrates in the Cantabrian Mountains (Ramil Rego et al. 1998; Costa Tenorio et al. 2001).

The appearance of NPP type 16C (van Geel 1978) also indicates a climate drier than today. In addition, the high percentages of *Anabaena* may be a consequence of low lake water levels, and the presence of *Glomus* cf. *fasciculatum* indicates the occurrence of land surface erosive processes (van Geel et al. 1989). Pollen curves associated with littoral taxa, including Cyperaceae and *Salix*, also suggest the occurrence of a well developed palustrine area in a generally open landscape with low proportions of AP.

The YD/Holocene transition was very fast and took place over less than a decade (e.g. Brauer et al. 2008). The rapid onset of more benign climatic conditions significantly modified the composition of plant communities, including an extraordinary increase of mesothermophilous taxa (Ammann et al. 2000). In the sequence obtained from Lago Enol, this rapid environmental change is clearly evident in vegetation (Fig. 4), but also in the sediments, through a marked increase in the percentage of carbonates (TIC %, Ca values) and a concomitant decrease in clay minerals and quartz (indicated by the K, Fe and Si values) (Fig. 3). With the YD/Holocene transition there was a marked change in the forest composition from open parkland (savanna?) of *Pinus, Betula* and *Quercus*, initially to a well developed deciduous *Quercus* forest, and subsequently to a co-dominance of *Quercus* and *Corylus* from about 9800 cal. yr BP. The presence of *Pinus* and other mesophytes (*Ulmus*, *Tilia* and *Acer*) from the beginning of the Holocene indicates that these forests were probably of mixed composition. It is likely that the forest now present in the study area became stable in the Lago Enol area after the Early Holocene. Unfortunately, other sequences reported from near Lago Enol do not cover this time interval, being limited to Mid and Late Holocene (e.g. Ercina Lake (Menéndez Amor 1975); Corteguero Range (Ruiz Zapata et al. 2001b, Jiménez Sánchez et al. 2003)), or lack continuity over this period (e.g. Comeya Hollow (Ruiz Zapata et al. 2001a, Jiménez Sánchez et al. 2003); Tarna Pass (Ruiz Zapata et al. 2000, Jiménez Sánchez et al. 2003)) and cannot be used to corroborate this interpretation. Nevertheless, sequences that cover the YD/Holocene transition from more distant locations in northwestern Iberia - Lago de Ajo (McKeever 1984; Allen et al. 1996), Laguna de la Roya (Allen et al 1996), Leitariegos Pass (García-Rovés 2007, northeastern Iberia - Bañolas (Pérez-Obiol and Julià 1994), Tramacastilla (Montserrat 1992), El Portalet (González-Sampériz et al. 2006) and Lake Estanya (Morellón et al. 2008) all indicate early forest stabilization with the amelioration of climatic conditions at the onset of the Holocene.

6.2. The Early Holocene and increased humidity (11,600−8700 cal. yr BP)

The start of the Holocene in southern Europe is typically characterized by improved climatic conditions, particularly warmer temperatures and increased effective moisture (Roberts et al. 2004) (Table 3). However, the timing, duration and intensity of this humid period show large regional variability. In Lake Estanya (Pre-Pyrenees, northeast Spain), for example, the increase in water availability did not occur until 9.2 ka (Morellón et al. 2008), while evidence from Mediterranean marine cores indicate that sea surface temperatures increased much earlier, at 11.6 ka (Cacho et al 2001). At a regional scale the period from 9 to 6 ka broadly corresponds to the development of the S1 sapropel in the eastern Mediterranean Sea (Martínez-Ruiz et al. 2000), and to the end of the Saharan humid period (deMenocal et al. 2000; Kröpelin et al. 2008). In the case of Lago Enol, an Early Holocene increase in rainfall is reflected in the increase of mesophytes, the decrease of *Juniperus* type, the low percentage of *Anabaena*, and the disappearance of type 16C (Fig. 4). This period is characterized by alternating sequence of Facies 1 and 2, and the high content of carbonate (% TIC, % calcite, Ca) and organic matter (% TOC), which are in agreement with the improvement in climatic conditions.

Although the onset of the Holocene in terms of temperature and humidity coincides with the boundary between PZ-2 and PZ-1d, a progressive increase in rainfall during PZ-1c (9750−8600 cal. yr BP) is indicated by the high percentages of *Corylus*, which along with deciduous *Quercus* dominate forest expansion. In addition, sedimentological and geochemical proxies also indicate that the Holocene optimum conditions, represented by the sedimentary subunit 1c (9750−8600 cal. yr BP), occurred later than is suggested in marine sediments (Cacho et al 2001). These optimum conditions were marked by maximum values of calcite and organic matter, and minimum percentages of siliciclastic particles. The maximum carbonate values point to an increase of dissolved calcite from surrounding rocks, as a consequence of CO_2-rich groundwater associated with soil formation and forest development and/or to higher detrital carbonate input as a consequence of increased rainout. The sediment density also changes at the boundary between subunit 1d and 1c (Fig. 3) where the first preserved ostracods were found (Fig. 6). *Cypria ophtalmica, Potamocypris Villosa* and *Candona* cf. *candida,* and minor amounts of *Candona neglecta*, were the dominant ostracod species during this period, consistent with findings from other high elevation deep lakes and springs in mountainous areas of the Spanish Pyrenees (Roca and Baltanás 1993). The continuous presence of *C. ophtalmica* in our sequence suggests a permanent lake or stable physical hydrology. In addition, consistent with pollen and sedimentological data, *Potamocypris villosa* and *Candona* cf. *candida* co-occurred during the Early Holocene, suggesting a time of high lake level, i.e. more precipitation and thus of more dilute waters.

6.3. Drier conditions in the Middle Holocene (8700−4650 cal. yr BP)

Based on paleohydrological records from the Mediterranean region, a bipartition of the Holocene period has been suggested (Harrison and Digerfeldt 1993; Jalut et al. 2000; Magny et al. 2002). After a generally more humid Early Holocene a shift toward drier conditions occurred, probably driven by insolation forcing (Wanner et al. 2008). Generally dry conditions are also recorded in paleoclimate records from the northern Iberian Peninsula (e.g. Muñoz Sobrino et al. 2004; Santos et al. 2000), as well as in other interior regions of Iberia (e.g. Morellón et al. 2008) and in marine sequences (e.g. Frigola et al. 2007). For example, most of the saline lakes in the Central Ebro valley (northeastern Spain) were desiccated or ephemeral during the Middle Holocene

(González-Sampériz et al. 2008; Valero-Garcés et al. 2000). This shift starts after 8600 cal. yr BP in Lago Enol, where Ca, calcite and TIC values start to decrease although remaining relatively high, and Fe, K and Si values (together with clay and quartz percentages) tend to increase slightly (Fig. 3). Additionally, the organic rich layers so common during the previous stage (Subunit 1c) are less abundant. This trend to slightly drier conditions is also supported by the pollen spectra. The increase of *Juniperus* type, riparian taxa (*Fraxinus*, *Salix* and *Alnus*) as a possible consequence of a drop in the lake level), hydro-hygrophytes (Cyperaceae and Ranunculaceae) and ferns corroborate the occurrence of this drier climate during the Middle Holocene (Table 3). Of particular significance are the increases in percentages of *Anabaena* (van Geel 2001; van Geel et al. 1994; Riera et al. 2006) and *Glomus* cf. *fasciculatum*, which indicate more xeric conditions and increased landscape erosion (van Geel et al. 1989). Although a regional decrease in humidity was detected, the high arboreal percentages remaining during the Middle Holocene indicate continuation of favorable temperatures and the presence of very stable forested landscapes. It is known that well developed and stable forests are not so sensitive to abrupt changes as is evolving vegetation cover, or vegetation near ecotones.

Evidence for the preservation of diatoms begins during the Middle Holocene period, and points to a relatively low lake level as the assemblage was dominated by benthic types, fragilarioids, epiphytes and taxa associated with littoral habitats. These fragilarioid taxa are common today in Arctic lakes (Bouchard et al. 2004), and are also abundant in palaeoecological records (e.g. Smith 2002), usually associated with oligotrophic alkaline conditions (Camburn and Charles 2000; Fallu et al. 2000). In addition, the 60–40 cm interval (7500–6500 cal. yr BP) is characterized by the marked presence of the ostracod *Candona neglecta* which may indicate relatively saline conditions, and by the maximum abundances of *Anabaena* during the Holocene.

Superimposed on the general trend toward aridity, several oscillations in arboreal percentages and the appearance/disappearance of several NPPs occur in the Middle Holocene (Fig. 4). The major oscillation may be related to the well recognized 8200 cal. yr BP event, which was characterized by cold and dry conditions in the North Atlantic area (Tinner and Lotter 2001; (Alley and Ágústsdóttir 2005) as a consequence of the weakened meridional overturning circulation, triggered by a freshwater outburst

(Kleiven et al. 2008). In this period a small decrease in the arboreal percentages and an increase of *Juniperus* type and Poaceae occur, pointing to a short period of climate deterioration. The small decrease was the most significant change in the arboreal pollen percentage during the Holocene (Fig. 4). In other palaeoenvironmental studies in northwest Iberia (Allen et al. 1996; Leira 2005) and the Pyrenees (González-Sampériz et al., 2006), a climatic deterioration in the Iberian Peninsula during the Early Holocene (9000–8000 yr BP) has also been suggested, and similar evidence has been recovered from a marine record in the Bay of Biscaye (Naughton et al., 2007a). However, the short-term climatic change indicated in the Lago Enol sequence needs to be confirmed by new dates and higher resolution data.

6.4. The Late Holocene and the beginning of human impact (4650–2200 cal. yr BP)

The interpretation of the record for the last ~4500 years is complicated by the interaction between climate and human impact on the environment. In general, a trend toward cooling is evident in North Atlantic climate records (Davis et al. 2003), and it is considered a period of 'neoglaciation', as many alpine glaciers advanced (Matthews 2007) (Table 3). As for paleohydrological changes, lake records from central Europe indicate an unstable climate punctuated by periods of higher lake levels (4150–3950, 3500–3100, 2750–2350, 1800–1700, 1300–1100 and 750–650 cal. BP, and after 1394 AD; Magny 2004). In the Iberian Peninsula a succession of alternating dry and wet periods, inferred from lake and fluvial records (Macklin et al. 2006; Martín-Puertas et al. 2008), has been found for the last 4000 cal. yr BP: a generally dry phase from ≈ 4 to 2.7 ka; a humid phase during the Iron Age and the Roman Optimum from 2.7 to 1.6 ka; another dry phase during the Medieval Climate Anomaly; and a final increase in humidity associated with the Little Ice Age. The pollen record in a marine core from offshore Galicia (northwest Spain) points to the occurrence of an open deciduous oak forest, indicating a humid and temperate climate in northwestern Iberia during the last 3000 years, although a two-step forest reduction associated with cold periods (the sub Atlantic period from 975 to 250 cal. yr BC, and the Dark Ages from 450 to 950 cal. yr AD) has been detected (Desprat et al. 2003). Nevertheless, this variability may also be related to major increases in anthropogenic activity in the landscape since the Neolithic and Calcolithic periods (agricultural and pastoral activities; 7–4.2 cal. kyr BP), during the Bronze and Iron ages (metallurgy and mining, 4.2−2.02 cal. kyr BP), in the Roman period (intensification of human impact; 2.02−1.6 cal. kyr BP), and from the Visigothic period and Medieval times (1.6−0.5 cal. kyr BP) to the present.

The palaeoenvironmental record of Lago Enol for the Late Holocene only covers the period 4650–2200 cal. yr BP. Siliciclastic material percentage continues to increase, while the carbonates decrease (Fig. 3). An increase in organic matter (TOC %) is also noticeable during this period. This time period includes the transition from the sub-boreal period (≈ 4.6 to 2.8 ka), usually considered to have been dry and warm, to the sub Atlantic (≈2.8 to 2.2 ka in the Lago Enol sequence), which was characterized by a wetter climate (Van Geel et al. 1996). The most marked change in the fossil diatom assemblages found in the core occurs around 3400 cal. yr BP, when the diatom assemblages shifted from a community characterized by taxa associated with littoral habitats to one composed almost exclusively of *Cyclotella comensis* and *C. ocellata* (Fig. 5). The genus *Cyclotella* is generally considered to be planktonic, although several species are known to occur as tycoplanktonic forms. Nevertheless, in most recent ecological studies *Cyclotella ocellata* is considered to be primarily planktonic (Edlund et al. 2003, Gurbuz et al. 2004, Cremer 2006). This change from benthonic to planktic community suggests a modification of the habitats available for diatoms. Many planktonic species require water temperatures of 10° C or higher (Stoermer and Ladewski 1976), so fluctuations in abundance of these taxa in alpine and/or subalpine lakes may reflect Holocene seasonal climatic variations to higher summer water temperatures (Smol et al. 1991). In addition, the appearance of *Cyclotella ocellata* in the fossil record of lakes has commonly been interpreted as indicating higher lake water levels (e.g. Punning and Puusepp 2007). Wetter climates result in consistently higher lake water levels. The increase in water level is accompanied by changes in available habitat, light, chemical conditions, stratification and mixing regimes, which can lead to increased opportunities for the development of planktonic diatom communities in the lake. Consistent with the diatom assemblage, the simultaneous occurrence of the ostracods *Potamocypris villosa* and *Candona* cf. *candida* at ≈3500 cal. yr BP supports the presence of more dilute waters in Lago Enol.

After 4650 cal. yr BP, a small decrease in the arboreal percentages in Lago Enol can be seen. Particularly significant is the decrease of *Pinus* sp., *Corylus* and deciduous *Quercus*, which is accentuated after 2700 cal. yr BP. The observed disappearance of *Pinus* in the Late Holocene is consistent with the results of Rubiales et al. (2008), and was probably mediated by anthropogenic factors. In contrast, the percentages increased for other taxa including *Alnus*, *Castanea* and *Fagus*, and there were also increases in shrub formations (mainly Ericaceae, which were previously very rare), *Plantago* sp. and *Rumex acetosella* type. These changes may have been related to the beginning of human activity in the zone, with clearing for grazing resulting in establishment of a more open landscape, as has been suggested to have occurred in the Late Bronze Age and the beginning of the Iron Age (Blas Cortina and Fernández Manzano 1992). The increase in relative percentage of *Castanea* and the appearance of *Juglans* is also indicative of human impact (Conedera et al. 2004). In addition, the development of *Fagus* forests was likely to have been favored by human disturbances in the area (Ramil-Rego et al. 2000; López-Merino et al. 2008). Although the last 2200 years of the record in the Lago Enol core were not recovered, these findings are consistent with those reported for the Comeya Hollow sequence (Ruiz Zapata et al. 2001a; Jiménez Sanchez et al. 2003), which is the nearest to our study site. The pollen spectra from Comeya Hollow shows similar characteristics as those of the Lago Enol since 4650 cal. yr BP, with indications of an opening of the landscape and increases in shrub abundance (Ericaceae), and greater representation of *Fagus*, *Castanea*, *Juglans*, *Alnus* and *Plantago* sp. Although the effect of climate cannot be ruled out, the evidence points to major human impact that changed the forest structure after 4650 cal. yr BP.

7. Conclusions

The Lago Enol sedimentary record revealed significant environmental fluctuations covering the last 13,500 years, which were identified by a multiproxy study combining sedimentological and geochemical techniques, diatom and ostracod species assemblages, and palynological analyses. Four distinctive periods were distinguished. Firstly, a cold and dry period from 13,500 to 11,600 cal. yr BP, thus including the Younger Dryas, was identified based on the presence of gray, massive siliciclastic silts with low organic matter, during which the landscape was dominated by grassland and forests were poorly developed. The second period coincided with the transition to the

Holocene, which was characterized by a change in the sedimentary facies, increasing organic and carbonate contents, and a major change in the forest composition from open woodlands of *Pinus, Betula* and *Quercus* to a well developed deciduous *Quercus* forest. A progressive increase in rainfall from 9750−8600 cal. yr BP was inferred from the high percentages of *Corylus*, which co-dominated the forest expansion with deciduous *Quercus*, and by the ostracod species associations. Thus, the most humid Holocene conditions were reached at about 9000 cal. yr BP, a finding consistent with other southern European records (e.g. Morellón et al., 2008).

The third period (8700−4650 cal. yr BP) involved a trend to drier conditions indicated by the pollen spectra (increased abundance of *Anabaena* and *Juniperus* type); a trend of slight increases in Fe, K and Si (together with clay and quartz percentages); and the dominance of benthonic diatoms: fragilarioids, epiphytes and taxa associated with littoral habitats. The fourth period (4650−2200 cal. yr BP) is characterized by a significant change in the fossil diatom assemblages in the core to almost exclusively planktonic diatoms. This is interpreted as an improvement in climatic conditions (longer ice-free seasons and a wetter climate), although the pollen spectra point to the importance of human impact since 4650 cal. yr BP, indicated by the increased abundance of *Plantago* sp. and *Rumex acetosella* type, and a decrease in the arboreal component.

A strong agreement exists in the timing of the main hydrological and landscape evolutionary stages with major phases of climate changes during the Holocene in southern Europe was evident in the Lago Enol sediments. In addition to these general tendencies, which were largely controlled by variations in insolation, some short-term events were detected that highlight the complexity of Holocene climates. However, the Lago Enol pollen sequence indicates that a well established forest in the Cantabrian Mountains was resilient to the succession of abrupt climate changes, as only minor vegetation fluctuations were observed. Investigation of more records, particularly from sensitive areas and at greater temporal resolution, is necessary to clearly establish the response of terrestrial ecosystems to rapid climate changes during the Holocene.

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Table captions

Table 1. Physical and chemical properties of Lago Enol water obtained during (a) July 2007 and (b) February 2008. TSS: total suspended solids; TDS: total dissolved solids. Concentration data in mg/l.

(a)

Prof.	Cond	pH	TSS	M.O	TDS	Carb	Bicarb	alc total	F^-	Cl^-	NO^2-	Br^-	NO_3^{2-}	SO_4^{2-}	Na^+	Ca^{++}	Mg^{++}
Sup	170	8.6	2.2	1.8	116	10.2	76.6	86.8	0.014	3	0.011	0.000	0.524	1.578	2.010	18.509	1.268
2 m	165	8.6	1.8	1.6	120	9.7	80.2	89.9	0.020	2	0.015	0.000	0.514	7.682	1.877	22.761	0.663
4 m	166	8.7	1.8	1.4	112	14.6	75.7	90.3	0.022	2	0.013	0.007	0.512	1.562	2.064	17.020	0.200
6 m	170	8.6	2	2	104	8.9	81.5	90.4	0.035	3	0.011	0.007	0.528	1.655	1.916	23.254	0.391
8 m	178	8.4	1.6	1.4	140	5.7	87.8	93.5	0.025	3	0.010	0.014	0.771	1.754	1.878	22.791	0.258
10 m	184	8.3	1.2	1.2	152	3.4	87.7	91.2	0.033	3	0.011	0.009	0.901	2.179	1.774	24.810	0.325
12 m	190	8	1.2	1.2	132	0	98.1	98.1	0.024	2	0.006	0.006	0.695	1.756	2.081	29.170	0.351
14 m	206	8	1.2	1.2	144	0	95.8	95.8	0.035	3	0.011	0.012	0.896	2.380	1.955	28.440	0.243
16 m	209	7.8	1.4	1.4	116	0	99.8	99.8	0.023	3	0.009	0.010	0.714	2.258	1.932	29.859	0.164
18 m	214	7.8	43.6	8	136	0	99.5	99.5	0.025	3	0.011	0.010	0.749	2.426	1.790	29.628	0.000

(b)

Prof.	Cond	pH	TSS	M.O	TDS	Bicarb	alc total	F^-	Cl^-	NO^2-	Br^-	NO_3^{2-}	SO_4^{2-}	Na^+	K^+	Ca^{++}	Mg^{++}
Sup	202	8.4	1.8	1.6	116	4.2	103.6	0.026	5	0.009	0.008	0.988	1.581	1.924	3.778	25.058	0.737
1 m	202	8.3	1.8	1.4	116	4	100.8	0.020	5	0.019	0.011	0.963	1.656	2.049	3.645	27.524	0.999
2 m	200	8.3	3.6	1.8	116	3.8	97.1	0.017	2	0.017	0.012	0.991	5.231	1.758	0.255	29.382	0.603
3 m	187	8.3	1	1	96	3.8	96.8	0.017	2	0.014	0.007	0.904	1.522	1.938	0.000	26.805	0.784
4 m	188	8.3	1.8	1.8	104	4.1	100	0.018	2	0.014	0.014	0.918	2.651	1.942	0.105	24.726	0.778
6 m	188	8.3	1.8	1.6	104	3.9	93.6	0.017	2	0.010	0.010	0.926	1.485	2.294	0.252	26.603	0.922
8 m	190	8.3	2.2	1.6	104	3	98.4	0.019	2	0.009	0.010	0.929	1.505	2.181	0.349	27.732	0.872
10 m	189	8.3	1.4	1.4	104	2.5	98.6	0.026	2	0.015	0.012	0.985	1.565	2.061	0.005	26.770	0.785
12 m	192	8.2	1.8	1.4	104	0	102.4	0.018	2	0.013	0.013	1.035	1.750	1.840	0.559	26.479	0.573
14 m	190	8.1	1.2	1.2	112	0	101.5	0.019	2	0.007	0.006	0.965	1.619	1.929	0.329	26.436	0.781
16 m	189	8.2	2.2	1.4	116	2.1	105.3	0.021	2	0.010	0.013	0.966	1.705	1.943	0.494	28.035	0.654
17 m	192	8.1	2.8	1.4	112	0	103.7	0.018	2	0.011	0.011	0.972	1.811	1.956	0.200	27.863	1.049

Table 2. Radiocarbon dating of Lago Enol cores, analyzed at the Poznan Radiocarbon Laboratory, Poland (Poz-) and the Lawrence Livermore National Laboratory (Law-). Dated samples were 1-cm thick. The last column indicates the calendar age average probability provided by the CALIB software.

Sample ID	**Lab code**	**Material**	**Depth (cm)**	**^{14}C ages**	**Cal. years BP (1σ)**	**Calendar age BP**
ENO04-1D-1K-1- 7	Poz-18434	Bulk sediment	3	2515 ± 35	2501-2595	2590
EN04-1D-1K-1 35	Law-135490	Charcoal	31	5270 ± 60	5986-6029	6060
ENO04-1D-1K-1, 64	Poz-15968	Bulk sediment	60	6660 ± 40	7507-7575	7530
ENO04-1D-1K-1, 95	Law-137659	Charcoal	90	7875 ± 50	8594-8728	8690
ENO04-1D-1K-1, 137	Poz-12967	Bulk sediment	133	8780 ± 50	9697-9900	9800
ENO04-1D-1K-2- 2	Poz-18435	Terrestrial plant remains	150	9050 ± 50	10194-10242	10220
ENO04-1D-1K-2, 12	Poz-20060	Bulk sediment	160	10560 ± 50	12581-12710	12600

Table 3. Climate conditions inferred from Lago Enol sediments for the last 13,500 years, compared to regional and global reconstructions.

Period	**Lago Enol (N Spain)**		**Regional climate (N Spain)**	**Global reconstructions**
	Hydrological situation	**Vegetation cover**		
4650-2200 Recent Holocene	Significant change towards a diatom association dominated by planktonic species and simultaneous occurrence of the ostracods *Potamocypris villosa* and *Candona* cf. *candida* suggesting more precipitation.	General decrease of the arboreal percentages (*Pinus* sp., *Corylus* and deciduous *Quercus*) while *Alnus*, *Castanea* and *Fagus* increase and *Juglans* appears (anthropogenic influence). Increase of the shrub formations and raise of *Plantago* and *Rumex* (human activities).	A humid and temperate climate is detected by Desprat et al. (2003) from a pollen record for offshore NW Spain for the last 3000 years. Anthropogenic activities in the landscape prevent disentangling the climatic signal (deforestation, pastoral activities, agriculture).	Cooling trend is observed in North Atlantic climate records (van Geel et al., 1996) while an arid period is detected at a global scale between 3500–2500 cal. yr BP (Mayewski et al, 2004).
8700-4650 Middle Holocene	Increase of Fe, K and Si (together with clay and quartz) and decrease of organic-rich layers. Diatom assemblage dominated by benthic types and fragilarioids, epiphytes and taxa associated with littoral habitats. Presence of the ostracod *Candona neglecta* indicating more saline conditions.	Increase of *Anabaena* percentages and *Glomus*, indicating more xeric conditions and an erosive phase. Increase of *Juniperus* type, riparian taxa (as a possible consequence of a drop of the lake level), hydro-hygrophytes and ferns pointing to the existence of a drier trend during the Mid-Holocene.	Dry situation recorded in N Iberia (e.g. Muñoz Sobrino et al. 2004; Santos et al. 2000). Cooling trend detected in the Bay of Biscaye (Naughton et al., 2007a)	Shift towards drier conditions likely forced by the orbitally-driven decrease of seasonality (Wanner et al. 2008). End of the African Humid Period and of the S1 sapropel deposition (deMenocal. et al., 2000).
11,600-8700 Early Holocene	High lake level and increase in the percentage of carbonates (TIC %, Ca values) and organic matter. CO_2-rich groundwater due to the soil formation. *P. villosa* and *C.* cf. *candida* occur together suggesting more precipitation and dilute waters.	Increase of mesophytes, decrease of *Juniperus* type, minimum percentages of *Anabaena* and disappearance of Type 16C. Increase in rainfall after 9750 cal. yr BP indicated from the high percentages of *Corylus*, (co-dominance with deciduous *Quercus*).	Warmer and wetter conditions in N Spain (e.g. Naughton et al., 2007b; Peñalba et al., 1997; González-Sampériz et al., 2006, 2008; Morellón et al., 2008). *Optimum* at ≈ 9 kyrs	Improved climate conditions in terms of temperature and increase in effective moisture (Roberts et al. 2004) as a result of insolation forcing and consequent ice-sheet retreat.
13,500-11,600 ≈ Younger Dryas	Low lake level and low lacustrine productivity (low TOC, no diatoms or ostracods). Low carbonate content as a consequence of low CO_2 dissolved in groundwater due to scarce soil development in an open landscape with low AP proportions.	Grassland dominates. AP reaches minimum values (*Pinus*, *Betula*). Highest proportions of steppe taxa (*Artemisia*, Compositae, *Juniperus*). *Anabaena* maximum and *Glomus* presence imply low lake water levels and erosive processes. Deciduous and evergreen *Quercus, Corylus* & *Fagus* present (refuges).	Colder temperatures (SST offshore Oporto about 10ºC lower than present-day, de Abreu et al., 2003) and decrease of precipitation in northern Spain (e.g. Naughton et al., 2007b; Peñalba et al., 1997) and southern France (Genty et al., 2006).	Weakening of meridional overturning likely due to freshwater input (McManus et al., 2004). Cold and dry conditions in Europe as a result of increased westerly winds (Brauer et al., 2008)

Figure captions

Figure 1. Geographical setting and location of the core from Lago Enol. Maps of the Iberian Peninsula and Asturias are included to indicate the location of the study area.

Figure 2. Chronological model of the studied sequence, based on a mixed effect regression function (Heegaard et al. 2005) of seven AMS ^{14}C dates (the dashed line framed by continuous lines indicates the dating error). Radiocarbon dates obtained from organic remains (charcoal or terrestrial plant macrorests) are indicated by (M). Averaged linear sedimentation rate (LSR) for each unit are shown together with the sedimentological units and climatic intervals.

Figure 3. Sedimentary facies, magnetic susceptibility (SI units) and bulk density (g/cm^3) for core ENO04-1D-1K, measured by GEOTEK, sediment lightness (L*), percentage of total inorganic carbon (TIC) and total organic carbon (TOC), and the main X-ray fluorescence data (Si, K, Ca, Mn, Fe). The percentages of carbonates, clays and quartz obtained from XRD and the X-ray image are also plotted. Vertical scale is in cm. The available dates and the correlation with pollen zones are indicated.

Figure 4. Synthetic pollen percentages diagram from core ENO04-1D-1K (Lago Enol). Exaggeration is 5%. The available dates and pollen zones are indicated, together with the sedimentological subunits.

Figure 5. Summary diatom diagram for the upper 56 cm of core ENO04-1D-1K (Lago Enol). Only selected taxa are shown (taxa representing > 1%). Correlation with pollen subunits is indicated.

Figure 6. Relative ostracod percentages in the upper 150 cm of core ENO04-1D-1K (Lago Enol). Correlation with sedimentological and pollen subunits is indicated.

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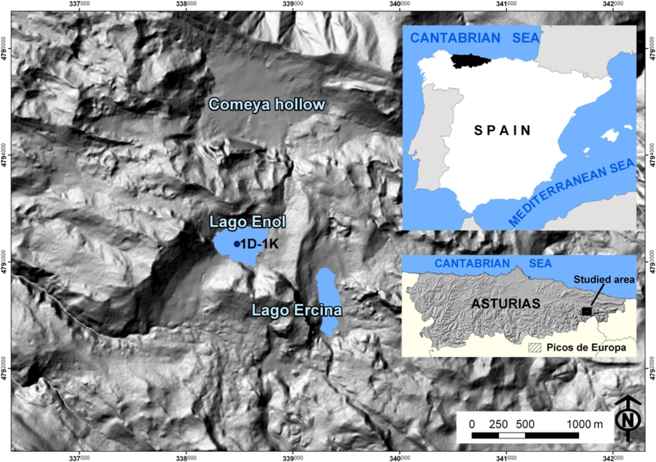
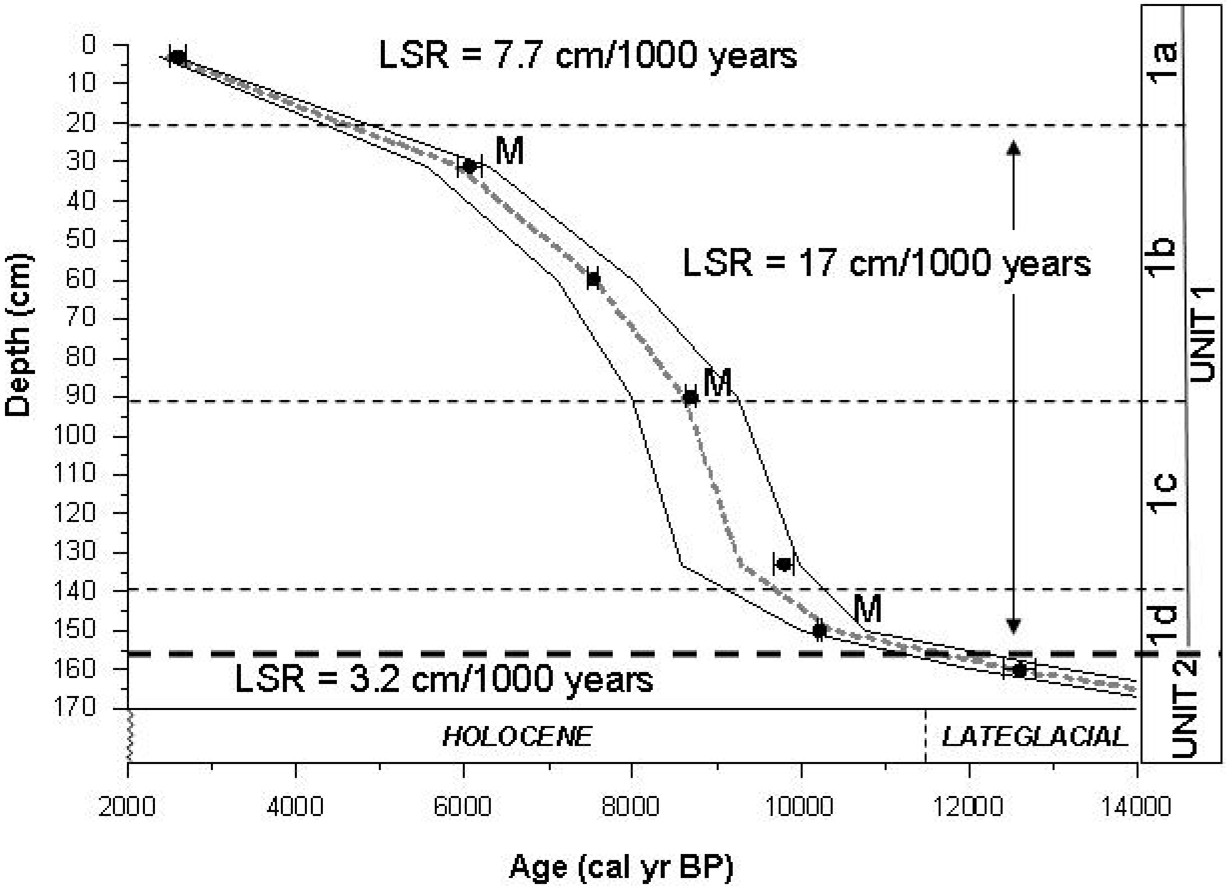
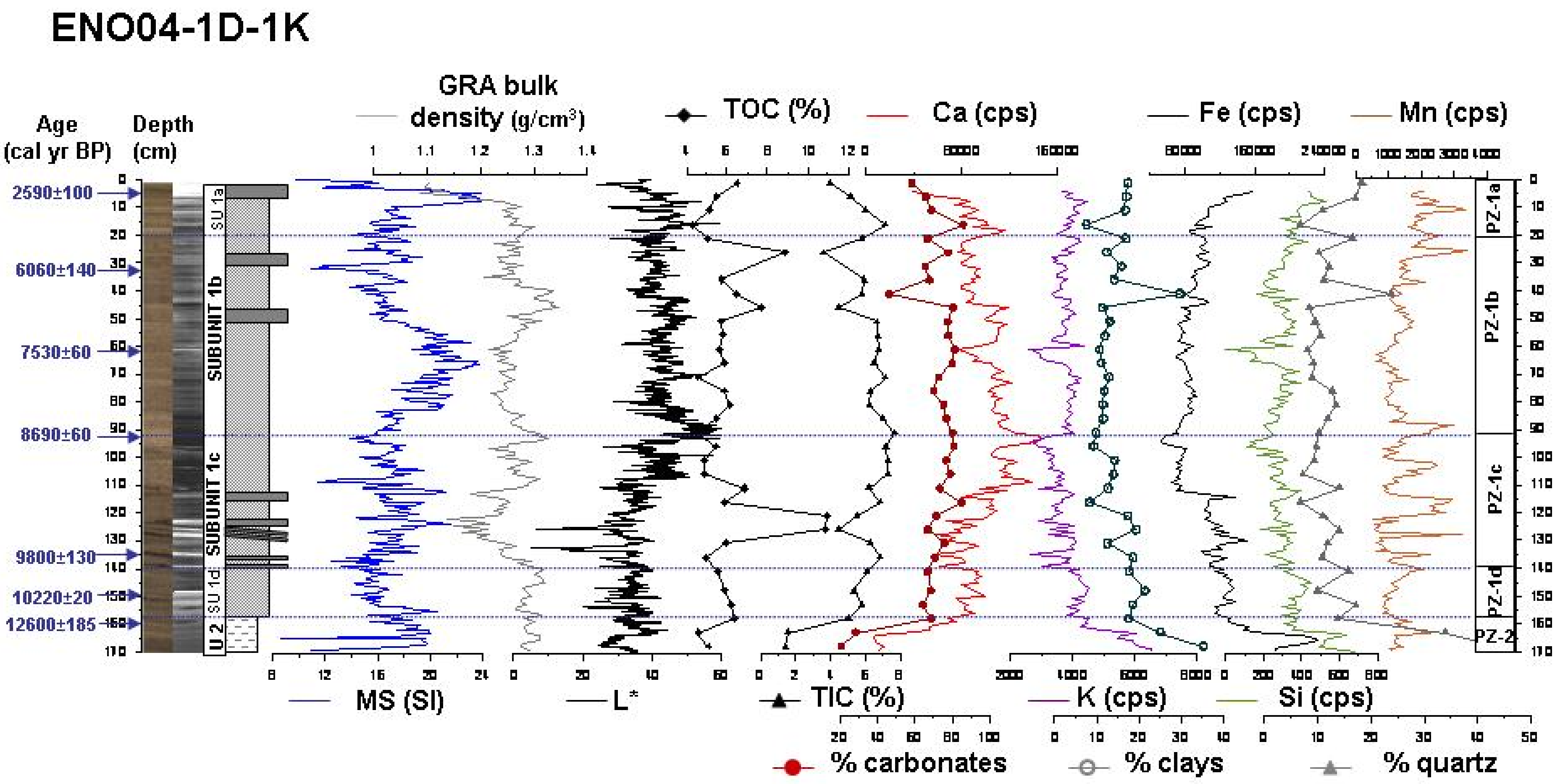

337000
338000
339000
340000
341000
342000
4795000
4794000
4793000
4792000
Comeya hollow
Lago Enol
1D-1K
Lago Ercina
CANTABRIAN SEA
SPAIN
MEDITERRANEAN SEA
CANTABRIAN SEA
ASTURIAS
Studied area
Picos de Europa
0 250 500 1000 m
N



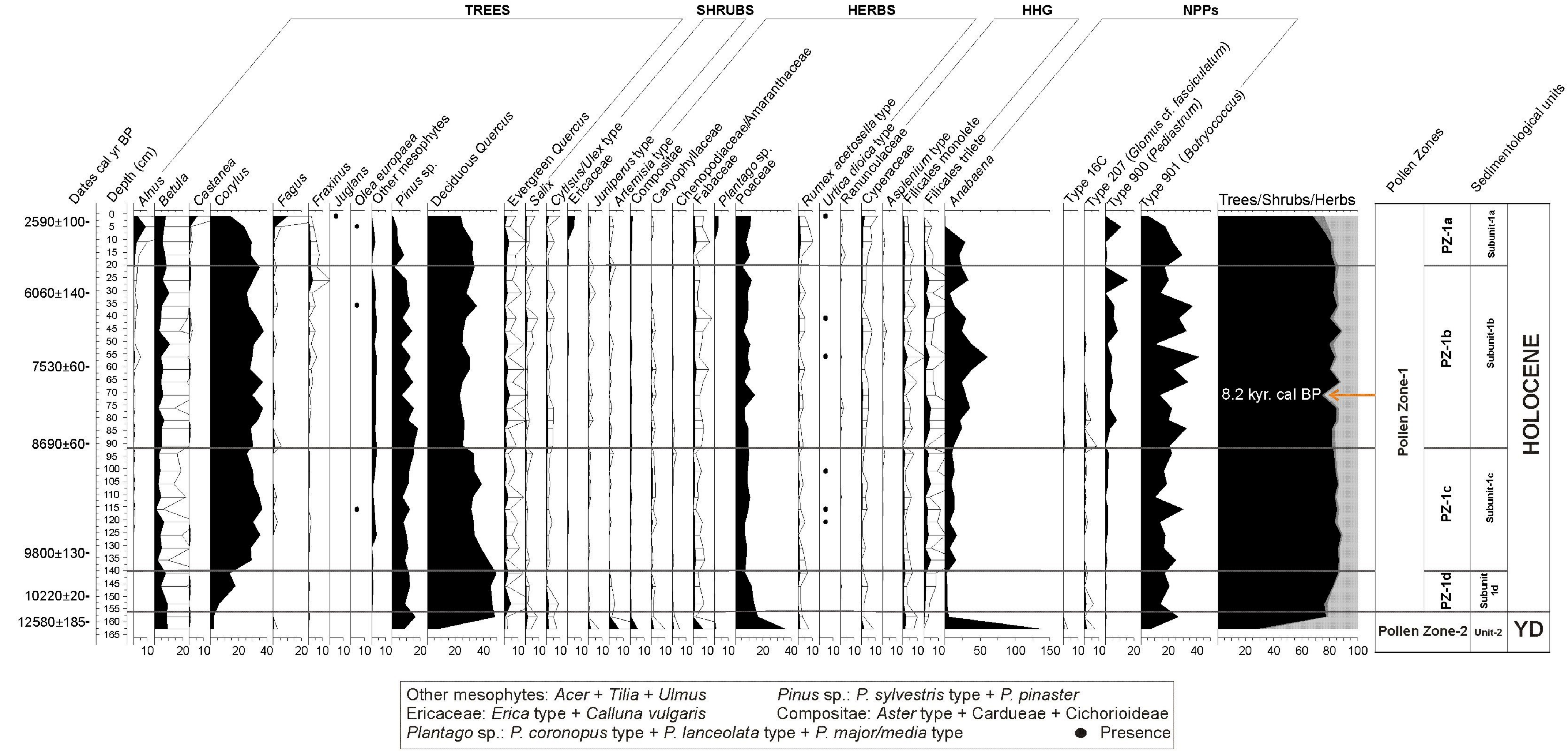
ENO04-1D-1K

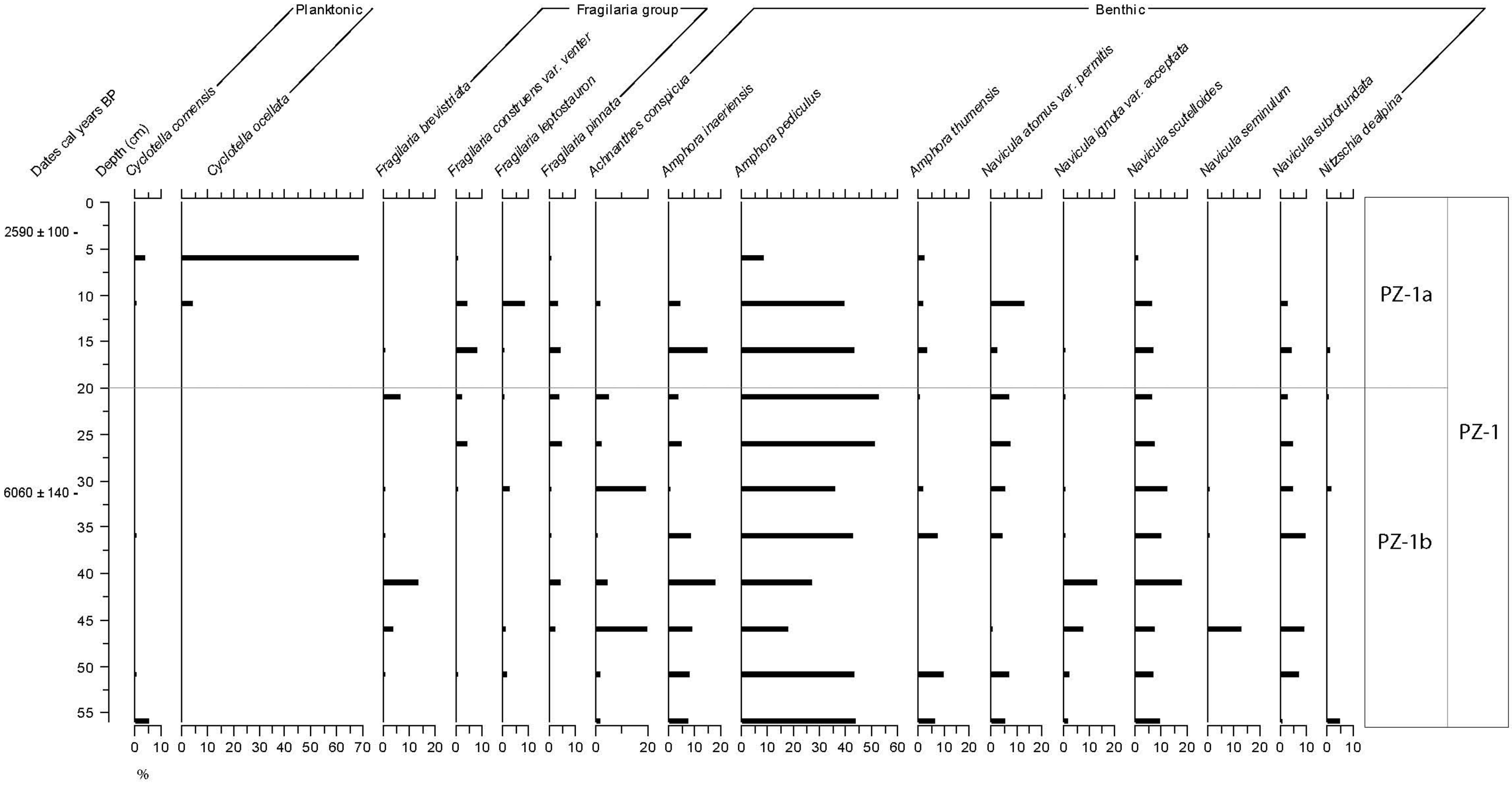
LSR = 7.7 cm/1000 years
LSR = 17 cm/1000 years
LSR = 3.2 cm/1000 years
M
M
M
Depth (cm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
HOLOCENE
LATEGLACIAL
2000
4000
6000
8000
10000
12000
14000
Age (cal yr BP)
1a
1b
1c
1d
UNIT 1
UNIT 2



LEGEND

	Facies description	*Physical properties and carbon content*	*Grain-size*		
			% Clay	% Silt	% Sand
▨	**Facies 1**: Brown to dark brown, massive to faintly banded carbonatic silts to silty-sands.	High MS (≈20 SI); low density; high TIC (4-6%). TOC: 5-6%.	37.69	61.61	0.69
■	**Facies 2**: Dark brown mm-thick laminae composed mostly by macrophyte remains	Lower MS than Facies 1 (≈ 15) but similar density; TIC 4-5% and TOC above 8%, mostly terrestrial plants.	34.04	63.60	2.37
▤	**Facies 3**: Grey massive to faintly banded siliciclastic silty-clay with rare biogenic material	Variable magnetic susceptibility (8-20 SI); low density; TIC: 1-2%; TOC: 4%	52.68	47.33	0.00


TREES
SHRUBS
HERBS
HHG
NPPs
Dates cal yr BP
Depth (cm)
Alnus
Betula
Castanea
Corylus
Fagus
Fraxinus
Juglans
Olea europaea
Other mesophytes
Pinus sp.
Deciduous Quercus
Evergreen Quercus
Salix
Cytisus/Ulex type
Ericaceae
Juniperus type
Artemisia type
Compositae
Caryophyllaceae
Chenopodiaceae/Amaranthaceae
Fabaceae
Plantago sp.
Poaceae
Rumex acetosella type
Urtica dioica type
Ranunculaceae
Cyperaceae
Asplenium type
Filicales monolete
Filicales trilete
Anabaena
Type 16C
Type 207 (Glomus cf. fasciculatum)
Type 900 (Pediastrum)
Type 901 (Botryococcus)
Trees/Shrubs/Herbs
Pollen Zones
Sedimentological units
2590±100
6060±140
7530±60
8690±60
9800±130
10220±20
12580±185
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
135
140
145
150
155
160
165
8.2 kyr. cal BP
PZ-1a
PZ-1b
PZ-1c
PZ-1d
Pollen Zone-1
Pollen Zone-2
Subunit-1a
Subunit-1b
Subunit-1c
Subunit 1d
Unit-2
HOLOCENE
YD
10 20 10 20 40 20 10 10 10 10 20 20 40 10 10 10 10 10 10 10 10 10 10 10 20 40 10 10 10 10 10 10 50 100 150 10 10 20 20 40 20 40 60 80 100
Other mesophytes: Acer + Tilia + Ulmus
Pinus sp.: P. sylvestris type + P. pinaster
Ericaceae: Erica type + Calluna vulgaris
Compositae: Aster type + Cardueae + Cichorioideae
Plantago sp.: P. coronopus type + P. lanceolata type + P. major/media type
● Presence


Planktonic
Fragilaria group
Benthic
Dates cal years BP
Depth (cm)
Cyclotella comensis
Cyclotella ocellata
Fragilaria brevistriata
Fragilaria construens var. venter
Fragilaria leptostauron
Fragilaria pinnata
Achnanthes conspicua
Amphora inaeriensis
Amphora pediculus
Amphora thumensis
Navicula atomus var. permitis
Navicula ignota var. acceptata
Navicula scutelloides
Navicula seminulum
Navicula subrotundata
Nitzschia dealpina
2590 ± 100
6060 ± 140
0
5
10
15
20
25
30
35
40
45
50
55
0 10
0 10 20 30 40 50 60 70
0 10 20
0 10
0 10
0 10
0 20
0 10 20
0 10 20 30 40 50 60
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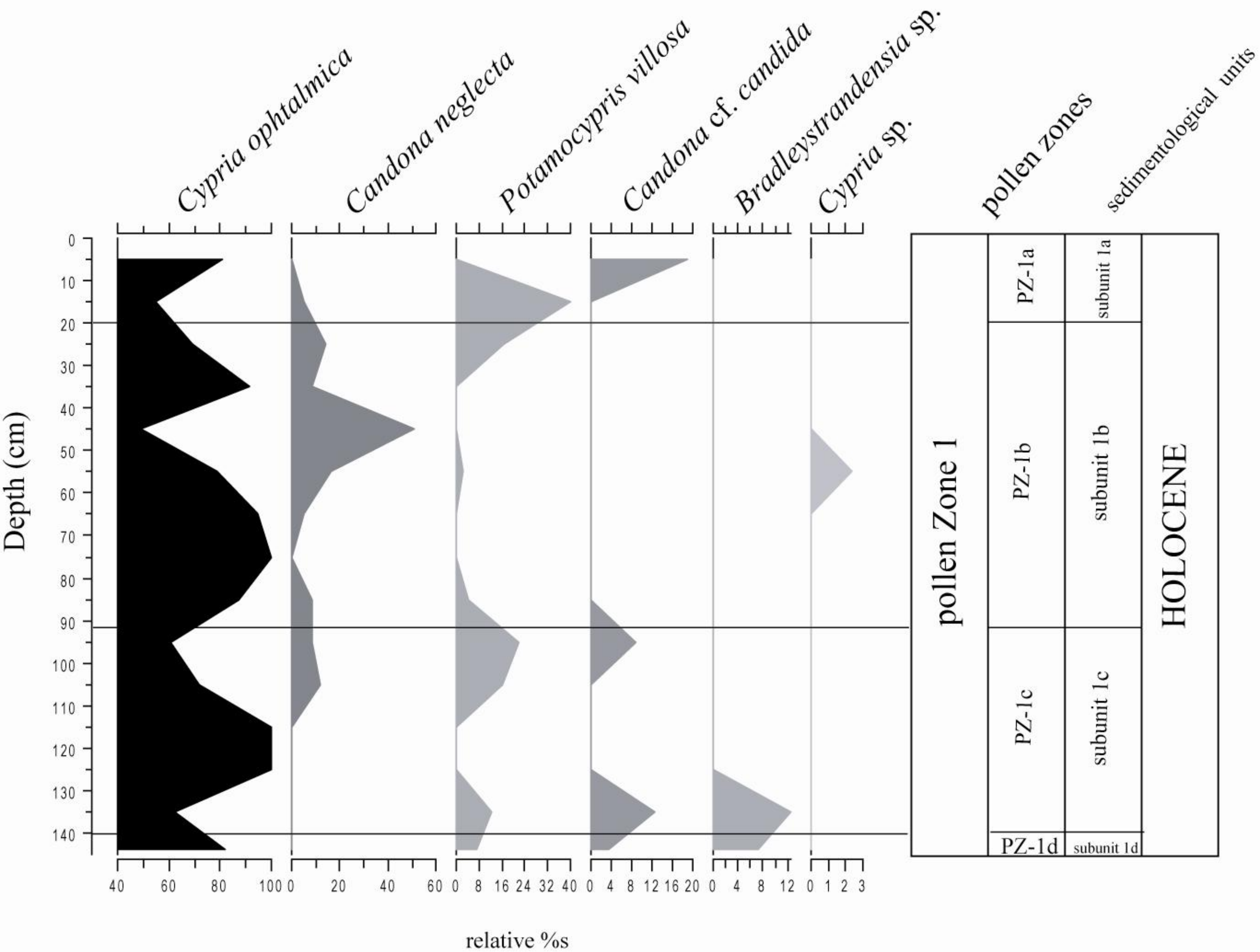
%
PZ-1a
PZ-1b
PZ-1


Cypria ophtalmica
Candona neglecta
Potamocypris villosa
Candona cf. candida
Bradleystrandensia sp.
Cypria sp.
pollen zones
sedimentological units
Depth (cm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
40 60 80 100
0 20 40 60
0 8 16 24 32 40
0 4 8 12 16 20
0 4 8 12
0 1 2 3
relative %s
pollen Zone 1
PZ-1a
PZ-1b
PZ-1c
PZ-1d
subunit 1a
subunit 1b
subunit 1c
subunit 1d
HOLOCENE