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Northern Iberian abrupt climate change dynamics during the last glacial cycle: A view from lacustrine sediments

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ABSTRACT

We present a palaeoclimatic reconstruction of the last glacial cycle in Iberia (ca. 120,000–11,600 cal yrs BP) based on multi-proxy reconstructions from lake sediments with robust chronologies, and with a particular focus on abrupt climate changes. The selected lake sequences provide an integrated approach from northern Iberia exploring temperature conditions, humidity variations and land-sea comparisons during the most relevant climate transitions of the last glacial period. Thus, we present evidence that demonstrates: (i) cold but relatively humid conditions during the transition from MIS 5 to MIS 4, which prevailed until ca. 60,000 cal yrs BP in northern Iberia; (ii) a general tendency towards greater aridity during MIS 4 and MIS 3 (ca 60,000 to 23,500 cal yrs BP) punctuated by abrupt climate changes related to Heinrich Events (HE), (iii) a complex, highly variable climate during MIS 2 (23,500 to 14,600 cal yrs BP) with the "Mystery Interval" (MI: 18,500 to 14,600 cal yrs BP) and not the global Last Glacial Maximum (LGM: 23,000 to 19,000 cal yrs BP) as the coldest and most arid period. The last glacial transition starts in synchrony with Greenland ice records at 14,600 cal yrs BP but the temperature increase was not so abrupt in the Iberian records and the highest humidity was attained during the Allerød (GI-1a to GI-1c) and not during the Bølling (GI-1e) period. The Younger Dryas event (GS-1) is discernible in northern Iberian lake records as a cold and dry interval, although Iberian vegetation records present a geographically variable signal for this interval, perhaps related to vegetation resilience.

1. Introduction

The last glacial cycle (ca. 120,000–11,600 cal yrs BP) was a dynamic period when rapid climate changes, called Dansgaard/Oeschger (D/O) cycles and characterized by abrupt warming and gradual cooling, occurred with a periodicity of ca. 1450 years (Wolff et al., 2010). Understanding the response of different ecosystems to these rapid climatic events is of special interest in the context of present-day global warming but, unfortunately, the mechanism behind rapid climate oscillations, the teleconnections that transfer the signal all around the globe, and the impacts of rapid climate changes on terrestrial and marine ecosystems are still far from being totally understood (Broecker, 2000). In fact, it is known that some of the climate events of the last glacial cycle were not synchronous, such as the timing for the maximum glacier advance at different latitudes (Hughes and Woodward, 2008; Clark et al., 2009), but the causes remain unexplained. In particular, the last glacial-interglacial transition (LGIT, 15,000–9000 cal yrs BP) has a special interest since many processes and components of the climate system were involved in a total restructuring of the climate at a global scale. That transition occurred in several steps, some of them still poorly known in terms of their hydrological signal or internal structure, such as the Mystery Interval (MI) (17.5–14.5 cal kyr BP) (Denton et al., 2006). To address all these questions, it is necessary to assess the synchrony or asynchrony between different records from different archives, and this is one of the foci of INTIMATE (INTegration of Ice-core, MArine and TEerrestrial records) group (Hoek et al., 2008).

The Iberian Peninsula (IP) constitutes a key location for answering questions related to the transference of the climate signal from high- to mid-latitudes. The IP is an especially sensitive region to climate changes due to its location at geographical

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(subpolar *versus* subtropical latitudes) and atmospheric (westerly winds *versus* north-African influences) boundaries (Moreno et al., 2005; Bout-Roumazeilles et al., 2007). In addition, its location leads to the expression of some of the "cold northern events" during last glacial cycle as "dry southern events", as inferred from dust accumulation (Moreno et al., 2002) and pollen composition in marine cores surrounding the IP (Sánchez-Goñi et al., 2002; Fletcher et al., 2010). It remains necessary to evaluate the precise spatiotemporal nature of terrestrial ecosystem change, as suggested by recent lake (González-Sampériz et al., 2006) and speleothem records (Moreno et al., 2010). Understanding the effects of past abrupt climate changes may help to predict and minimize the impact of future global warming (Costanza et al., 2007) in the IP, one of the most vulnerable areas in the context of the Mediterranean region (Solomon et al., 2007).

Iberian terrestrial records, supported by the study of terrestrial tracers (pollen) in marine cores, have allowed the characterization of the response on land to climate change and the discrimination of local or regional signatures, both necessary tasks to complete and improve the palaeoclimate reconstructions carried out in Europe during the last glacial cycle (e.g., Wohlfarth et al., 2008). Additionally, lakes are systems where changes in water availability can be recorded in the sediments in a more direct way than temperature variations (e.g., Cohen, 2003). Thus, the integration of several proxies (physical properties, sedimentary facies, geochemical composition, diatom and pollen assemblages, etc.), can lead to the reconstruction of past lake levels, and thus to the estimation of precipitation-evaporation balance (e.g., Morellón et al., 2009a). Furthermore, other environmental changes such as vegetation cover and land use can be inferred from palynological studies (Morellón et al., in press; Rull et al., in press). Lake sediments can often provide continuous, high-resolution records with robust chronologies, thus providing detailed and comprehensive palaeoenvironmental reconstructions.

The study of Iberian Quaternary lake sequences with the aim of reconstructing palaeoclimatic or palaeoenvironmental conditions is rooted in the long history of sedimentological studies of pre-Quaternary formations (Cabrera and Anadón, 2003; Valero-Garcés, 2003). However, only recently and thanks partly to new technical improvements (both in the field and laboratory) and to the consolidation of new Spanish research groups, has climate reconstruction been tackled using a multi-proxy strategy and robust chronological frameworks. Thus, the number of palaeoclimate studies from lake records in the IP has markedly increased as well as the quality of the records, in terms of their continuity, chronological accuracy, effective temporal resolution and the range of analytical methods combined (Valero-Garcés and Moreno, in press). We consider a review of the key published data timely because, since lake response to climate is non-linear, it is critical to synthesize large data sets to distinguish clearly local influences from broad-scale regional patterns (Fritz, 2008). In addition, we highlight the most critical gaps in the information (in terms of both spatial and temporal coverage) to help plan future research in the IP.

2. Study sites

The purpose of this paper is not an exhaustive compilation of last glacial Iberian lake records but a summary of the most recent work that fulfills the following requisites: (1) the palaeoclimate interpretations are based on multi-proxy reconstructions from lake sediments, including sedimentological description and physical or geochemical data from the lacustrine sequences and not only palynological data as occurs in the case of many well-known studies, and (2) the chronology is independent, robust and accurate, based on calibrated AMS ^{14}C dates, U–Th dating or Optically Stimulated Luminiscence (OSL), if applicable. With the selected records, this study aims to carry out a regional palaeoclimate synthesis (Table 1, Fig. 1) covering the last glacial cycle, since last glacial inception (about 120,000 cal yrs BP) to the onset of the Holocene (11,600 cal yrs BP). Up to now, none of the available climate reconstructions from southern IP lake records spanning the last glacial and deglaciation intervals is based on a multi-proxy strategy. Thus, Padul peatbog from southeast IP is only based on pollen data for

Table 1
Lake records from the IP reviewed in this paper.

	Coordinates	Lake type	Proxies	Chronology	References
Northern Iberia					
1. Enol Lake	43°11′N; 4°09′W; 1070 m asl	Karstic – glacial	PHYS, SED, GEO, BIO, POL	38–2.5 cal kyr BP	Moreno et al. (in press-a)
2. Comella Hollow	43°16′N; 4°59′W; 850 m asl	Karstic – glacial	SED, GEO	Base at 42 cal kyr BP	Jiménez Sánchez and Farias (2002)
West-Northwestern Iberia					
3. Sanabria Lake	42°07′N; 6°42′W; 1000 m asl	Glacial	PHYS, SED, GEO, BIO	25–0 cal kyr BP	Rico et al. (2007)
Iberian range and Central Iberia					
4. Laguna Grande	42°02′N; 3°01′W; 1500 m asl	Glacial	SED	20–0 cal kyr BP	Vegas (2007)
5. Fuentillejo maar	38°56′N; 4°3′W; 635 m asl	Volcanic	SED, GEO, POL	700–0 cal kyr BP	Vegas et al. (in press) for last 50 cal kyr BP
6. Laguna del Hornillo	41°58′N 2°0′W	Glacial	SED	27–0 cal kyr BP	Vegas (2006)
Pyrenees and Northeastern Iberia					
7. Banyoles Lake	42°07′N; 2°45′E; 173 m asl	Karstic	SED, GEO, POL	30–5 cal kyr BP	Pérez-Obiol and Julià (1994), Valero-Garcés et al. (1998)
8. Villarquemado palaeolake	40°30′N; 1°18′W; 987 m asl	Tectonic depression	SED, GEO	120–0 cal kyr BP	Valero-Garcés et al. (2007)
9. El Portalet peatbog	42°48′N; 0°23′W; 1980 m asl	Glacial	SED, GEO, POL	33–5 cal kyr BP	González-Sampériz et al. (2006)
10. Saladas de Monegros (Salineta, La Playa, Mediana…)	41°28′N; 0°09′W; 350 m asl	Dissolution and aeolian deflaction	SED, GEO, POL	ca 20–0 cal kyr BP	Gonzalez-Samperiz et al. (2008) and references therein
11. Ibón de Tramacastilla	42°43′N 0°23′W; 1640 m asl	Glacial	SED, GEO, POL	30–0 cal kyr BP	García-Ruíz et al. (2003), Montserrat (1992)
12. Estanya Lake	42°02′N; 0°32′E; 670 m asl	Karstic	PHYS, SED, GEO, BIO	20–0 cal kyr BP	Morellón et al. (in press, 2009a)

Proxies: PHYS, physical properties; SED, sedimentological description; GEO, geochemistry; BIO, biological indicators (diatoms, ostracods, quironomids); POL, palynological reconstruction.

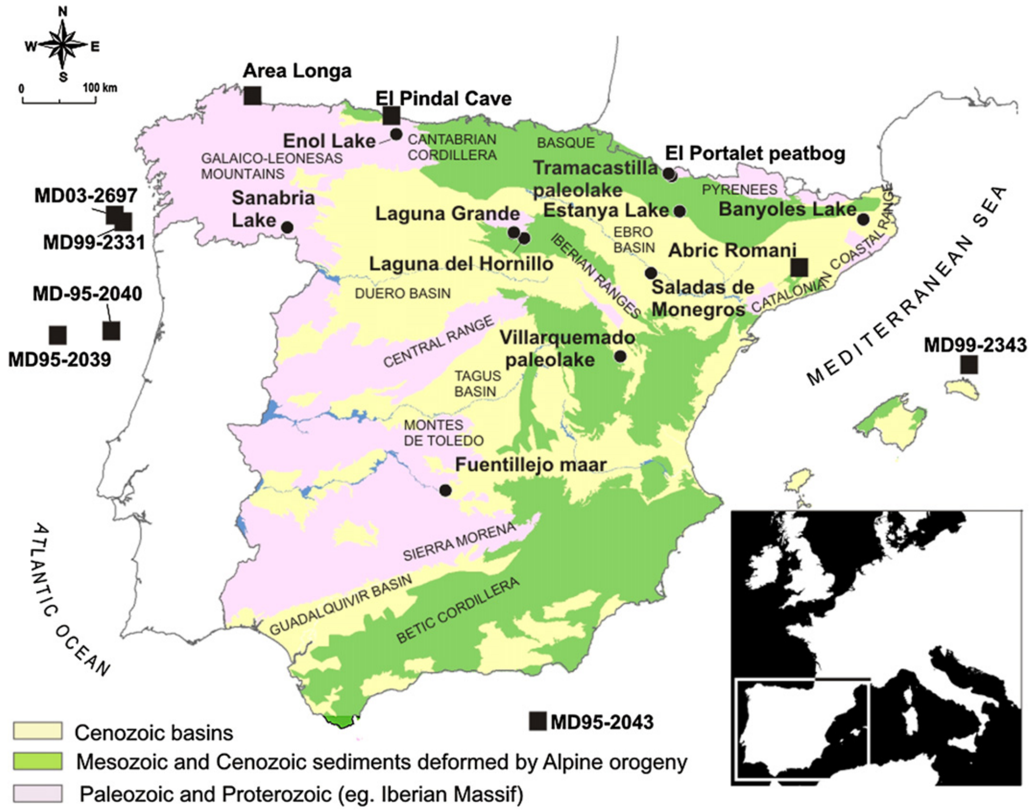

Fig. 1. Outline map of mainland Spain and the Balearic Islands showing the broad division into "Variscan" (pink) and "Alpine" (green) Spain and the Cenozoic basins (light yellow) (modified from Gibbons and Moreno, 2002; Vera, 2004). Lake sites considered in this study are indicated by black circles (see also Table 1) while black squares mark the position of other sites cited in the text (marine, speleothem and pollen sequences). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the glacial interval (Pons and Reille, 1988) and the chronology for this interval is not well constrained in the new 107-m long borehole from the same basin (Ortiz et al., 2004). Other multi-proxy reconstructions from southern IP span only the Holocene or part thereof (e.g., Laguna de Zoñar; Martín-Puertas et al., 2008). As a consequence, the selected records are distributed mostly across the northern IP, with the exception of Fuentillejo maar, which is located in central Spain (Table 1, Fig. 1).

The geology of the IP is remarkably diverse, but, in a simplistic way, can be divided into three main geological units (Gibbons and Moreno, 2002), although their exact boundaries are still under discussion (Vera, 2004): (1) Palaeozoic and Proterozoic rocks forming the Iberian Massif and the basement of other mountain ranges (e.g., Pyrenees); (2) Mesozoic and Cenozoic sedimentary formations affected by the Alpine orogeny, and mostly constituting the Pyrenees, Betics and Iberian Ranges, and (3) large tectonic Cenozoic basins, such as the Ebro or Tagus basins and other small basins located within the Alpine ranges (Fig. 1). Thus, in northern Iberia, the Pyrenees, Cantabrian Cordillera and Galaico-Leones Mountains constitute the most important orographic features while the central IP is crossed by the Central Range, which divides the central plateau in two northern and southern "mesetas". The Iberian Range, which runs north-west to south-east, constitutes the hydrological divide between the Atlantic and Mediterranean watersheds (Fig. 1). Due to the geographic situation and topographic conditions, the climate of the IP is extremely varied, but roughly, a moderate Continental climate characterizes the inland areas, an Oceanic climate dominates in the north and west and a warm Mediterranean climate is experienced along the Mediterranean coast (Capel Molina, 1981). Both geography and climate critically influence the distribution of vegetation and determine the biogeographical features of all the provinces within the Eurosiberian and Mediterranean regions (Blanco-Castro et al., 1997; Rivas-Martínez, 2007) (see also Fig. 1 in González-Sampériz et al., in press).

Unfortunately, the large geological, climatic and biogeographic diversity of the IP is far from being representatively sampled by the selected lake records included in this work (Table 1 and Fig. 1). Some areas remain poorly covered, such as the central region, due to the lack of multi-proxy studies on the scarce lacustrine systems (cf. Fuentillejo maar; Vegas et al., in press), while other environments are over-represented, such as the montane sectors, due to more abundant permanent, deep lakes, which originated during the last deglaciation (e.g., Enol Lake; Moreno et al., in press-a). To cover some of the gaps, other well-known, relatively long records (e.g., Area Longa in the NW; Gómez-Orellana et al., 2007, or Abric Romaní in the NE, Burjachs and Julià, 1994) are included in the discussion despite the fact that they do not fulfill the palaeoenvironmental criteria established above for site selection since they mainly concern vegetation reconstruction. Furthermore, the last glacial cycle is not homogenously represented by the selected records since lake sequences including MIS 4 or MIS 5a–d in the IP are very rare. For these intervals, we support the palaeoclimate discussion with other terrestrial (moraines, speleothems) or marine archives (both represented by black squares in Fig. 1). An exhaustive compilation of pollen records from the IP covering the Pleistocene has been recently published by González-Sampériz et al. (in press). In addition, a new issue of *Journal of Paleolimnology* (Valero-Garcés and Moreno, in press) includes a good compilation of papers based on Iberian lake records, though mostly focused on the Holocene.

3. Methods

An important advance in palaeoclimate reconstruction based on lake records in the IP has been the consistent application of a multi-proxy methodology, following the PAGES strategy and the procedure implemented, among others, by the Limnological Research Center from the University of Minnesota (http://lrc.geo.umn.edu). This procedure starts with the Initial Core Description (ICD) including non-destructive measurement of physical properties (usually carried out by a multi-sensor core logging GEOTEK and including the measurement of magnetic susceptibility -MS-, bulk density, etc.), core splitting into working and archive halves, imaging of the core sections, and macro- and microscopic identification of sedimentary structures and composition using visual and microscopic observations (Schnurrenberger et al., 2001) (Fig. 2). The sedimentological analyses characterize the evolution of the depositional environment of the lake and, in combination with other geological and biological data, allow reconstruction of past climatic variability (Valero-Garcés et al., 2003) (Fig. 2).

Among the geological proxies, the main palaeoindicators used to identify and characterize the sedimentary processes controlling the input, transport and deposition of sedimentary particles, i.e. essential information for understanding the infilling of the lacustrine system are: (1) mineralogical composition, derived from X-ray diffraction analyses; (2) elemental geochemistry, obtained at high-resolution by X-ray fluorescence (XRF) core scanning (Last, 2001) or as discrete samples by other methods (ICP, conventional XRF); (3) concentration of total organic (TOC) and inorganic (TIC) carbon, and (4) stable isotope composition ($\delta^{18}O$ and $\delta^{13}C$) in carbonates or bulk organic matter (Fig. 2). The combined analysis of these proxies provides important information regarding, for example, the input and composition of detrital minerals *versus* the precipitation of endogenic components (Corella et al., in press), or data about the hydrological balance and temperature of lake water (Morellón et al., 2009a). Among the biological proxies used for palaeolimnological reconstructions, the most commonly employed are (1) pollen, (2) diatoms, (3) ostracods and/or (4) chironomids (e.g., Moreno et al., in press-b) (Fig. 2). These indicators provide information related to the type and extension of the vegetation cover (e.g., Carrión, 2002) and also environmental (temperature, precipitation) and limnological (pH, lake level, nutrients, water column mixing) conditions in the lake (e.g., Leira, 2005). The integrated multi-proxy approach in the study of lake sequences is critical for disentangling the different forcings influencing lacustrine systems, an indispensable pre-requisite for robust reconstructions of climatic variability.

The chronology in the selected records was mainly based on the AMS ^{14}C technique and the dates were calibrated for this review using the INTCAL09 calibration curve (Reimer et al., 2009) (see Supplementary Table S1). Additionally, other dating techniques were used, such as U–Th disintegration series in the carbonates from Banyoles record (Pérez-Obiol and Julià, 1994); Optically Stimulated Luminescence (OSL) in Villarquemado palaeolake (Valero-Garcés et al., 2007), and palaeomagnetism excursions in Fuentillejo maar (Vegas et al., in press). Final construction of the age models was carried out by linear interpolation between the obtained dates, except on Enol and Estanya lakes where a generalised mixed-effect regression was used, following Heegaard et al. (2005). Although the records selected for this review are characterized by robust chronological control, some general problems are nevertheless evident (e.g. calibration difficulties for the dates beyond 45,000 years in longer sequences such as Fuentillejo maar,

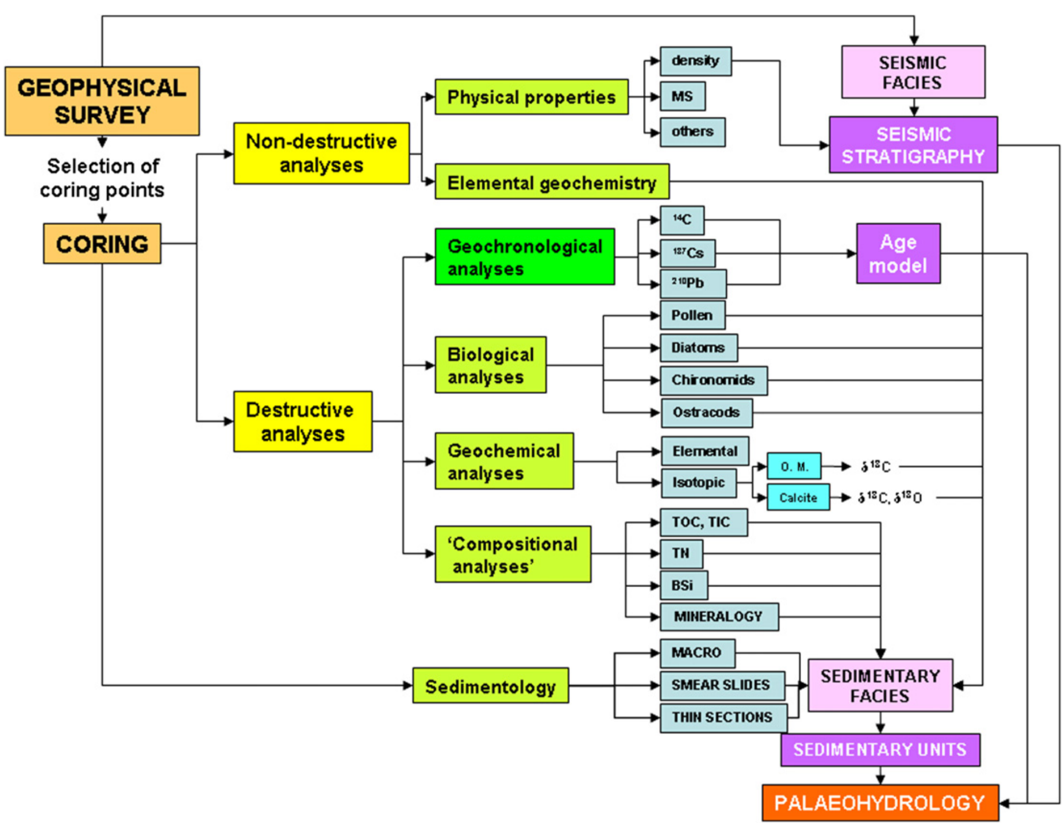

Fig. 2. Flow diagram showing the multi-proxy approach followed in palaeoclimate reconstructions from lake sediments (modified from Morellón, 2009). MS, magnetic susceptibility; OM, organic matter; TOC, total organic carbon; TIC, total inorganic carbon; TN, total nitrogen; BSi, biogenic silica.

scarcity of organic terrestrial remains in glacial lakes such as Enol Lake, etc.) that remain difficult to overcome. However, when necessary, these limitations are discussed in order to avoid misinterpretation of the main climate trends.

4. The Iberian climate reconstruction during last glacial cycle

Very few multi-proxy studies from lake records in the IP cover the time interval from last glacial inception (ca. 120 ka) to the "global LGM".[1] In fact, from Table 1 we can only cite Fuentillejo maar (142.4 m) (Vegas et al., in press) and Villarquemado palaeolake (74 m) sequences, both obtained in present-day dry lakes using a truck-mounted drilling system. Several sequences cover MIS 3 and a larger number includes MIS 2 (Table 1).

4.1. The beginning of last glacial cycle in Northern Iberia (MIS 5 and MIS 4)

The Greenland NGRIP ice core offers an undisturbed record of the last glacial inception and reveals a rapid event, D/O 25, occurring about 115,000 yrs ago when the northern hemisphere ice volume reached about one third of its glacial extent (NGRIP Members, 2004). Mediterranean pollen data show that the interglacial forest environment is preserved during this period (mean percentage of temperate pollen around 40–50%) but also responded to rapid D/O events, indicating that the early glacial millennial-scale variability in Greenland has an European counterpart (Tzedakis et al., 2003; Masson-Delmotte et al., 2005; Sánchez-Goñi et al., 2008). In the IP, the full details of the nature and timing of the onset of last glacial cycle and its possible correlation with other North Atlantic marine records and Greenland ice cores are not fully constrained. The most detailed available information comes from Iberian margin marine records, which yield information about palaeoceanographic conditions and, through pollen analysis and direct land-sea correlation, provide evidence of regional-scale vegetation changes during the last glacial inception (e.g., ODP977/A: Martrat et al., 2004; Pérez-Folgado et al., 2004; ODP976: Combourieu Nebout et al., 2002; MD95-2042: Sánchez-Goñi et al., 1999, 2008; MD99-2331: Sánchez-Goñi et al., 2005; MD04-2845: Sánchez-Goñi et al., 2008). These studies indicate a $\sim 10^{\circ}$ southward displacement of vegetation belts in western Europe as early as ~121 ka as part of continental-scale vegetation changes which may have played a role in triggering the last glaciation (Sánchez-Goñi et al., 2005). Overall, an apparent synchrony with global climate events is shown, both in sea surface temperatures (Martrat et al., 2004) and pollen data (Sánchez-Goñi et al., 2008), reflecting millennial-scale climate variability associated with MIS 5 substages and D/O events 25–19, and following a long-term trend towards a cold and arid glacial scenario.

In the terrestrial realm, the lack of well-dated lacustrine sequences for this period prevents the detailed characterization of the beginning of last glacial period on land and the nature and impacts of rapid climate oscillations. As an example, the available chronology for the Fuentillejo maar record is not yet clear beyond the limits of the ^{14}C method, except for a magnetic reversal at the base that provides evidence of the Matuyama-Brunhes boundary (780 ka) (Vegas et al., in press) and extends the record to at least the beginning of the Middle Pleistocene.

The Villarquemado palaeolake sequence was dated by combining ^{14}C (for the uppermost 20 m) and OSL (for the remaining 52 m) techniques, yielding a basal age of ca. 120 ka, thus covering the period from MIS 5 to present-day (Fig. 3). This record lacks an adequate time control for the interval between 20–48 m (corresponding to ~41.5 ka–72.5 ka). Thus, boundaries between MIS5–MIS4 and MIS4–MIS3 were placed in Fig. 3 on the basis of sedimentary unit boundaries. The Villarquemado sequence is composed of peatbog, alluvial fan and carbonate lake deposits and the basin was likely a variable mosaic of these three depositional environments during its evolution. In this sense, development of a carbonate lake (with high contents of Ca and TIC and lower MS values) represents higher lake levels than a peatbog setting (higher TOC, lower MS) while alluvial fan deposits (lower carbonate and TOC content, higher MS) represent the lowest lake levels in the basin. Thus, in the Villarquemado sequence, TOC values are higher during the Holocene (Unit I, 0–3 m) and MIS 5 (Units VI and VII, 37–74 m) (Fig. 3) with the most significant development of wetlands of the whole sequence, characterized by the alternation of peatbog and shallow carbonate lake environments. A significant depositional change in the basin is recorded at the onset of MIS 4, with the retreat of the wetlands and the progradation of the distal alluvial fans indicative of a tendency towards lower lake levels (Unit V, 29–37 m, Fig. 3).

Other Iberian records based on pollen data also show large changes at the onset of the last glacial cycle. In the NW IP, the Area Longa sequence, recovered from a beach cliff, spans the interval from MIS 5c to MIS 3 (Gómez-Orellana et al., 2007) (Fig. 1). The base of this pollen record (ascribed to MIS 5c, corresponding to St. Germain I phase) is dominated by deciduous woodland (*Alnus*, *Quercus robur* type, *Corylus*, *Betula* and *Carpinus*) with high proportions of *Fagus*. During MIS 4, high percentages of *Erica*, *Calluna* and Poaceae indicate heath and temperate grassland as the predominant vegetation types with a low abundance of conifers and persistence of meso-thermophytes such us *Quercus robur* type, *Corylus*, *Fagus*, *Carpinus*, *Ulmus* and *Ilex*. The authors' interpretion is that while the NW IP was affected by cooling that occurred globally during MIS 4, its climate continued to be relatively humid, mostly based on the high Ericaceae and Poaceae percentages and the low steppe taxa values (*Artemisia*, Chenopodiaceae) that dominate the herbaceous component. In NE Spain, the Abric Romaní travertine rock shelter provides palaeobotanical information for the interval 70,000–40,000 years BP (Burjachs and Julià, 1994) (Fig. 1). Tree pollen percentages in the oldest deposits (attributed to MIS 5a) reach 40–60%, dominated by pines but with a continuous presence of *Juniperus, Rhamnus, Quercus, Olea-Phillyrea, Betula, Fagus, Pistacia* and other mesothermophilous taxa. The transition to MIS 4 represents a cold but humid phase with less thermophilous taxa (Burjachs and Julià, 1994).

Therefore, up to now and until more data from Villarquemado palaeolake are available, we can summarize from the scarce available terrestrial records covering MIS 5 to MIS 4 that a consistent climatic change was observed across the IP in terms of temperature, with cooling after ca. 65,000 cal years BP. In contrast, patterns of moisture availability appear more variable, as detected from marine pollen data. Thus, records from the northern and northwestern margins of the IP indicate cool, humid conditions promoting the development of Ericaceae and conifers during MIS 4 (e.g., MD04-2845 and MD99-2331 marine cores: Sánchez-Goñi et al., 2005, 2008, respectively), while records from the southern margins indicate drier conditions, with greater development of semi-desert vegetation (e.g., MD95-2042 and ODP site 976, reviewed in Fletcher et al., 2010). At all sites, however, a trend of

[1] We will use the term "global LGM", according to EPILOG (Environmental Processes of the Ice Age: Land, Oceans, Glaciers, http://www.glacialoceanatlas.org/index.php?option=com_content&view=artilcle&id=55&itemid=2) project, for the period from 23,000 to 19,000 yrs BP that refers to the time of maximum extent of the ice sheets during the last glaciation – the Würm or Wisconsin glaciation (Mix et al., 2001). In Iberian Peninsula, the time of maximum glacier extension does not correspond to the global LGM.

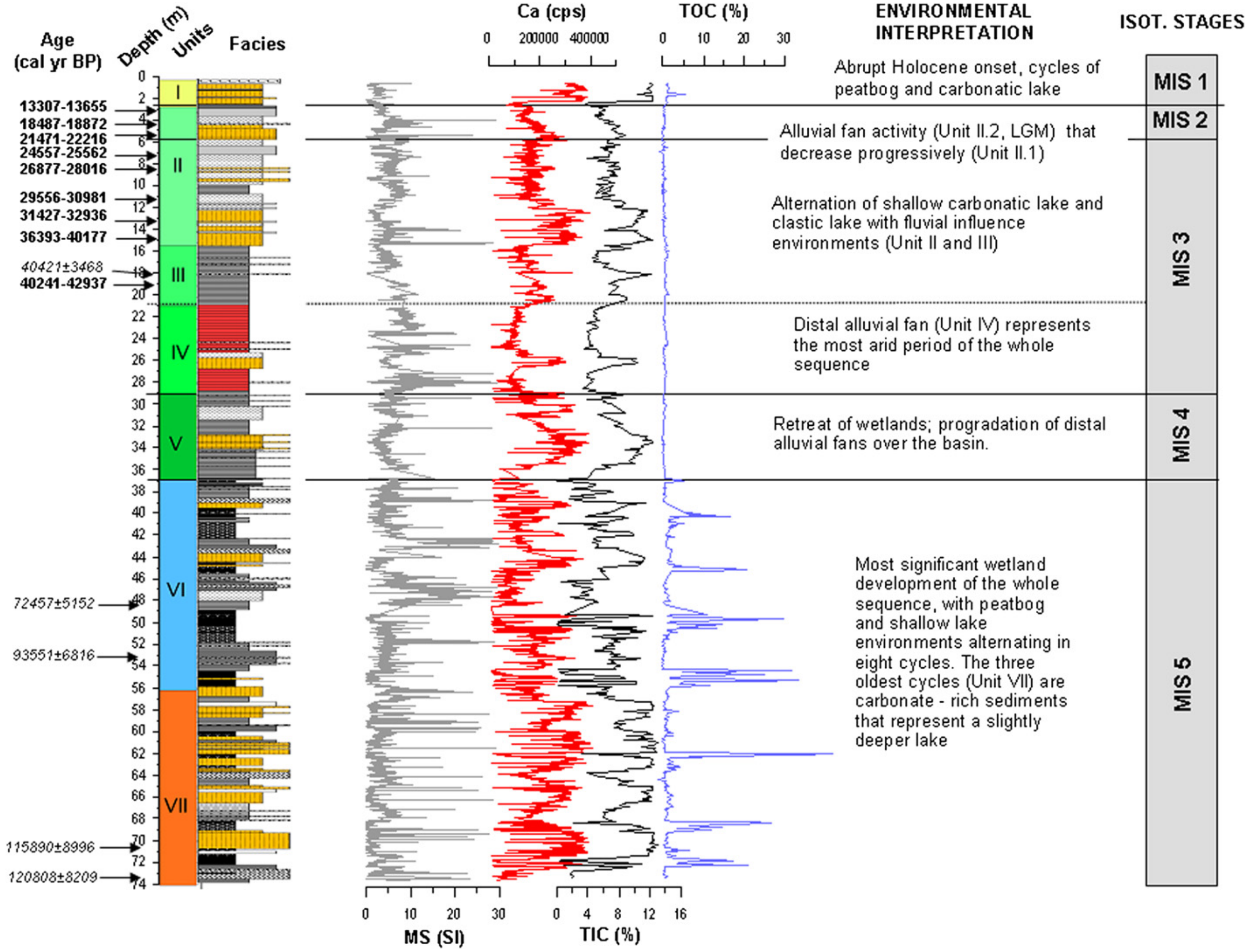

Fig. 3. Sedimentary sequence for Villarquemado palaeolake record. From left to right: sedimentary units and sedimentological profile, magnetic susceptibility (MS) (in SI units), Ca (in counts per second units) measured by the X-ray Fluorescence (XRF) core scanner, and TIC (total inorganic carbon) and TOC (total organic carbon) percentages. An interpretation of the inferred depositional environments for each unit is presented together with the preliminary chronology (marine isotope stages – MIS – from 5 to 1). Available AMS ^{14}C (in bold type) and –OSL dates (in italics) are shown to the left.

gradually increasing aridity over the MIS 4 interval is apparent (Sánchez-Goñi et al., 2008; Fletcher et al., 2010).

Glacier records from the Central Pyrenees (García-Ruíz et al., 2003; Pallàs et al., 2006; Lewis et al., 2009) provide coherent support for the prevalence of relatively humid conditions at the transition between MIS 5 and MIS 4 in northern IP. Thus, the most external moraines in the Spanish Central Pyrenees are dated by OSL at 85 ± 5 ka (Peña et al., 2003; Lewis et al., 2009), placing the timing of the "Iberian last glacial maximum" close to the transition between MIS 5 and MIS 4 (García-Ruíz et al., 2010). This scenario of cold temperatures, significant humidity across the northern IP, and a gradual decline in humidity across MIS 4, may partly underline why the timing of maximum extent of other Mediterranean glaciers is much earlier than the global LGM (see a review in Hughes and Woodward, 2008). Besides the asynchrony in the maximum ice extent, there is also a discrepancy in the timing of last deglaciation, which appears to have occurred earlier in the Pyrenees (García-Ruíz et al., 2003; Pallàs et al., 2006; Lewis et al., 2009) and the Cantabrian mountains (Jiménez Sánchez and Farias, 2002) than in other European mountains. An explanation for this early glacier retreat may be found in the abrupt climate changes that occurred later, during MIS 3.

4.2. The record of rapid climate cycles in lake sediments (MIS 3)

Since the study carried out by Lebreiro et al. (1996), where the first evidence of Heinrich layers was found in marine sediments offshore Portugal, many other records, mostly from marine cores, have highlighted abrupt fluctuations in the Iberian climate during MIS 3 synchronous with HE and D/O cycles (e.g. Cacho et al., 1999; Frigola et al., 2008). From the palynological study on marine cores, it is now accepted that those fluctuations also produced important changes on land, mostly via changes in water availability and temperature that could have a great impact on vegetation cover (Sánchez-Goñi et al., 2000, 2002, 2008; Roucoux et al., 2001, 2005; Combourieu Nebout et al., 2002, 2009; Fletcher and Sánchez-Goñi, 2008; Naughton et al., 2009; Fletcher et al., 2010). In addition, other terrestrial tracers measured on marine sediments, such as indicators of fluvial and aeolian activity (Moreno et al., 2002, 2005; Bout-Roumazeilles et al., 2007; Frigola et al., 2008), also point to millennial-scale D/O fluctuations in IP aridity (Fig 4). Recent high-resolution studies detected a two-phase hydrological pattern for some HE in a marine core offshore Galicia (Naughton et al., 2007) which has been subsequently confirmed by a speleothem record from northern Iberia (Moreno et al., 2010).

In contrast to the relatively high number of marine records covering this time interval, lake sequences from the IP covering MIS 3 and demonstrating a response on land to rapid climate oscillations are scarce. In fact, even considering lacustrine records at a European scale, the lake sequences where D/O cycles have been clearly observed and dated are limited (e.g., Allen et al., 1999; Wohlfarth et al., 2008). Considering that lakes are very sensitive ecosystems to small environmental changes, why are MIS 3 climate fluctuations not more clearly recorded? The most plausible explanation is that sampling resolution has generally not been high enough, limited in some cases by low glacial sedimentation rates and compounded by the difficulties of constructing accurate chronologies for this time period (i.e., the ^{14}C method is close to its maximum limit and, additionally, lake sediments, particularly from proglacial lakes, are characterized by low organic content during this interval thus restricting even more the dating potential (Moreno et al., in press-a)). Although laminated records from karstic lakes will probably provide better candidates (with more robust chronologies supported by counting annual laminae and higher sedimentation rates permitting the detection of abrupt changes), there is no record in the IP studied up to now with such features.

In the Villarquemado palaeolake, the aridity trend that started during MIS 4 continued and peaked during the lower part of MIS 3

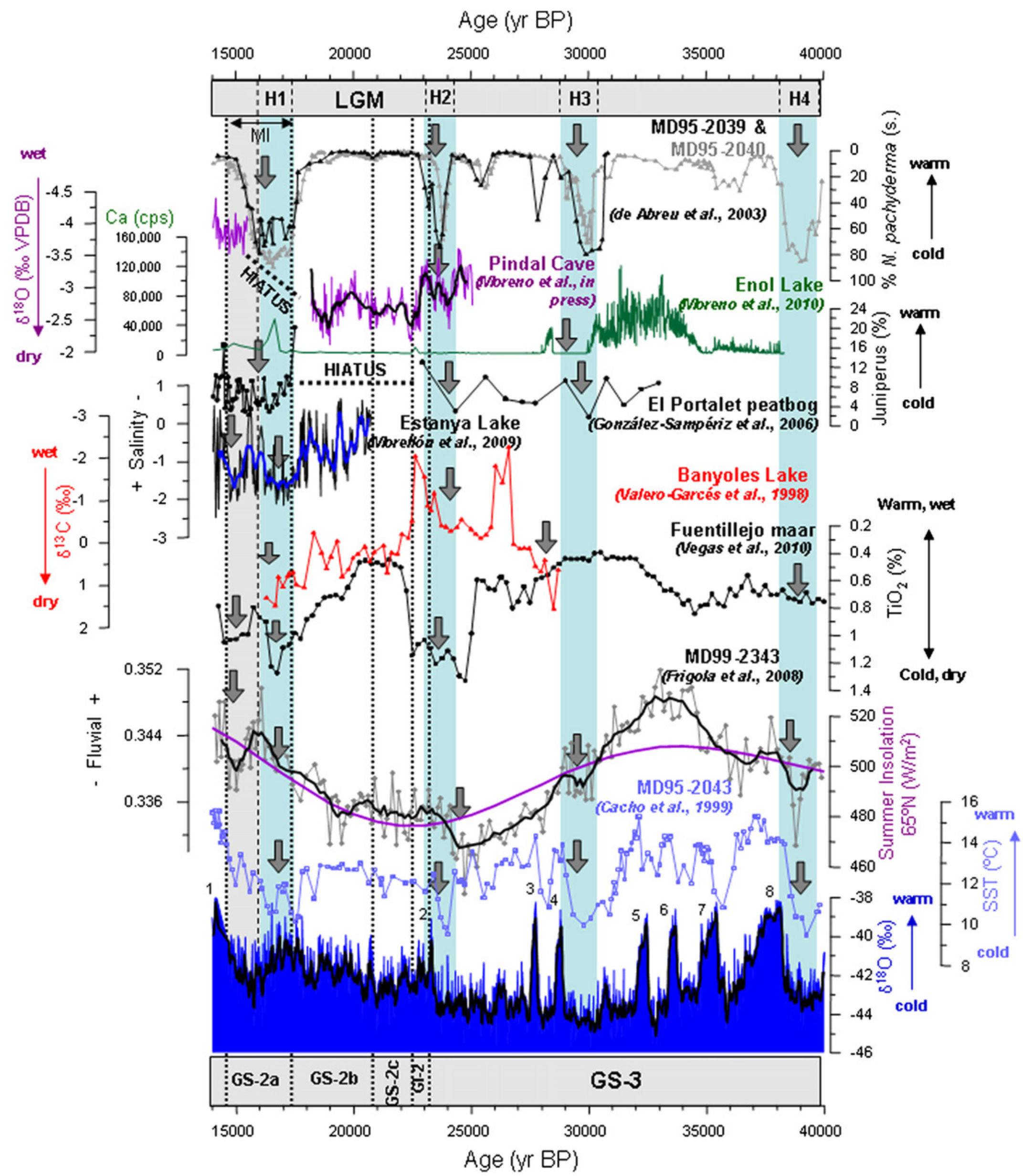

Fig. 4. Selected marine and terrestrial records from the IP covering GS-2 and GS-3. From up to down: (%) of *N. pachyderma* (sinistra) from MD95-2039 and MD95-2040 cores offshore Oporto, Portugal (de Abreu et al., 2003); $\delta^{18}O$ (‰ VPDB) from El Pindal cave (Moreno et al., 2010); Ca (cps) profile from Enol Lake (Moreno et al., in press-a); (%) *Juniperus* from El Portalet peatbog (González-Sampériz et al., 2006); reconstructed salinity from Estanya Lake (Morellón et al., 2009a); $\delta^{13}C$ (‰ VPDB) from Banyoles Lake (Pérez-Obiol and Julià, 1994; Valero-Garcés et al., 1998); (%) TiO_2 from Fuentillejo maar (Vegas et al., in press); reconstructed fluvial activity from MD95-2343 record (Frigola et al., 2008); summer insolation at 65°N; SST (°C) from MD95-2043 record (Cacho et al., 1999) and NGRIP $\delta^{18}O$ (‰ VSMOW) record from Greenland (Rasmussen et al., 2006) and smoothed with a 5-point moving average (thicker line). DO-I are labelled from 1 to 8. Shaded bands indicated the amplitude of HE, positioned following the record of *N. pachyderma* (sinistra) from MD95-2039 and MD95-2040 cores (de Abreu et al., 2003).

(Unit IV, 21–29 m; Fig. 3) where sedimentological evidence for ephemeral lake conditions (dolomite formation, red, oxidized fine sediments) is present. After around 40,000 cal yrs BP, an alternation of shallow carbonate lake deposits and distal clastic alluvial fan materials reflect rapid hydrological and climate fluctuations during MIS 3, although the ascription to individual events is still not possible with the available chronological model. More dates throughout the MIS3 interval and the palynological study of the whole sequence, currently in progress, will aid the detection of MIS 3 variability. Although dating uncertainties are high in the Fuentillejo maar record from central IP (Table 1, Fig. 1) due to linear interpolation between very few dates (6 AMS ^{14}C dates for the last 50,000 years), several fluctuations ascribed to HE and other stadials of the D/O cycles have been identified and interpreted as arid periods (Vegas et al., in press). Based on the combination of several proxies (sedimentology, geochemistry, pollen, etc.), HE5 and HE3 have been identified as relatively warm periods while HE4, 2 and 1 were significantly colder (TiO_2 percentage is plotted in Fig. 4 as a proxy for dry/cold conditions). The authors refer to regional processes as the cause of modifications in the intensity and persistence of these rapid climate oscillations (Vegas et al., in press).

The site that provided initial clues about MIS 3 climate fluctuations in the IP is the Banyoles pollen record, first published by Pérez-Obiol and Julià (1994). A later study of sedimentary facies and stable isotopes on charophytes from the same littoral core reveals impacts on the sediments of HE 3 and 2 that are interpreted as dry periods characterized by lower lake levels (Valero-Garcés et al., 1998) (Fig. 4). Besides Banyoles, other locations in the northern IP, notably El Portalet peatbog and Enol Lake (Table 1, Fig. 1), responded to the arid and cold conditions of HE3 and HE2 (González-Sampériz et al., 2006; Moreno et al., in press-a) (Fig. 4). Particularly clear is the record of El Portalet peatbog where an increase in steppe taxa and a decrease in *Juniperus* frequencies, together with a more abundant siliciclastic component in the sediments, occurred during cold and arid phases associated with rapid events of climate change (González-Sampériz et al., 2006).

Dating the base of sedimentary sequences obtained from proglacial lakes or glaciolacustrine deposits has provided useful information for reconstructing the deglaciation stages in the Spanish mountains during MIS 3 (González-Sampériz et al., 2005). There are four noteworthy proglacial lake records that support an early deglaciation: (1) a basal age of 32.5 ka from El Portalet peatbog at 1802 m a.s.l. (González-Sampériz et al., 2006); (2) a basal age of around 33.9 ka from Tramacastilla glacial lake at 1640 m a.s.l. (García-Ruíz et al., 2003; Pallàs et al., 2006; Lewis et al., 2009), both located in the Pyrenees; (3) a basal age of 38 ka from Lago Enol in the Cantabrian Mountains at 1075 m a.s.l. (Farias-Arquer et al., 1996; Moreno et al., in press-a); and (4) a basal age of 25.5 ka from Lago de Sanabria in NW Spain at 997 m a.s.l (Rico et al., 2007). All these ages postdate glacier activity in the area and, since the lakes are located at or close to the headwaters of the different basins, and behind terminal moraines, it means that the glaciers had already retreated to their cirques or very close to them by 40–30 ka.

Although several hypotheses have been postulated, up to now a satisfactory explanation for the early glacier retreat has not yet been found (Gillespie and Molnar, 1995). However, it seems clear that it was related to the high sensitivity of Mediterranean mountain glaciers to climate changes resulting from their distinctive characteristics such as their geographical location and their smaller size (Hughes and Woodward, 2008). Recently, García-Ruíz et al. (2010) have proposed that the sustained increase of the Scandinavian *inlandsis* between 80 and 55 ka BP (Svendsen et al., 2004) had parallels in the Mediterranean mountains, with rapid glacier growth that lead to maximum ice extension of some of the glacier tongues approximately at the transition from MIS 5 to MIS 4. Later on, during MIS 3, and due to the well-known abrupt climate fluctuations associated with the D/O cycles, the Scandinavian *inlandsis* may have stabilized thanks to its larger inertia, but the Mediterranean glaciers may have experienced a noticeable retreat during warm events. It is interesting to note that the Villarquemado record also points to more humid conditions during MIS 4 and MIS 2 than during MIS 3 (Fig. 3), coherent with higher long-term moisture availability in the IP as a pre-requisite for glacier advances.

More records from lakes and glacier evolution and an increased effort on dating, possibly combining dating techniques (^{14}C, OSL), are necessary to go further in the identification of the effects on land of rapid climate changes during MIS 3.

4.3. From the global LGM to the Holocene onset (MIS 2/GS-2)

The global LGM can be defined as the most recent interval when global ice sheets reached their maximum integrated volume during the last glaciation (Mix et al., 2001). However, as we noted above, the glacier advance associated with the global LGM may be of smaller magnitude for Mediterranean, and particularly Iberian glaciers, than that which occurred during MIS 4 (García-Ruíz et al., 2010). The period since the global LGM to the Holocene onset (GS-2, GI-1 and GS-1 in the INTIMATE nomenclature; Lowe et al., 2008) is well-represented in many marine records surrounding the IP (e.g., Cacho et al., 2001; Jiménez-Espejo et al., 2007; Naughton et al., 2007; Combourieu Nebout et al., 2009; Fletcher et al., 2010), and it appears as a period with high variability, including events of abrupt climate change such as HE2 and HE1 and rapid climate fluctuations during LGIT (GI-1, GS-1). Additionally, many Iberian lake records (see Table 1, Figs. 4 and 5) cover this time interval and can provide some answers to questions about the nature, timing, regional particularities and spatial variability of the main climate changes in the IP since global LGM.

4.3.1. Was the global LGM the coldest and driest interval of MIS 2 in the IP?

One of the most important questions to be addressed in relation to climate variability in the IP is the signal on land of the global LGM (GS-2b). Although it is now evident that the global LGM does not correspond in most Iberian mountains to the maximum glacier extension (Lewis et al., 2009), was that period the coldest interval of the last ca. 25,000 years? Was it relatively wet or dry? Marine records from Iberian margins indicate that the global LGM, although undoubtedly cold, was not the coldest interval in the marine realm (e.g., Alboran Sea, Cacho et al., 1999; Portuguese margin, de Abreu et al., 2003) (Fig. 4). In contrast, HE1 (dated about 16,000 years BP) is generally marked by the highest percentages of cold foraminifer *Neogloboquadrina pachyderma (s)*, the highest values of IRD, or the lowest SST reconstructed for the last 23,000 years. In terms of hydrological changes, HE1 appears also drier than global LGM in offshore Menorca record (based on the K/Al ratio as indicator of fluvial activity in Frigola et al., 2008, see Fig. 4) and in many marine pollen records (Beaudouin et al., 2007; Naughton et al., 2007; Combourieu Nebout et al., 2009; Fletcher et al., 2010). Model simulations obtained a clear reduction in both temperature of the coldest month and in precipitation for the HE1 interval respect to global LGM in Iberia and highlighted a more significant response on the European Atlantic coast that decreases very rapidly inland (Kageyama et al., 2005). Data from continental sequences in the IP, related to temperature and water availability comparing global LGM and HE1, are available to corroborate or reject those model outputs.

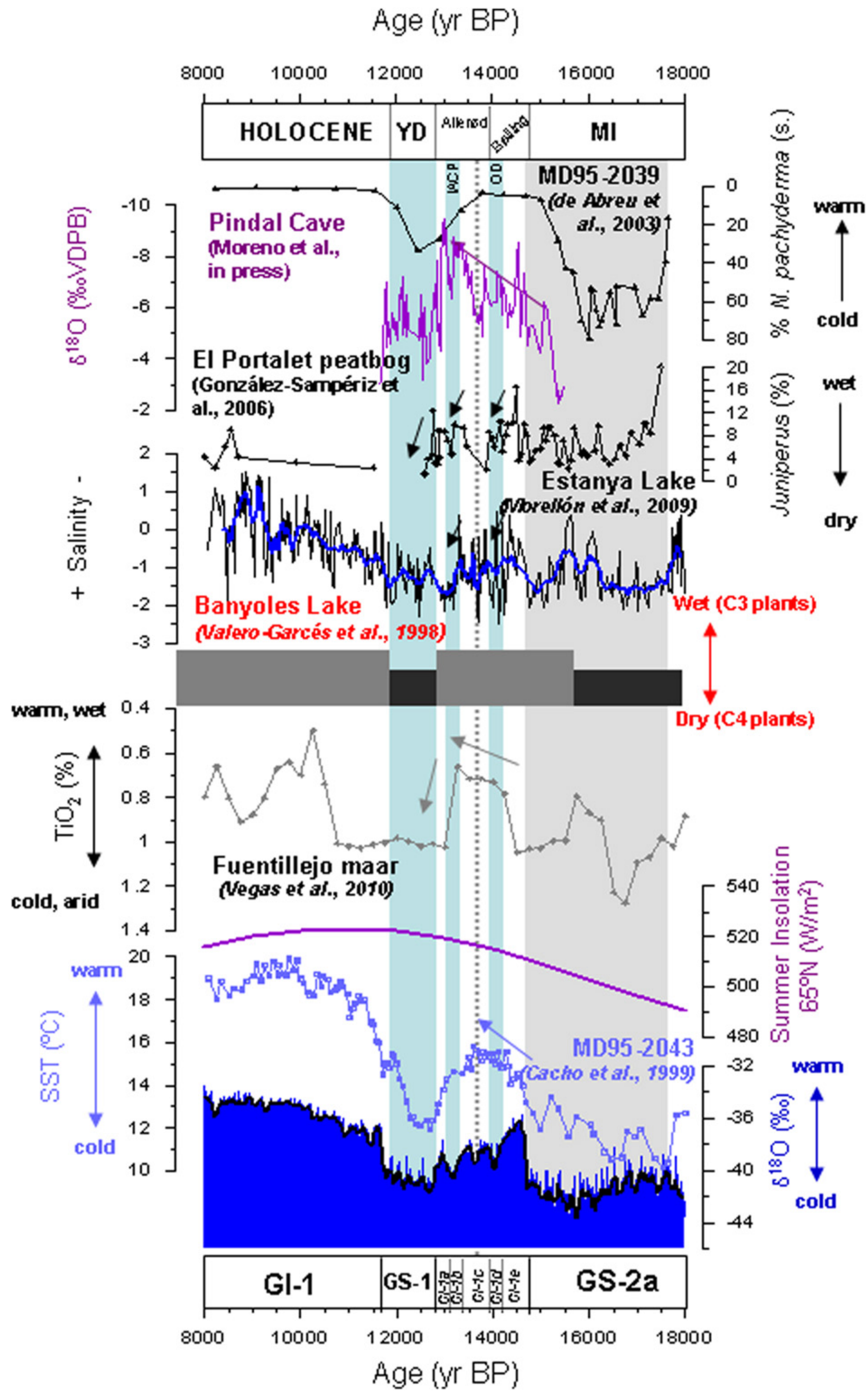

Fig. 5. Selected marine and terrestrial records from the IP covering from 18,000 to 8000 cal yrs BP. From up to down: (%) of *N. pachyderma* (sinistra) from MD95-2039 offshore Oporto, Portugal (de Abreu et al., 2003); $\delta^{18}O$ (‰ VPDB) from El Pindal cave (Moreno et al., 2010); (%) *Juniperus* from El Portalet peatbog (González-Sampériz et al., 2006); reconstructed salinity from Estanya Lake (Morellón et al., 2009a); broad tendencies of $\delta^{13}C$ (‰ VPDB) from Banyoles Lake (Pérez-Obiol and Julià, 1994; Valero-Garcés et al., 1998); (%) TiO_2 from Fuentillejo maar (Vegas et al., in press); summer insolation at 65°N; SST (°C) from MD95-2043 record (Cacho et al., 1999) and NGRIP $\delta^{18}O$ (‰ VSMOW) record from Greenland (Rasmussen et al., 2006) and smoothed with a 5-point moving average (thicker line). Shaded bands indicated the amplitude of short abrupt events during deglaciation and arrows mark tendencies (see text for discussion).

In general, recently studied lake sequences from the IP support previous interpretations from marine sediments, and in particular are in agreement with the relatively humid hydrological signal of global LGM. In Villarquemado palaeolake (Figs. 1 and 3), MIS 2 is characterized by a decrease in alluvial fan activity and more development of carbonate lake environments than before, pointing to relatively humid conditions during the LGM. In Estanya Lake (Fig. 1, Morellón et al., 2009b), a shallow carbonate-producing lake system during the global LGM (from the onset of the lake sequence, ca. 21,000–18,000 cal yrs BP), contrasts with a closed, permanent saline lake characterized by an evaporitic dominant sedimentation (starting at 18,000 and lasting until 14,000 cal yrs BP) (Fig. 4). Therefore, the global LGM was not the driest interval in the Pre-Pyrenees and the significant reduction in runoff occurred afterwards (Morellón et al., 2009a). Additionally, the preservation of lacustrine sediments in several records from playa-lakes in the Central Ebro Basin during the global LGM (see summary in Gonzalez-Samperiz et al., 2008), suggests phases of increased moisture during this period. Thus, the global LGM was probably characterized by periods of positive hydrological balance perhaps caused by reduced summer insolation at the latitude of Iberia (Fig. 4). If that was the case, evapotranspiration during the summer months may have decreased, contributing to relatively high lake levels without a significant increase in rainfall, as suggested by the reconstruction provided by the Estanya Lake record (Morellón et al., 2009a). An additional factor with the potential to increase water availability in certain areas is the expected high fluvial discharge produced in relation to the deglaciation process in the mountains (Valero-Garcés et al., 2004; González-Sampériz et al., 2005) which had already started by this time. There is some evidence of that process in the form of flood deposits in global LGM terraces indicative of a period of high discharge (Sancho-Marcén et al., 2003) that correlates with an increase in fluvial activity just after global LGM (Frigola et al., 2008).

Although temperatures are usually more difficult to reconstruct from lake sediments than hydrological balance (Cohen, 2003), pollen data from lacustrine sequences provide clear evidence for the IP of a cold scenario for the global LGM until the beginning of the Bølling/Allerød (see compilation in González-Sampériz et al., in press): the landscape was dominated by cold steppe formations with a minor presence of conifers and restricted occurrence of meso-thermophytes. In sequences with higher sample and temporal resolution, detailed interpretation of pollen spectra provides evidence for a particularly cold interval associated with HE1. Thus, in El Portalet peatbog, HE1 is detected by the presence of gray siliciclastic silts indicating low lake productivity, a decrease in *Juniperus* and increase of steppe taxa (González-Sampériz et al., 2006). Similarly, more positive values of $\delta^{13}C$ in carbonates were found in Banyoles record (Pérez-Obiol and Julià, 1994; Valero-Garcés et al., 1998) (Fig. 4).

From all the recent evidence outlined above, we can conclude that the most arid and coldest period in the IP during GS-2 occurred in within the GS-2a (Fig. 4). This interval has been called the “Mystery Interval” (MI) (Denton et al., 2005), and embraces the marine HE1 thus corresponding to the first phase of last glacial termination (17.5–14.5 cal kyr BP). In the Enol Lake record, the MI corresponds to the lowest linear sedimentation rate of the whole sequence pointing to very low runoff and thus little transport to the lake (Moreno et al., in press-a). In addition, the MI coincides with a hiatus in the formation of a speleothem from El Pindal Cave, in northern Spain, also suggesting a dry (and cold) period (Moreno et al., 2010). The same stalagmite grew during the global LGM, pointing to less extreme climate conditions at that time compared to the MI (Fig. 4). However, up to now, the evidence from lakes (or speleothems) has not been sufficiently accurate to discriminate chronologically whether the arid period includes the whole MI interval (ca. GS-2a) or whether it is more constrained to HE1, as seems to be the case from marine temperature records (Cacho et al., 2001). In fact, some sequences record two pulses during the MI (e.g., Estanya Lake salinity reconstruction or Fuentillejo maar TIO_2 aridity indicator) while others (e.g., *Juniperus* percentages in El Portalet peatbog) only point to one longer cold/dry event embracing the whole GS-2a interval (Fig. 4).

Despite chronological uncertainties and the different responses suggested by the available lake records (i.e. one or two pulses), the important effect of the Meridional Overturning Circulation (MOC) on the IP climate and the rapid response of terrestrial ecosystems to MOC variability is evident. The MI marks the start of the first phase of the last glacial termination (T1a) and was characterized by the strong reduction of MOC (McManus et al., 2004) in comparison to LGM levels due to high rates of freshwater input during iceberg discharges of HE1. The shutdown in MOC lasted 2000 yr and caused extremely cold winter temperatures in the North Atlantic area (Denton et al., 2005) and likely formed sea ice, reduced sea surface evaporation and consequently produced dry conditions in Europe (Wohlfarth et al., 2008) and into Asia (Cheng et al., 2006). Therefore, as a consequence of the close connection between western European temperatures and MOC intensity, IP temperatures are colder during the MI than during the earlier global LGM period.

4.3.2. When and how did the last deglaciation occur in the IP?

Terminology for the last deglaciation was first defined from the Fennoscandian region based on pollen sequences and the corresponding vegetation changes, including periods such as the Bølling-Allerød or the Younger Dryas (Mangerud et al., 1974), that correspond in the INTIMATE nomenclature referring to Greenland ice records to GI-1 and GS-1, respectively (Björck et al., 1998) (Fig. 5). The last deglaciation was characterized by a series of abrupt climatic changes (GI-1a–GI-1e, GS-1), with broadly similar trends identified in palaeoclimate records obtained from many sites throughout the North Atlantic region. However, the extent to which the North Atlantic sequence of climatic changes is reflected in palaeoclimatic records from the IP, in terms of timing and pattern of the abrupt climatic changes, is still a matter of debate (e.g., Carrión et al., in press). From marine cores surrounding the IP, at least two particularities with respect to Greenland records have arisen: (1) the earliest onset of warming associated with the first phase of the last deglaciation occurred at ~15.5 cal kyr BP, prior to further and more marked warming at the onset of the GI-1 (Fletcher et al., 2010), and (2) a stable – to warming trend in sea surface temperatures during GI-1 is observed in contrast to the cooling trend recorded in Greenland (Cacho et al., 2001). Furthermore, recent analyses of pollen records in southern Iberian marine cores indicate short-lived intervals of forest decline consistent with cooling and drying during the GI-1d (Older Dryas) and GI-1b (Inter-Allerød Cold Period) (Combourieu Nebout et al., 2009; Fletcher et al., 2010). The lack of accurate chronologies and high-resolution analyses in continental records has precluded the identification of abrupt climate changes within GI-1 until recently (e.g., González-Sampériz et al., 2006). New lake sequences like Villarquemado palaeolake, combining the study of vegetation and the response of the lake system itself to climate changes, will provide key information for the characterization of abrupt changes experienced during last deglaciation.

In the northeastern IP, the hydrological response to abrupt climate change during the last deglaciation has been described in Estanya Lake (Fig. 1). In this record, the onset of GI-1 is detected by changes in sedimentation in the lake and a significant negative excursion of δ^{13}Corg values reflecting an increase in organic productivity likely related to deeper lake level conditions (Morellón et al., 2009a). The salinity reconstruction also points to a more positive hydrological balance during GI-1 and shows minor changes in response to short abrupt cold events, such as GI-1d and GI-1b, pointing to slightly drier conditions (Fig. 5). Similarly, the montane peatbog record from El Portalet reflects a decline in herbaceous steppe association, typical of glacial conditions, and an expansion of pioneer deciduous trees at the beginning of GI-1. Vegetation cover and sediment composition also reacted rapidly to shorter cold events with the deposition of siliciclastic silts and an increase in steppe plants and a decrease in *Juniperus* (González-Sampériz et al., 2006) (Fig. 5).

In Laguna Grande and Laguna del Hornillo, both located in the western Iberian Range, the sequence of events within GI-1 have been identified by characterizing the laminations and the type and content of organic matter (Vegas, 2006). In these two lakes, an arid and cold event (GI-1d) is found between GI-1a (Allerød) and GI-1e (Bølling) but there is no signal around GI-1b, probably due to the low temporal resolution of the record. In other lakes from the wider Mediterranean region, a similar hydrological response to GI-1d and GI-1b events is observed (e.g., Lago dell'Accesa in Central Italy; Magny et al., 2006). On the contrary, an opposed palaeohydrological pattern is observed in central-western Europe, where G1-1d and GI-1b are characterized by higher lake levels in the Swiss Plateau, Jura mountains and French Pre-Alps (Magny, 2001). This latitudinal division in the hydrological response during abrupt climate changes occurring throughout last deglaciation, has been recently explained by the prevalence of "blocking episodes" that will favor or prevent cyclone penetration into the Mediterranean or northern and central Europe (Fletcher et al., 2010).

In the available lake records (Fig. 5), the onset of the warming trend associated with the Bølling period is synchronous, within age model uncertainties, with the onset of GI-1 in Greenland, but the pattern observed is more gradual than abrupt. Additionally, in Estanya Lake record, the Allerød period appears wetter than the Bølling period, in a similar way to that recorded in El Pindal cave located in northwestern Spain (Moreno et al., 2010) (Fig. 5). Similarly, the El Portalet pollen record reflects a generally reduced presence of steppe taxa and the first development, as opposed to occasional presence, of *Corylus* during the Allerød in contrast to the Bølling (González-Sampériz et al., 2006). Therefore, this pattern is consistent with Mediterranean marine SST records (Cacho et al., 2001) and differs from Greenland ice record where warmer temperatures over Greenland were reached abruptly at the onset of the Bølling period and declined afterwards (Fig. 5). The similar response of some lake (González-Sampériz et al., 2006; Morellón et al., 2009a) and speleothem (Moreno et al., 2010) sequences from northern IP and Mediterranean marine SST records (Cacho et al., 2001) to the global warming related to the first phase of the last glacial termination 1 (T1a), reflects a particular reaction in terms of temperature and water availability of this southern European region. This pattern may relate to a continental-scale N–S latitudinal pattern of changing climatic evolution over the GI-1 interval as proposed by Genty et al. (2006), which should be better characterized for the IP with future studies.

4.3.3. Timing, synchrony and ecosystems response to the Younger Dryas and the Holocene onset

The second phase of last glacial termination (T1b) corresponds to the second weakening of the MOC during the Younger Dryas cold period, probably also triggered by a discharge of glacial meltwater (Hughen et al., 2000; McManus et al., 2004). While a clear response during the GS-1 interval (or Younger Dryas, YD) is detected in marine environments of the Iberian margin, mostly in terms of reduced sea surface temperatures (e.g. Cacho et al., 2001), clear response is less evident in continental archives from the Iberian Peninsula where a variable vegetation response is observed depending on the altitude and latitude of the studied records (Carrión et al., in press). Thus, changes in the landscape and vegetation cover during the YD appear to be more marked in mountainous areas (e.g., El Portalet peatbog record indicates that the lake was frozen all-year round, González-Sampériz et al., 2006) than in mid-to-low altitude sites (e.g., Lake Banyoles; Pérez-Obiol and Julià, 1994).

Other indicators measured in lake sequences besides vegetation are plotted in Fig. 5 and their combination supports the existence of a YD event in the northern IP as a dry and cold period without clear geographical variability. Thus, a lake level drop and salinity increase in Estanya Lake were indicated by the return to deposition of gypsum-rich facies and an abrupt decrease in organic productivity (marked by positive excursion of δ^{13}Corg and a sharp decrease in Bio Si) (Morellón et al., 2009a). In Banyoles Lake, the isotopic composition of authigenic carbonates (δ^{18}O and δ^{13}C) reaches peak values at around 12,000 years (Valero-Garcés et al., 1998) while sedimentation in El Portalet decreased dramatically or even ceased during the GS-1 in response to the previously mentioned permanent freezing of the lake (González-Sampériz et al., 2006). In Enol Lake, gray siliciclastic silts with low organic content and pollen spectra dominated by herbaceous taxa characterize an open landscape with scarce vegetation during the GS-1 unit (Moreno et al., in press-b). Similarly, the presence of massive clayey silts with low organic content in the Fuentillejo maar record (Vegas et al., in press), and significant changes in sediment stratigraphy and diatoms association in the Laguna Grande at Sierra de Neila (Vegas et al., 2003), indicate a cold and arid climate associated with the GS-1 interval.

Thus, considering high and low altitude sites, the response to GS-1 in the IP lake records seems identical (Fig. 5). This finding may indicate that the different signals to the same climatic event recorded in the pollen spectra from different IP regions was linked to the distance to vegetation refuges that controlled the timing and intensity of the vegetation response. In addition, since most of the cases that are considered to show an "unexpected" response to GS-1 lie in the Mediterranean-influenced climate region (Fig. 1), a centennial to millennial-scale resilience of the established forests can be presented as another explanation to account for the different vegetation responses (Gil-Romera et al., 2010; Carrión et al., in press). This view, however, is not in agreement with the findings of palynological research on Mediterranean marine cores, which suggest a rapid response of the Mediterranean forest cover to centennial-scale variability, both at the abrupt onset of the YD and within the GS-1 interval (Combourieu Nebout et al., 2009; Fletcher et al., 2010).

The onset of the Holocene represents an abrupt climate change towards warmer and, in general, wetter climates at 11,600 cal yrs BP (e.g., Hoek et al., 2008). Although this transition was apparently synchronous in different records from the IP, optimum Holocene climate conditions were not reached at the same time (Morellón et al., 2009a). In Estanya Lake, sedimentary and geochemical proxies indicate that the lowest lake level of the whole sequence (last 20,000 years) occurred from 11,600 to 9400 cal yrs BP, when full Holocene conditions were finally reached (Morellón et al., 2009a). The Lake Banyoles sequence also records the eventual decrease in steppe taxa at 9500 cal yrs BP (Pérez-Obiol and Julià, 1994). In Enol Lake record, wetter conditions were not found until 9800 cal yrs BP when Ca, TOC and TIC percentages increase while siliciclastic particles decrease (Moreno et al., in press-b). In that record, arboreal pollen values increase markedly at the onset of the Holocene, dominated by a rapid increase of deciduous *Quercus* (45%), although the highest values were recorded at 9700 cal yrs BP. Accordingly, pollen records from the Alboran Sea indicate that the temperate Mediterranean forest expanded dramatically in response to increased humidity not developed at the Holocene onset but at 10,600 cal yrs BP (Fletcher et al., 2010). This delay may be related to a restricted rainy season during the boreal summer insolation maximum (Tzedakis, 2007). Thus, it seems from the available records, that the delay in the Holocene onset is related more to hydrological parameters than to temperature changes, pointing to a possible impact of the monsoon dynamics on the IP climate.

5. Summary and ideas for the future work

Selected lake records show the IP response to abrupt climate changes during last glacial cycle. Although, in general, there is a synchrony and a high correlation with North Atlantic region climate, the IP presents some peculiarities likely related to its southern location and the mix of African and European influences on its climate. Thus, the transition from MIS 5 to MIS 4 appears as a cold but relatively wet period, and corresponds to the maximum glacier extension in the northern Iberian mountains (e.g., Pyrenees, Cantabrian Mountains). Subsequent deglaciation occurs rapidly, probably associated with the general tendency towards greater aridity during MIS 4, and due to abrupt climate changes that characterized the MIS 3 interval, which includes some of the most arid periods in Iberian continental records. Abrupt climate changes, particularly HE, are observed in several records by changes in the sediment and vegetation cover and composition, thus demonstrating the effect of rapid climate variability on land. The global LGM is not the coldest or the most arid interval of the last 25,000 years since the MI, and the embedded HE1 event, are characterized by the highest aridity in the studied sequences. As detected in the lake sequences, the Lateglacial period starts synchronously to temperature increase in Greenland (14,600 cal yrs BP), but the pattern is not so abrupt and, additionally, the highest humidity is reached at the end of GI-1 (Allerød) and not at the beginning (Bølling). Finally, the GS-1 (YD) is observed in the hydrological response of the lake records but variable signals in the pollen spectra, suggesting different sensitivity of the vegetation in different localities with respect to altitude, topography and microclimate, and possibly relating to vegetation resilience at this time. The Holocene climatic optimum in terms of humidity seems to be delayed with respect to other European records, being reached in different locations only after 10.5–9.5 cal yrs BP.

From this compilation, it is evident that a major advance has been achieved recently in terms of palaeoclimate reconstructions obtained from lake records in the IP. Many of the records that provide critical information have been published recently or are in press (Estanya Lake, Enol Lake, etc.). However, despite the increased number of new studies, several questions remain open due to the lack of high-resolution records in key geographic regions. Thus, the southern IP region was not extensively discussed in this paper due to the scarcity of multi-proxy high-resolution lake records. It is clear that more records are necessary, especially from low altitude areas, that are currently underrepresented in the compilation. The greatest effort must be made to obtain laminated records, e.g., in karstic lakes such as Banyoles Lake, that will provide better resolution permitting the detection and characterization of abrupt climate changes during the last glacial cycle. In addition, long sequences such as Villarquemado palaeolake will provide new information on climate changes during the last glacial inception and the IP LGM. It is strongly advisable to compare and combine information from lake records with those obtained from other continental palaeoarchives, particularly speleothems and glacial deposits, and terrestrial tracers in marine sediment sequences. The integration of data from different palaeoarchives is critical to developing the understanding of the response of continental Iberia to rapid climate changes during last glacial cycle.

The multi-proxy approach has been found to be the best (if not only!) option to discriminate climate changes from other more local influences on the lake records (particular response of vegetation, etc.). However, further efforts are required not only to combine indicators, but to improve their calibration with the instrumental record. Greater use of quantitative estimations of temperature and precipitation would be highly informative and this remains an under-explored approach in the IP. Proxy calibration, together with an improvement of transfer function databases, will lead to better reconstruction of climate signals and will thus also contribute to the improvement of climate models.

Finally, the construction of robust chronological frameworks is indispensable for palaeoclimate reconstruction, particularly for the characterization of rapid climate changes. More effort must be made to look for high-quality dating material (terrestrial macroremains, charcoal) suitable for ^{14}C AMS in lake sediments. In addition, other methods, such as the tephrochronology, have not been explored in the IP terrestrial records and may be worth trying despite the non-favourable situation with respect to major volcanic zones and prevailing wind directions. Comparing records with independent chronologies (i.e., not tuned respect to Greenland ice cores) is essential for the identification of leads and lags in the continental response to different climate events.

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Appendix. Supplementary material

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.quascirev.2010.06.031.

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