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Millennial-scale climatic variability between 340 000 and 270 000 years ago in SW Europe: evidence from a NW Iberian margin pollen sequence

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Abstract

We present a new high-resolution marine pollen record from NW Iberian margin sediments (core MD03-2697) covering the interval between 340 000 and 270 000 years ago a time period centred on Marine Isotope Stage (MIS) 9 and characterised by particular baseline climate states. This study enables to document the vegetation changes in north-western Iberian Peninsula and therefore the terrestrial climatic variability at orbital and in particular at millennial scales during MIS 9, directly on a marine stratigraphy. Suborbital vegetation changes in NW Iberia in response to cool/cold events are detected throughout the studied interval even during MIS 9e ice volume minimum. However, they appears more frequent and of higher amplitude during the 30 000 years following the MIS 9e interglacial period and during the MIS 9a-8 transition which correspond to intervals of an intermediate to high ice volume and mainly periods of ice growth. Each suborbital cold event detected in NW Iberia has a counterpart in the southern Iberian margin SST record. High to moderate amplitude cold episodes detected on land and in the ocean appears related to changes in deep water circulation and likely to iceberg discharges at least during MIS 9d, the mid-MIS 9c cold event and MIS 9b. This work provides therefore additional evidence of a pervasive millennial-scale climatic variability in the North Atlantic borderlands throughout past climatic cycles of the Late Pleistocene, regardless of glacial state. However, ice volume might have an indirect influence on the amplitude of the millennial climatic changes in southern Europe.

1 Introduction

An increasing number of studies on previous climatic cycles shows that millennial-scale variability is an inherent pattern of the Late Pleistocene climates affecting glacial periods (Bond et al., 1993; Bond and Lotti, 1995; Dansgaard et al., 1993; Grootes et al., 1993; Grimm et al., 2006; Allen et al., 1999; Sanchez Goñi et al., 2000) but also intervals of reduced ice volume such as the current or the last interglacial (Bond et al., 1997; Delmotte et al., 2004, EPICA community members, 2004; Martrat et al., 2004, 2007; McManus et al., 1999; Oppo and Lehman, 1995; Oppo et al., 1998, 2001, 2007). However, the origin of this variability remains unclear. Several hypotheses have been proposed including internal ocean oscillations, periodic calving of ice-sheets or solar forcing (Bond et al., 2001; Broecker et al., 1990; Mayewski et al., 1997; Sakai and Peltier, 1997; van Kreveld et al., 2000; van Geel et al., 1999).

So far, few studies focused on the climatic variability of the interval between 340 000 and 270 000 years ago, encompassing the interglacial complex Marine Isotope Stage (MIS) 9. Ruddiman (2007) lately called attention to this isotopic stage: based on the caloric summer half-year insolation, the early part of MIS 9 is the closest analog to the late Holocene throughout the last 450 000 years. The Antarctica ice cores record during the MIS 9 peak interglacial the highest greenhouse gas concentrations of the past 650,000 years, excluding the Holocene industrial period (Petit et al., 1999; Siegenthaler et al., 2005; Spahni et al., 2005). Pollen analysis, from the southern Portuguese margin core MD01-2443, revealed suborbital vegetation change during the MIS 9e ice volume minimum bringing to an end the interglacial forest stage (Tzedakis et al., 2004; Roucoux et al., 2006). These authors pointed out the potential role of the suborbital climatic variability on the duration of the interglacials. MIS 9 is therefore a valuable complement to the better studied intervals such as MIS 5 or 11 to investigate the climate of interglacial periods.

Despite a different astronomical forcing but a similar range of sea level, the interval ~310–290 kyr ago (MIS 8.6 or 9b) and MIS 3 are marked by a suborbital variability of similar pacing and amplitude in the Vostok deuterium record (Siddall et al., 2007). In the southern Portuguese margin region, frequent moderate to high amplitude decreases in sea surface temperatures (SST) strikingly punctuate the 30 000 years following the MIS 9e interglacial period (Martrat et al., 2007). Over this period covering one and a half precession cycle, the summer insolation maximum at high latitudes was not particularly strong (Berger, 1978), CO_2 concentrations decreased following a particular gradual general trend (Petit et al., 1999) and although some sea level reconstructions give somehow divergent results (Shackleton et al., 2000; Stirling et al., 2001), ice volume appears to have increased following a quite gradual general trend (McManus et al., 1999; Waelbroeck et al., 2002). MIS 9 period gives, therefore, the opportunity to study the millennial-scale climatic variability under different baseline climate states related to different astronomical forcing, ice volume and greenhouse gas concentrations. Documenting the response of the different Earth's environments would ultimately bring new insights in the mechanisms controlling the rapid climatic changes. However, the vegetation and terrestrial climate response to this high frequency climatic variability remains ill-documented for the MIS 9 time interval.

We present here a high resolution marine pollen record covering the interval 340 000–270 000 years ago from the north-western Iberian margin core MD03-2697. It will allow us to refine and characterize the sequence of suborbital climatic events affecting the Iberian region during MIS 9. Pollen analysis of marine sediments permits to perform a direct correlation of the terrestrial and marine climatic indicators and to record the vegetation change against a marine isotopic time-scale. Marine pollen sequences from the Iberian margin have already shown their particular ability to detect the millennial scale climatic variability and to delineate the linkage between atmospheric and oceanic changes over the previous (Desprat et al., 2005; 2006) and more recent climatic cycles (Naughton et al., submitted; Roucoux et al., 2005, 2006; Sanchez Goñi et al., 1999, 2000, 2005, in press; Tzedakis et al., 2004).

On the basis of a large forest development at southern European sites during MIS 8.5 terrestrial equivalent which appears of similar extent to those of deglacial substages such as MIS 5a and 5c, Tzedakis et al. (1997) first suggested that substage 8.5 should belong to MIS 9. The direct land-sea correlation from SW Iberian margin confirmed that a large southern European forest expansion is coeval with the anomalous light benthic oxygen isotopic event, which is usually labeled 8.5 according to the isotopic stratigraphy of Imbrie et al. (1984) and Prell et al. (1986) (Tzedakis et al.; 2004). Although sea level reconstructions show similar lowstands during MIS 8.6 and 3, they display a sea level maximum during MIS 8.5 as high or higher than during the previous deglacial substage 9.1 (McManus et al., 1999; Shackleton et al., 2000; Siddall et al., 2003; Stirling et al., 2001; Waelbroeck et al., 2002) and generally of similar range to the MIS 5.1 or 5.3 highstands (Shackleton et al., 2000; Siddall et al., 2003; Waelbroeck et al., 2002). Throughout this paper, we will follow accordingly the isotopic stage notation applied by Tzedakis et al. (2004), Roucoux et al. (2006) and Martrat et al. (2007) to the Portuguese margin benthic $\delta^{18}O$ record over the interval 340–270 kyr. This implies including the isotopic substages 8.5 and 8.6 in MIS 9 and labelling them from now "MIS 9a"and "MIS 9b", respectively.

2 Environmental setting

We examined sediments from MIS 9 interval from core MD03-2697 located on the north-western Iberian margin, at ~100 km off the Galician coast (42°09.6′N, 09°42.1′W, 2,164 m). This site is under the influence of the North Atlantic Deep Water mass. The present-day climate of north-western Iberia is temperate and humid with mean annual temperatures between 10 and 17°C and mean annual precipitation between 1000 and 2000 mm.an^{-1} (Atlas Nacional de España, 1992). This region is incised in the north by the Rias Baixas valleys (Galician coast basin) and the Miño-Sil river (Sil basin) (Atlas Nacional de España, 1993) and crossed in the south by the Douro river which are the main suppliers of terrestrial sediments to the shelf (Naughton et al., 2007). North-western Iberia belongs to the Eurosiberian and sub-Mediterranean regions (Ozenda, 1982) where deciduous oak woodlands with heaths dominate (Alcara Ariza et al., 1987).

3 Material and methods

Core MD03-2697, retrieved in 2003 during the PICABIA campaign, is constituted of hemi-pelagic clays. The sedimentological description reveals an apparently continu-

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ous sedimentation. We have achieved a multiproxy study of the sediments from MIS 9 interval, including pollen analysis, stable oxygen isotope measurements from planktonic and benthic foraminifera and planktonic foraminifera counting and derived SST estimations. The MIS 9 interval in core MD03-2697 was initially located using planktonic $\delta^{18}O$ profiles from the complete sedimentary sequence (Desprat, 2005).

3.1 Isotopic analysis

For the benthic foraminifera oxygen isotopic data, 42 levels were subsampled between 2860 and 3260 cm at 20, 10, 5 or 2 cm interval between samples. Each specimen of benthic foraminifera (*Cibicides wuellerstorfi*) has been picked up within the 250–315 μm grain-size fraction, and cleaned with distilled water. Each aliquot (4 to 8 specimens, representing a mean weight of 80 μg) has been prepared using a *Micromass Multiprep* autosampler, using an individual acid attack for each sample. The CO_2 gas extracted has been analyzed against NBS 19 standard, taken as an international reference standard. Isotopic analyses have been carried out at the Laboratoire des Sciences du Climat et l'Environnement (LSCE, Gif-sur-Yvette, France), using a delta plus Finnigan isotope mass spectrometer. All the isotopic results are presented versus PDB. The mean external reproducibility of powdered carbonate standards is ±0.05‰ for oxygen. Absence of the foraminifera species *C. wuellerstorfi* and *M. barleeanus* at the bottom of the studied interval precluded a benthic isotopic record of the MIS 10-9 glacial-interglacial transition.

The same preparation technique was applied to analyze stable oxygen isotopes of planktonic foraminifera from 70 levels subsampled at 20 to 2 cm intervals. The planktonic foraminifera *Globigerina bulloides* was used between 2860 and 3270 cm and *Neogloboquadrina pachyderma* left coiling over the intervals 2720–2860 and 3260–3400 cm.

3.2 Planktonic foraminifera quantitative climatic reconstruction

Summer and winter sea surface temperatures (SST) were estimated from planktonic foraminifera assemblages using the Modern Analogue Technique from the database of Pflaumann et al. (1996) improved by Cortijo E. (LSCE) and Duprat J. (EPOC UMR-CNRS 5805).

3.3 Pollen analysis

Pollen analysis was completed on 70 levels between 3300 and 2860 cm at 10 to 2 cm intervals. Pollen samples preparation followed the procedure described by de Vernal et al. (1996) and modified at EPOC UMR-CNRS 5805, Bordeaux I University (Desprat, 2005). After chemical and physical treatments using cold HCl, cold HF and sieving through 10 μm nylon mesh screens, the residue was mounted unstained in glycerol. Pollen counting was achieved using a Zeiss Axioscope light microscope at 500 and 1250 (oil immersion) magnifications. A minimum of 100 pollen grains without *Pinus* and 20 taxa were identified in each sample. The pollen percentages for each taxon are based on a main pollen sum that excludes *Pinus* because of its over-representation in marine sediments (Heusser and Balsam, 1977; Turon, 1984), aquatic plants, pteridophyte spores and indeterminable pollen grains. *Pinus* percentages were calculated from the main sum plus *Pinus*. Spores and aquatic pollen percentages were obtained from the total sum including pollen, spores, indeterminables and unknowns. We have defined the major forested phases as periods showing a classical tree succession which is known in southern Europe and in particular in NW Iberia for beginning with the development of *Betula*, deciduous *Quercus*, and ending by the expansion of late successional trees such as *Carpinus betulus* and *Fagus* (Tzedakis et al., 2001; Desprat et al., 2007). Local names are given to these major forested periods.

3.4 Chronology

We established the chronology of core MD03-2697 by graphical correlation between its planktonic δ^{18}O curve and that of core MD01-2443 located on the southern Portuguese margin (Tzedakis et al., 2004; Martrat et al., 2007). Based on the similarity between the benthic δ^{18}O record of southern Iberian margin cores and Antarctica temperatures (Shackleton et al., 2000), MD01-2443 benthic δ^{18}O signal was aligned to the EPICA Dome C isotopic record (edc2 age-scale) for developing the age model (Tzedakis et al., 2004; Martrat et al., 2007). The low resolution of the MD03-2697 benthic δ^{18}O signal and lack of measurements during Termination IV impeded us to develop the age-model of our core by lining up the benthic isotopic records. However, as both cores were retrieved on the Iberian margin, the major oscillations of their planktonic isotopic signals can be reasonably assumed synchronous. Despite the analysis-resolution difference, MD01-2443 major planktonic δ^{18}O changes are clearly identified in our sequence. We tied up 6 points of heavier isotopic values and the first point of the light MIS 9e isotopic values over the record, allowing a strong correlation (r^2=0.86) between the tuned and target planktonic δ^{18}O curves.

4 The north-western Iberian margin record – Results

The main features of the MD03-2697 pollen record and inferred vegetation changes during MIS 9 in NW Iberia are presented in Table 1, Fig. 2 and the direct land-sea correlation in Fig. 3. Three temperate forest periods (Pontevedra, Sanxenxo and Bueu) (Table 1, Fig. 3) characterize each interglacial substages of stage 9 (MIS 9e, c and a) interspaced by more or less open vegetation intervals. Afforestation in north-western Iberia generally began with *Betula* (birch), and deciduous *Quercus* (oak) followed by *Alnus* (alder), *Corylus* (hazel), *Carpinus betulus* (hornbeam), *Fagus* (beech), *Taxus* (yew) or *Pinus* (pine). These trees are the dominant components of the temperate and humid forests established in Europe during the current interglacial. In NW Iberia, colder

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climatic conditions influence the vegetation cover by promoting forest opening. In our pollen record, increase of Ericaceae (heath) or dry-grassland taxa (mainly Poaceae, *Taraxacum*-type and semi-desert plants such as *Artemisia*, *Ephedra distachya*-type, *Ephedra fragilis*-type and Chenopodiaceae) at the expense of the tree taxa, outlines the vegetation response to cold and cool events.

The first major forested period (Pontevedra, 12 kyr duration) occurring during MIS 9e displays a maximum expansion of deciduous oak forest and Mediterranean plants (evergreen *Quercus*, *Olea* and *Pistacia*) between 334 and 331 ka, revealing the climate optimum of this warm period in north-western Iberia. An abrupt decrease of deciduous oak populations at ~330 ka, principally in favor of heath, marks the end of this optimum in this region. Subsequently, deciduous oak populations weakly re-expand before beginning to reduce as yew, hornbeam and finally beech developed. The expansion of these latecomer trees reveals the temperature decrease on the continent characterizing the second part of Pontevedra. The climate optimum of this interval and the end-phase cooling observed on land are synchronously recorded in the ocean. The climate optimum is reflected by the lightest planktonic δ^{18}O values and by the maximal development of the warmest planktonic species of MIS 9, with summer SST estimates by at around 19°C, similar to Holocene reconstruction (Naughton, 2007). However, ocean surface warmed quickly before the beginning of Pontevedra and afforestation shown by the expansion of birch and deciduous oak occurred progressively over a couple of thousand years. Although the lack of data precludes the identification of the real beginning of the MIS 9e benthic isotopic plateau, the record shows that the lightest benthic δ^{18}O values are reached before the maximal development of the deciduous forest and Mediterranean plants. The end-phase cooling is also revealed by planktonic foraminifera assemblages indicating a 3°C summer SST drop and a planktonic δ^{18}O increase. This change is also contemporaneous with the end of the benthic isotopic plateau suggesting an initial accumulation of glacial ice in the high latitudes.

After the establishment of an open vegetation cover dominated by heathland and grassland during MIS 9d, a new forested period, named Sanxenxo, begins. Decidous oak forest briefly reached an expansion similar to that of Pontevedra at the beginning of Sanxenxo but in general the forest cover remained less extensive. Summer SST estimations indicate warm conditions (~18°C) during the second part of Sanxenxo (-B) but do not show a warming during the first part of Sanxenxo (-A) probably because of the relatively high *N. pachyderma* s. percentages. Such polar foraminifera percentages seem quite anomalous as the planktonic δ^{18}O signal would indicate a warming at the beginning of Sanxenxo. Moreover, the error on the summer SST estimations is large during the whole Sanxenxo-A interval. The Sanxenxo period occurs during the interglacial substage MIS 9c but the associated benthic δ^{18}O values are not clearly lighter than during MIS 9d and began to decrease quickly at 312 ka.

Interestingly, in addition to a relatively smaller extent of the temperate forest, the Sanxenxo period can be distinguished by abrupt fluctuations of the deciduous oak forest in favour of heathland or grassland. This suggests millennial-scale cooling events in NW Iberia at around 314, 311, 307 and 300 ka. The major one (at 307 ka) is a two-millennia cold episode during which the forest collapsed, explaining our division of this period into Sanxenxo-A and -B. Summer SST estimations clearly record this cold suborbital event by cooling of ~3°C but do not show the other cool events detected on land. However, this could be an artefact due to the lower time-resolution of the marine proxy records and to the anomalously high *N. pachyderma* s. percentages.

In contrast to Sanxenxo, the last forested period of MIS 9 (Bueu) is associated with a longer benthic δ^{18}O decrease which corresponds to the 9a isotopic substage. The expansion of the temperate forest during periods Bueu and Pontevedra are of similar magnitude. However, during phase Bueu, hornbeam and beech which grow preferentially in moister and cooler conditions than deciduous oak, play an important role and Mediterranean plants hardly expands.

Between Sanxenxo-B and Bueu, summer SST cooled by 3°C within MIS 9b and the north-western Iberian landscape is dominated by herbaceous plants, in paticular heaths. Oak populations decrease strongly at ~296 ka, reflecting a strong and abrupt cold climatic event in NW Iberia and weaker reduction occurs at 292 ka, just before the rapid oak forest expansion associated with the beginning of Bueu.

Finally, while the benthic $\delta^{18}O$ increases towards the glacial values of MIS 8, herbaceous communities become largely dominant, suggesting the establishment of the glacial cold conditions. However, at around 276 ka, some woodlands of birch, oak, hornbeam and hazel expanded while grassland decreased, summer SST increased and planktonic $\delta^{18}O$ became lighter. This change can reflect a rapid weak warm fluctuation occurring contemporaneously on land and in the ocean during the MIS 9-8 transition.

5 Discussion

5.1 Climatic variability at orbital scale

The MIS 9 marine pollen record off Galicia shows the response of the NW Iberian vegetation at orbital-scale by detecting three major periods of temperate forest development (Pontevedra, Sanxenxo, Bueu) related to the MIS 9 interglacial substages interspersed by 2 more or less open vegetation periods corresponding to the stadial substages 9d and 9b. Forest character and extent of the different periods assign the first major forested period (Pontevedra) as the climate optimum of MIS 9 in NW Iberia, and the second one, Saxenxo, as a period of intermediate climatic amelioration between the forested stages Pontevedra and Bueu occurring during MIS 9e and MIS 9a, respectively. These features are commonly recognized in the long southern European pollen sequences Tenaghi Philippon (Tzedakis et al., 2003; Wijmstra and Smit, 1976) and Praclaux (Reille and de Beaulieu, 1995; Reille et al., 2000) and the Portuguese margin pollen record MD01-2443 (Tzedakis et al., 2004; Roucoux et al., 2006). In a review of the long southern European pollen records, Tzedakis (2005) pointed out a broad correspondence between ice volume and southern European forest development over the previous glacial cycles. However, boundaries of isotopic substages and forest periods are generally not isochronous and amplitude of forest development in this region during temperate intervals exhibits an apparent closer relationship with summer insolation changes at 65°N than with ice volume extent, due to a vegetation response to climate regimes (Tzedakis et al., 2004; 2003, Tzedakis, 2005; Shackleton et al., 2002). Indeed, as the climate optimum in NW Iberia and in general in southern Europe, the highest sea level and 65°N summer insolation maximum of MIS 9 interval occurs during substage 9e (Lea et al., 2002; McManus et al., 1999; Siddall et al., 2003; Shackleton et al., 2000; Stirling et al., 2001; Waelbroeck et al., 2002). As noted by Tzedakis et al. (2003) for Tenaghi Philippon site, forest extent in NW Iberia is effectively weaker during MIS 9c than during MIS 9a like 65°N summer insolation (Fig. 5). The sea level reconstructions display MIS 9a highstand from equivalent to largely higher than that of MIS 9c (McManus et al., 1999; Siddall et al., 2003; Shackleton et al., 2000; Stirling et al., 2001; Waelbroeck et al., 2002). The relationship between forest extent, ice volume and insolation at orbital scale still remains difficult to state within MIS 9 interval.

Although all the records agree in indicating the warm period of MIS 9e as the climate optimum, the difference in warmth between MIS 9 warm periods displayed by the southern European pollen sequences does not always come out so well expressed in North Atlantic records. The highest summer SST from cores MD03-2697, MD01-2443 (Martrat et al., 2007) and ODP 980 (McManus et al., 1999) (Figs. 4 and 5) are as well included in the MIS 9e plateau, characterizing the ice volume minimum of MIS 9. And MIS 9e plateau corresponds to the period of maximal production rate of North Atlantic Deep Water (NADW), inferred from the deepest position of the Deep Western Boundary Current over the Blake-Bahama Outer Ridge (Yokokawa and Franz, 2002). SST during MIS 9a appears warmer than during most of the MIS 9c interval off SW Portugal, equivalent off Galicia and cooler in the subpolar North Atlantic. Further, in the eastern equatorial and southwest Pacific, Mg/Ca SST reconstructions, suggest a warm phase during MIS 9a of at least 1°C warmer than all along the interval following the interglacial period (Lea et al., 2000; Pahnke et al., 2003). Otherwise, in Antarctica, the deuterium records of Vostok or EPICA-Dome C ice cores show an important warm phase during substage 9a but not warmer than during substage 9c (Petit et al., 1999;

EPICA members, 2004, Jouzel et al., 2007) (Fig. 5). The degree of warming during the different MIS 9 warm periods remains difficult to assess because of the seasonal character of the different paleotemperature proxies used, the analysis time resolution and the regional signature of the records.

5.2 Millennial-sale climatic variability

5.2.1 Sequence of suborbital events in the Iberian region

NW Iberian vegetation response to millennial-scale climatic variability is clearly recorded in the MD03-2697 marine pollen sequence. Suborbital cold events are expressed by abrupt temperate forest reductions of moderate to high amplitude in particular during the interval from MIS 9d to 9b and during the MIS 9a-MIS 8 transition but also of smaller extent during the warmest interval Pontevedra. To examine the character of the suborbital variability detected in the NW Iberian region, we will compare our data with the Portuguese margin records from core MD01-2443 (Tzedakis et al., 2004; Martrat et al., 2007). Although core MD03-2697 chronology is based on core MD01-2443 age-scale, north-western Iberian vegetation and SST suborbital changes do not always appear synchronous with those of south-western Iberian region. However, such abrupt events during the last glacial period and MIS 5 have been related with rapid shifts in the polar front and considered simultaneous in eastern North Atlantic and in southern Europe (Tzedakis, 2005, Shackleton et al., 2000; Sanchez Goñi et al., 2005 and in press). A certain degree of age uncertainty in our chronology is the result of the graphical correlation of the isotopic signals which are of different time resolution, and because of likely different changes in sediment accumulation rate at each site. The close location of the sites allows us to assume the synchroneity of the abrupt events even if their timing seems slightly different.

During the ice volume minimum, a forest reduction in NW Iberia is recorded, at ~330 ka, marking the end of maximal extent of the deciduous oak forest and Mediterranean plants and therefore the end of the climate optimum. In southwestern Iberia, an abrupt cold/arid event, occurring at ~333 ka brought to an end the forested period while it led to the forest decline in France (Praclaux sequence) and Greece (Tenaghi Philippon) (Tzedakis et al., 2004). The 3000 age discrepancy between SW and NW Iberia for this event is probably an artefact of the age model of our record which is not well constrained over this time period. Like in France and Greece, the forest recovered in Galicia afterwards and cooler temperate tree taxa such as *Taxus* developed while deciduous oak forest kept reducing until the end of Pontevedra. Though such an abrupt event is not obvious in the southern and northwestern Iberian margin SST records, both direct land-sea correlations show that a cooling trend follows the SST optimum values (Fig. 4). Consequently, this suborbital event not only marks the end of the forested stage in SW Iberia (Tzedakis et al., 2004) but also the end of the Pontevedra climate optimum in and off Iberia some millennia before the end of the ice volume minimum.

From MIS 9d to MIS 9b, forest reductions in NW Iberia occur every 3 to 5 kyr. MD03-2697 planktonic δ^{18}O and summer SST estimates show cold conditions during MIS 9d and MIS 9b forest reductions and a particular synchronous strong SST decrease and forest decrease at 307 ka during MIS 9c. Unfortunately for most of the events detected by the pollen record, the lower resolution analysis of the marine proxies impedes us to evaluate a SST change counterpart. However, almost each reduction of the temperate and humid forest in NW Iberia corresponds within the chronology uncertainties to a summer SST cooling detected by the Portuguese margin record (Iberian Margin Stadials of the third climatic cycle (3IMS) 7 to 15, as named by Martrat et al., 2007). Cold events 3IMS- 14, 13, 12 and 11 have as well an impact on the southern Iberia vegetation (Fig. 5). In the Portuguese margin pollen record, the 3IMS-15 cooling does not correspond to a forest reduction but is contemporaneous of a replacement of Ericaceae by Poaceae in the herbaceous community which would reveal cooler conditions (Roucoux et al., 2006). Forest extent is strongly reduced at the end of MIS 9b in SW Iberia but the time resolution of MD01-2443 pollen record appears too low for indentifying individual vegetation response to cold oscillations 3IMS- 10 and 9. One additional cool/arid suborbital event at ∼315 ka which is not detected by the Iberian margin SST and Portuguese pollen records influenced the NW Iberian vegetation during the MIS 9c ice volume minimum.

Later synchronous vegetation and SST changes in the NW Iberian region are detected during the MIS 9a-8 transition. At ∼282 ka, a 2°C SST decrease is coeval with a minimum of the temperate forest extent and the maximum of *Fagus* development (Figs. 3 and 4) which reveal cool and wet climate while ice volume is still quite low. Though a cold SST fluctuation is not detected by core MD01-2443, a forest reduction occurred concurrently in southwestern Iberia as well as heavier planktonic δ^{18}O values. Finally, at ∼276 and 273 ka, two severe SST decreases and forest collapses punctuated the end of the MIS 9a-8 transition in both Iberian records while ice volume is already large.

The amplitude of vegetation changes in NW Iberia indicates that 3IMS-15a and 13a which occur during the MIS 9e and 9c ice volume minima, are the weakest oscillations. In contrast, NW Iberian forest collapses reveal the most severe cooling during 3IMS-14, 12 and 10. Intervals of open vegetation are also recorded in France (Reille et al., 1995) during MIS 9d and MIS 9b. However, in southwestern Iberia, the relative small contribution of steppe plants and high temperate tree representation implies moderate arid and cold conditions during 3IMS-14 in comparison with other stadials such as 3IMS-10 (Roucoux et al., 2006). In the ocean, the SST cooling also appears moderate off south Portugal (Martrat et al., 2007) while in subpolar North Atlantic SST estimates suggest a cooling of relatively high magnitude during MIS 9d though not extreme (McManus et al., 1999) (Figs. 4 and 5). The difference in the magnitude of vegetation change between the northernmost sites and the SW Iberia one can reflect the latitudinal temperature gradient and a certain degree of winter moisture availability during this period which allows maintaining a Mediterranean forest in this region. However, although climatic deterioration, in particular in winter, could have been stronger in NW Iberia and France during MIS 9d, the ecological threshold of the temperate trees could have been crossed at these northernmost sites and not in southern Iberia. Indeed, at sites where temperate trees are living near their critical tolerance limit, even a moderate climatic change can generate a forest collapse which consequently impedes us to decipher the intensity of different cold events from the pollen diagrams (Tzedakis et al., 2004). Therefore, cooling in NW Iberia could have been moderate during 3IMS-14 or at least less intense than during 3IMS-12 and 10 but as a forest collapse in NW Iberia requires a certain degree of cooling, temperatures must have been clearly lower than during 3IMS-15, 13, 11 and 9.

The NW Iberian pollen record not only allows us to document vegetation changes during MIS 9 in this region but to refine and characterize the sequence of suborbital climatic events previously identified by the south-western Iberian margin SST record. More importantly, this highlights the persistence of millennial-scale climatic variability in southern Europe throughout MIS 9 which appears coupled with North Atlantic SST changes. Effectively, suborbital climatic changes during stage 9 happened whatever ice volume extent but during low ice volume conditions the oscillations seem dampened (cf. events 15a and 13a) and somehow scarcer.

5.2.2 Climatic implications

Suborbital variability during ice volume minimum is not a special feature of MIS 9e. Millennial variability represented by North Atlantic surface cooling and ice-rafting episodes as well as vegetation changes in adjacent landmasses appears also a characteristic of Holocene records (Bond et al., 1997; Came et al., 2007; Viau et al., 2002). Within the MIS 5e ice volume minimum, several suborbital SST cooling are detected in the subpolar North Atlantic and Nordic Seas and one of them terminated the short-lived climate optimum of the substage (Cortijo et al., 1994; Fronval and Jansen, 1997; Oppo et al., 2001, 2007). At the Grande Pile site (France), a series of cooling episodes are detected during the Eemian and have been suggested possibly related to the oceanic circulation changes in the Nordic seas and North Atlantic (Rousseau et al., 2006). In the Iberian Peninsula, a deciduous forest reduction might also be associated to the suborbital event marking the end of the MIS 5e climate optimum in the North Atlantic. Indeed, before the substantial winter temperature decrease which are clearly indicated by the development of *Carpinus betulus* in NW and SW Iberian margin sequences, a temperate forest minimum (mainly deciduous oak) occurred in SW Iberia at ∼123–122 ka while deciduous oak forest in NW Iberia reduced (Fig. 4 from Sanchez Goñi et al, 2005). Although the drier or cooler nature of the suborbital event causing this forest reduction in SW Iberia appears difficult to determine regarding the pollen assemblages, this suborbital vegetation change seems concurrent to the beginning of SST decrease off Iberia during MIS 5e (Sanchez Goñi et al, 2005) as the MIS 9e observed suborbital event is coeval with the end of SST optimum. In the subpolar North Atlantic, SST cooling events during MIS 5e ice volume minimum are marked by a reduction in MOC (Meridional Overturning Circulation) and minor ice-rafting events (Oppo et al., 2007). The MD01-2443 hydrological indicator records (Fig. 5; Martrat et al., 2007) do not reveal, however, significant changes in deep ocean circulation associated with the suborbital oscillations recorded in sea and air surface temperatures during MIS 9e. High sensitive sites to changes in MOC such as ODP site 980 in the subpolar North Atlantic have to be analyzed in order to document the frequency and amplitude of MOC changes during MIS 9. Tzedakis et al. (2004) also showed a south-western Iberian forest collapse in response to an abrupt arid/cool event during the MIS 7e ice volume minimum. These authors pointed out that although the origin of this suborbital climatic variability within MIS 9e and 7e remains unclear, they may be the expression of a global modification in climate conditions though with no apparent change in ice volume as these millennial events appear coeval with the abrupt declines in methane concentrations recorded in Vostok ice core. Bond et al. (2001) interpreted the Holocene millennial variability as the result of atmospheric circulation changes forced by solar irradiance variability and put forward that solar-forced millennial-scale variability is a persistent feature of the past interglacials. The MIS 9e suborbital event could be the particular expression of such a variability. However, there is no consensus on the forcing mechanisms for millennial climatic change during interglacial periods; in particular the solar origin has been lately challenged by a Holocene subpolar North Atlantic record (Came et al., 2007). Regardless of the origin, as suborbital event marks the premature end of the climate optimum during MIS 9e but also MIS 5e ice volume minimum, when insolation decrease, we can wonder to which extent the millennial-scale variability and the astronomical forcing played each a role in the interglacial demise and further the glacial inception.

Of particular interest is the climatic variability during the 30 000 years following the interglacial period, which is characterized by frequent moderate to high amplitude vegetation and SST oscillations with recurrence time varying between 3 to 5 kyr even during the forest stage Sanxenxo. The variability of this interval from MIS 9d to 9b is even more outstanding when we look at the other interglacial complexes of the last 500 ka. Large amplitude suborbital oscillations affect also the course of MIS 11 (Desprat et al., 2005; Oppo et al., 1998) as well as MIS 5 in North Atlantic from the subtropics to the subpolar region and adjacent landmasses (Chapman and Shackleton, 1999; Dansgaard et al., 1993; Heusser and Oppo, 2003; Lehman et al., 2002; McManus et al., 1994, 2002; Kukla et al., 1997; Oppo et al., 2007; Sanchez Goñi et al., 2005). However, forest intervals of the previous climatic cycles from Iberian records (Desprat et al., 2007; Desprat et al., 2006; Martrat et al., 2007; Roucoux et al., 2006; Sanchez Goñi et al., 1999, 2005) do not present oscillations with such recurrence and amplitude as Sanxenxo. For example, the apparent higher stability of temperatures on land and in the ocean during MIS 7 forest stages in the Iberian region (Desprat et al., 2006; Martrat et al., 2007) makes a clear contrast with Sanxenxo. Insolation variations discriminate Sanxenxo from other forest intervals by a relatively low 65° N summer insolation forcing (Fig. 5) which probably played a role in the relatively low forest extent of this period by conditioning the climate regime (Tzedakis et al., 2003). However, there is no obvious direct relationship between the amplitude of the suborbital vegetation response and the magnitude of orbital parameter variations. For instance, the most severe cooling episodes in NW Iberia during MIS 9 occur either at high or low summer insolation values (Fig. 5).

A likely explanation for the particular high variability during MIS 9 is related to changes in oceanic circulation and ice-sheet size variations. Martrat et al. (2007) have shown that during the last 420 ka, prominent abrupt SST drops in the Portuguese margin region, which occur during increased ice-sheet extent period, are preceded by decreases in both $C_{26}OH$ ratio and benthic $\delta^{13}C$ which indicate increasing deep water ventilation by AABW inflow at the Iberian margin and reduction of NADW contribution (Martrat et al., 2007). Such prominent SST drops during MIS 9 are represented by 3IMS-7, 8, 9 and 10. The MD01-2443 data (Fig. 4; Martrat et al., 2007) also suggest the likelihood of deep water circulation changes in connection with terrestrial and marine cooling events of moderate amplitude during the interval MIS 9d to 9b. Small decreases in MD01-2443 benthic $\delta^{13}C$ which would reveal small weakening of the NADW occur with 3IMS- 15 and 14 cooling episodes. Later, in a context of low deep water oxygenation (high $C_{26}OH$ ratio), sharp benthic $\delta^{13}C$ drops with small $C_{26}OH$ ratio decreases are associated with the moderate SST cooling events 3IMS-12 and 11. Despite its low time resolution, the ODP site 980 record confirms a reduction in MOC during MIS 9d and 9b, and during a suborbital SST changes at ~307 ka which likely corresponds to the event 3IMS-12 (Fig. 5; McManus et al., 1999). Consequently, the climate variability detected in Iberian margin and borderlands is likely linked to recurrent reduction of the northward oceanic heat transport associated to a change in oceanic circulation and European atmospheric gradients. North Atlantic MOC changes whether caused by internal oscillations, ocean-atmosphere mechanisms or solar forcing, are generally involved as driver or amplifier of the millennial scale climatic variability (Bond et al., 1997; Broecker et al., 1990; McManus et al., 2004; Mayewski et al., 1997; Sakai and Peltier, 1997).

McManus et al. (1999) and Schulz et al. (1999) showed a control of ice volume on the amplitude of SST millennial-scale climatic variability. When ice sheets decay or grow, even in a limited extent during stadials, and ice volume surpasses a critical threshold (~–30 m sea level), suborbital SST decreases of larger amplitude occur in association with abundant iceberg discharges which amplify in turn the reduction in MOC (McManus et al., 1999). Similar mechanism has been proposed for explaining the large amplitude suborbital climatic instabilities during MIS 5 and 11 (Chapman and

Shackleton, 1999; Oppo et al., 1998, 2007). The benthic $\delta^{18}O$ signals of the different North Atlantic records suggest a first weak ice-sheet enlargement during MIS 9d, they even do not reach the 3.5 per mil threshold (Figs. 4 and 5). However, ODP 980 IRD record testifies of iceberg discharges in North Atlantic (Fig. 5) and severe cooling are experienced in the NW Iberian region during this interval. Glacier nucleation near surrounding coasts may have favoured ice margins to reach the sea, and therefore generation icebergs discharges, despite a relatively weak ice-sheet development (McManus et al., 1994). After a short-lived ice volume minimum during MIS 9c, ice sheet growth appears to begin early during Saxenxo and the benthic $\delta^{18}O$ values cross the 3.5 per mil threshold as early as ~312 ka, i.e. just before the first high amplitude cold event of MIS 9c (3IMS-13), and until ~290 ka and again during the MIS 9a-8 transition (Figs. 4 and 5). This suggests that ice-sheet size is favourable to instabilities over most of the interval MIS 9c-9b. ODP 980 IRD record testifies of important ice-rafting episodes during MIS 9b and MIS 9c (3IMS-12). However, bottom temperature variations can have a substantial influence on benthic $\delta^{18}O$ signal (Skinner and Shackleton, 2006) which consequently may not strictly represent ice volume variations.

A number of sea level reconstruction based on different approaches are available for the previous climatic cycles but for MIS 9 they significantly diverge, in particular for the amplitude of sea level drop and rise during MIS 9d and 9c, respectively (Bintanja et al., 2005; Lea et al., 2002; McManus et al., 1999; Siddall et al., 2003; Shackleton et al., 2000; Stirling et al., 2001; Waelbroeck et al., 2002). On the other hand, they broadly agree on the important sea level drop between the MIS 9c ice volume minimum and MIS 9b maximum, reaching glacial values similar to MIS 3. With the lack of IRD evidence we cannot put forward the amplification of MOC reduction by ice melting during each cooling event. However, it is noticeable that European vegetation and SST during MIS 9 particularly respond to millennial-scale variability when ice sheets were reorganizing, in particular when ice-sheets were building up and reached a significant size. Moreover, even if ice-rafting events do not actually accompanied some cold events, modeling experiments suggest that overturning circulation in the North Atlantic is more oscillatory when freshwater discharge is moderate, as might occur during periods of ice growth (Sakai and Peltier, 1997).

Recently, Siddall et al. (2007) noted that the Vostok ice record strikingly displays during MIS 9b (8.6, ∼290–310 kyr) millennial changes in deuterium and methane of similar frequency and amplitude than the "Bond cycles" during MIS 3 from ∼30 to 55 kyr (Siddall et al., 2007). In the Iberian region, the recurrence time of the suborbital changes over this MIS 9 interval accordingly evokes the MIS 3 glacial variability in terms of Dansgaard-Oeschger cycles or group of them. Between 310 and 290 ka, three Antarctic isotopic maxima are recorded in the Vostok, EPICA – Dome C or Dome Fuji Antarctic ice cores (Petit et al., 1999, EPICA community members, 2004; Kawumara, 2007) while the Iberian vegetation and SST records indicate three warming (3IMI-9 and 3IMI-10 and 11, included in Sanxenxo-B) (Fig. 5). The similarity between amplitude of SST changes during both MIS 3 (Martrat et al., 2007) and 9b intervals also seems relevant in the SW Portuguese region but amplitude of vegetation changes in SW and NW Iberia during this MIS 9 interval (in particular cycles 3IM-11 and 10) appears larger than during MIS 3 (Sanchez Goñi et al., in press). However, temperate forest in Iberia does not always record all the range of climate change due to the tolerance threshold of the temperate trees to cold conditions (Tzedakis et al., 2004). Indeed, the difference of cooling between D-O stadials and Heinrich events during the last glacial period is not detected by the Iberian vegetation record although it is evident at other southern European sites (Sanchez Goñi et al., 2000, Tzedakis et al., 2004). Assessment of the cooling difference between MIS 3 and MIS 9 stadials is hardly feasible from the Iberian pollen records. Moreover, after the pollen sequences and SW Iberian margin SST estimates, baseline conditions were warmer during Sanxenxo-B than during MIS 3 interstadials (1 to 3°C warmer) (Martrat et al., 2007, Sanchez Goñi et al., 2000, in press). Therefore, the larger amplitude of temperate forest changes in Iberia does not rule out a possible similar amplitude of climatic change on land during both intervals. In any case, the Iberian margin records confirm that high amplitude multi-millennial climatic oscillations which are likely associated with deep ocean circulation changes, occurred in the northern hemisphere during the interval ~290–310 kyr as predicted by the modelled Greenland $\delta^{18}O$ from the reverse seesaw calculation (Siddall et al., 2007) and the methane Vostok record (Delmotte et al., 2004). As a different astronomical forcing but a similar range of sea level marks the MIS 9b and MIS 3 intervals, Siddall et al. (2007) proposed that ice volume, in particular through the existence of floating ice shelves at the northern ice-sheet margins, is a key factor to predisposition the Earth climate system to the millennial-scale variability. In turn, Earth's orbital forcing would play an indirect role in governing the ice-sheet configuration (Siddall et al., 2007). Additionally, CO_2 reach the same range of concentrations during MIS 9b and MIS 3 (Petit et al., 1999; Indermühle et al., 2000). Greenhouse gases (primarily CO_2) and secondary albedo, mainly from northern ice-sheet brightness, which are considered as the major feedbacks on ice volume (Ruddiman, 2006), must also be a key factor, at least, in setting favourable ice volume conditions to millennial-scale variability. Consequently, the similarity of the suborbital change pattern in the SST records and eventually in the vegetation records from the Iberian margin between MIS 3 and MIS 9b *sensus lato*, which are periods characterized by lower CO_2 concentrations and larger ice volume, reinforce the potential role of the ice volume in modulating the millennial-scale variability. However, as suborbital variability seems a pervasive feature of glacial as well as interglacial periods, ice volume state does not explain its origin (Oppo, 1997).

6 Conclusions

The new marine pollen record MD03-2697 retrieved in the NW Iberian margin provides a detailed reconstruction of the vegetation changes during MIS 9 in the adjacent landmasses. As shown by the other long European pollen records, the vegetation response in NW Iberia to orbital climatic variability is represented by three forest stages of different extent, indicating a short-lived climate optimum on land coeval with SST maximum in the mid-latitudes of the eastern North Atlantic ocean during the MIS 9e ice volume minimum, and a second forested interval of moderate warming. More importantly, this sequence gives a detailed picture of the vegetation response to millennial-scale climatic variability in NW Iberia. The comparison with the southern Portugueuse margin pollen, SST and hydrological indicator records allowed us to refine and characterize the millennial-scale variability in the Iberian region during this stage. Moreover, the MD01-2443 record (Martrat et al., 2007) shows that the suborbital cold events of high to moderate amplitude detected on land and in the ocean are likely related to changes in deep water circulation and an amplification of the reduction in MOC by iceberg discharges is probable at least during MIS 9d, the mid-MIS 9c cold event and MIS 9b. However, improving the resolution of the sensitive subpolar North Atlantic site ODP 980 is necessary to assess more accurately the changes in MOC and the ice-rafting episodes related to suborbital cooling of MIS 9. Finally, our work provides additional evidence of the pervasive millennial-scale climatic variability in southern Europe throughout past climatic cycles of the Late Pleistocene, regardless of glacial state. However, suborbital vegetation changes associated with SST changes, appears more frequent and of higher amplitude during the 30 000 years following the MIS 9e interglacial period and during the MIS 9a-8 transition. As these intervals can be distinguish by an intermediate to high ice volume and are mainly periods of ice growth, this points at an indirect control of the ice volume on the expression of the millennial climatic change.

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Table 1. Description of the MIS 9 northwestern Iberian margin pollen record.

Pollen zones MD03-2697	Main features of the pollen assemblages	Vegetation formations	Forest stages
M97-10-1	High values of *Pinus*, herbs taxa (mainly Poaceae) and semi-desert taxa. Low *Betula* and deciduous *Quercus* percentages.	Dry grasslands with birch and deciduous oak woodlands and pine populations	
M97-9-1	Highest *Betula* values, continuous Cupressaceae curve and deciduous *Quercus* percentages increase. Steady Ericaceae and *Artemisia* values. Fall of *Pinus* and Poaceae percentages.	Establishment of a temperate and humid forest with pioneer tree development	Pontevedra
M97-9-2	Phase with maximum deciduous and evergreen *Quercus* values, *Alnus* increase and *Pistacia*, *Olea* and *Cistus* occurrences. Fall of herbs taxa and *Pinus* percentages.	Dominant deciduous oak forest with some Mediterranean plants	
M97-9-3	Deciduous *Quercus* values drop and maximum and percentages of *Alnus*, *Taxus*, *Fraxinus excelsior*-type *Carpinus betulus*, occurrence of *Corylus*, and *Fagus*. Increase of *Betula*, semi-desert taxa, Ericaceae and *Pinus* percentages	Deciduous oak forest mixed with hornbeam, yew and birch, and some groves of hazel, beech, ash, yew, and heathland	
M97-9-4	Low deciduous *Quercus* and Betula values, *Corylus*, *Carpinus betulus* and *Fagus* occurrences. High *Pinus*, Poaceae, *Taraxacum*-type and Ericaceae percentages	Heathland and grassland with temperate taxa woodlands and pine populations	
M97-9-5	Phase with deciduous *Quercus*, *Alnus*, *Carpinus betulus*, *Pinus*, Ericaceae and Poaceae. Mediterranean taxa occurrence. Sharp fluctuations of deciduous *Quercus*, Ericaceae and Poaceae.	Open oak forest with hornbeam, beech and evergreen oak groves and with heathland and grassland	Sanxenxo -A
M97-9-6	Phase dominated by NAP taxa, in particular Poaceae, *Taraxacum*-type and Ericaceae. Minimum of deciduous *Quercus* and *Betula*	Grassland and heathland with deciduous oak and birch groves	
M97-9-7	*Betula* peak at the beginning, high deciduous *Quercus*, *Carpinus betulus* and *Corylus* percentages, *Fagus* occurrence, decreasing NAP taxa values but steady Ericaceae percentages	Mixed deciduous oak-hornbeam-hazel forest with beech groves	Sanxenxo -B

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Table 1. Continued.

Pollen zones MD03-2697	Main features of the pollen assemblages	Vegetation formations	Forest stages
M97-9-8	Decrease of deciduous *Quercus*, *Carpinus betulus* and *Corylus* and *Fagus* occurrence. Poaceae, *Taraxacum*-type and *Calluna* rise	Open deciduous forest with grassland	Sanxenxo -B
M97-9-9	Phase with deciduous *Quercus* peak, Ericaceae, *Pinus*	Open oak forest with heathland	
M97-9-10	AP taxa drop, high Ericaceae, Poaceae, *Taraxacum*-type and Cyperaceae percentages, Pinus and semi-desert taxa values increase	Heathland and grassland	
M97-9-11	Phase with intermediate of deciduous *Quercus* and *Betula* values, mesic taxa occurrence and high Ericaceae, Poaceae and semi-desert taxa percentages.	Open temperate and humid forest with heathland	
M97-9-12	Phase with high deciduous *Quercus* percentages and continuous *Alnus*, *Carpinus betulus* and *Fagus* curves, low Poaceae and Ericaceae values, *Pinus* decrease	Deciduous temperate and humid forest with oak dominance	Bueu
M97-9-13	Decreasing values of deciduous *Quercus*, rise of Corylus, *Carpinus betulus* and *Fagus* percentages, low semi-desert taxa and Poaceae values	Mixed hornbeam-beech-deciduous oak forest with hazel groves	
M97-8-1	*Carpinus betulus*, *Fagus* and deciduous *Quercus* fall, NAP taxa rise (mainly Ericaceae, Poaceae and *Taraxacum*-type)	Heathland and grassland with relics of temperate forest	
M97-8-2	Phase with high Ericaceae values, deciduous *Quercus* and *Betula* peaks and *Taraxacum*-type and Poaceae decreases	Heathland with oak and birch groves	
M97-8-3	Rise of the herbs taxa (mainly Poaceae, *Taraxacum*-type and Cyperaceae) and semi-desert plants, Ericaceae decrease, low deciduous *Quercus* values	Open vegetation dominated by grasses (Poaceae and *Taraxacum*) and heath with relics of temperate forest	

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Millennial-scale climatic variability between 340–270 kyr

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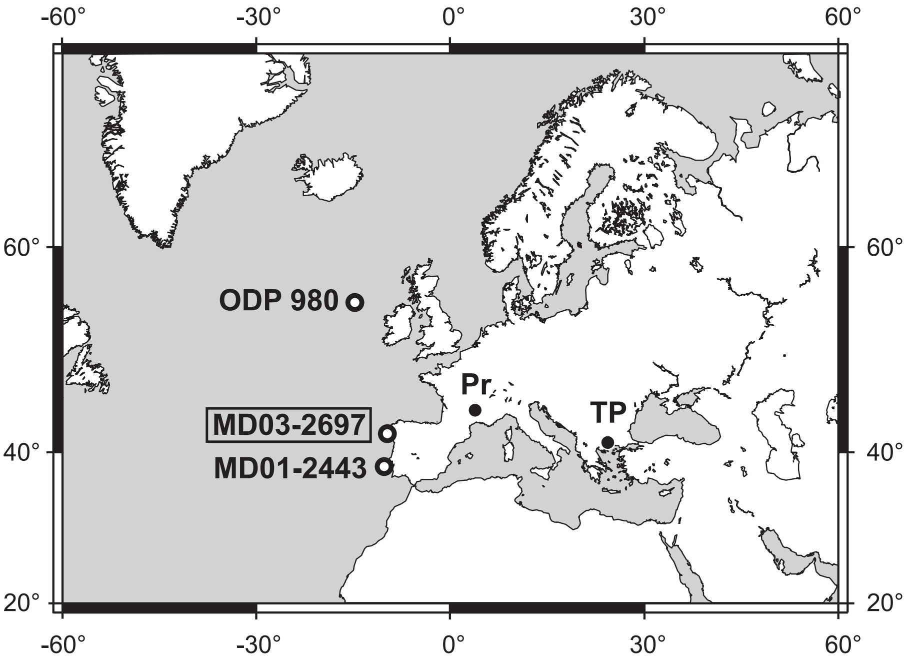

Fig. 1. Location of core MD03-2697 and other marine and terrestrial sequences discussed in the text.

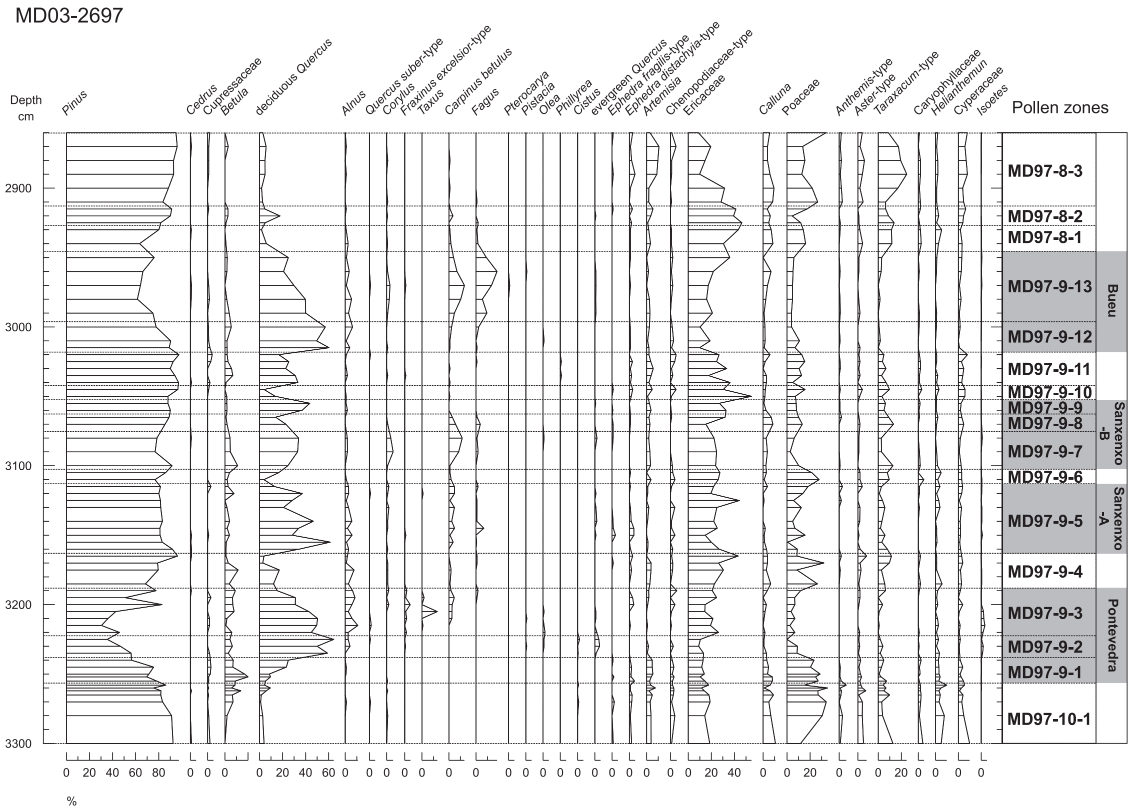

Fig. 2. Percentage pollen data versus depth for core MD03-2697. Pollen zones indicated on the right of the diagram are described in Table 1. The pollen zones are designated by the abbreviated core name (MD97) followed by the MIS number and numbered from the bottom to the top. Local names are given to superzones corresponding to the major forested phases (shaded areas).

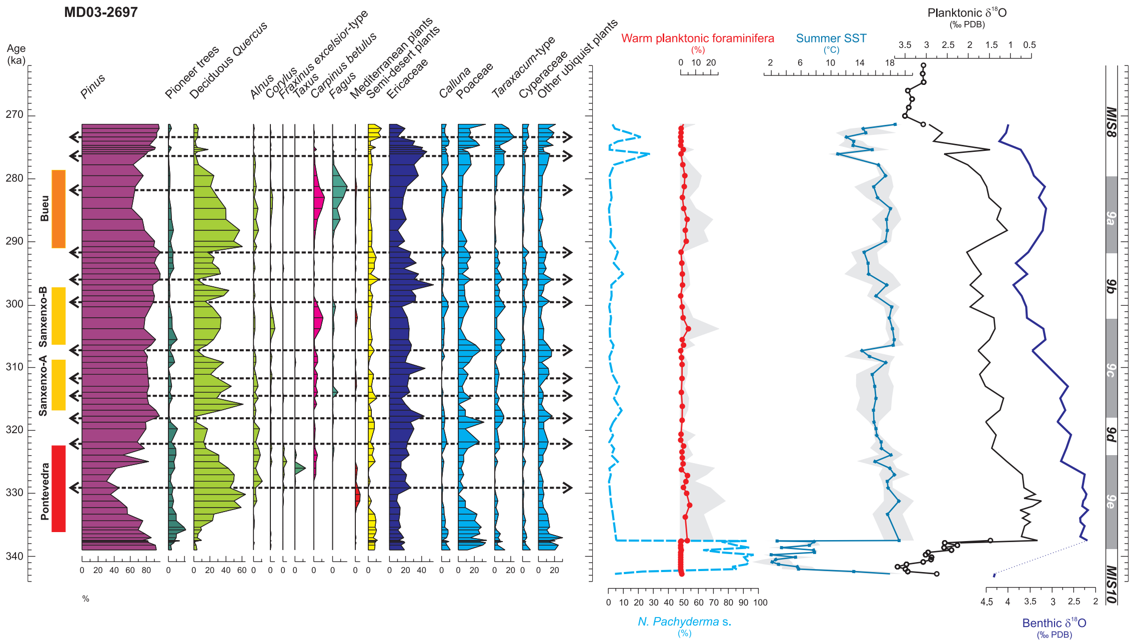

Fig. 3. Percentage pollen data for the main taxa and ecological groups and marine data plotted against age. Major forested intervals and assigned names (filled bars on the left of the diagram). Arrows underline rapid vegetation changes. Marine data are: planktonic foraminifera percentages of polar (*N. pachyderma* s.) and warm (tropical and subtropical) species as defined in Bé (1977), summer sea surface temperature (°C) derived from planktonic foraminifera assemblages, planktonic and benthic δ^{18}O data. Shaded areas show 10 times exaggeration of warm planktonic foraminifera percentages and SST estimation error.

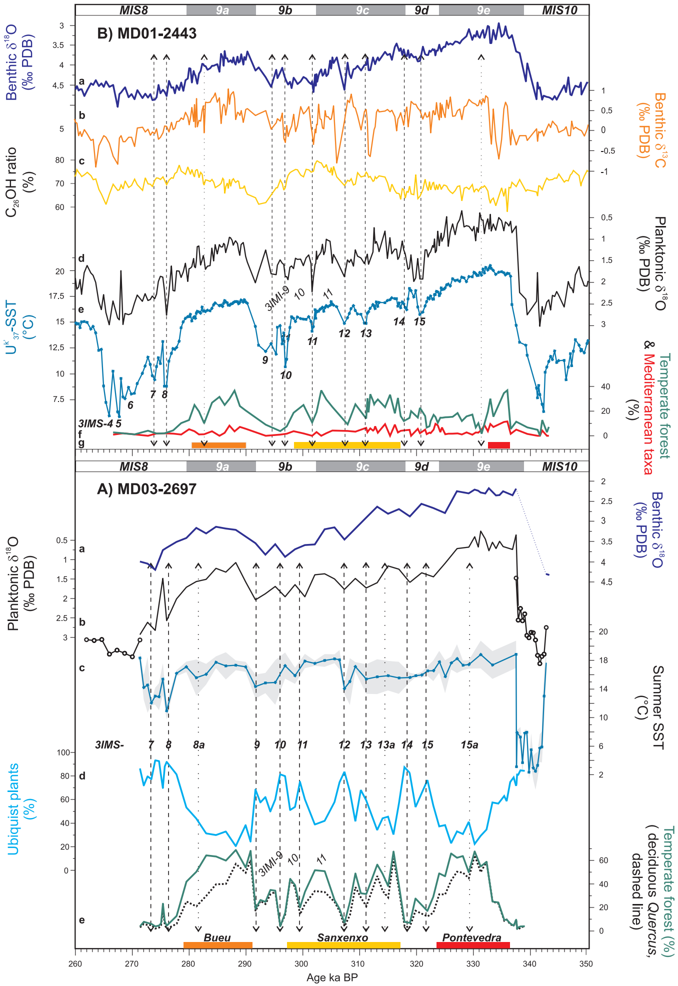

Fig. 4.

Fig. 4. **(A)** MIS 9 multiproxy record from the northwestern Iberian margin (core MD032697, this study) including from the top to the bottom: **(a)** benthic $\delta^{18}O$; **(b)** planktonic $\delta^{18}O$; **(e)** summer SST derived from planktonic foraminifera assemblages (shaded area: SST estimation error); **(f)** Ubiquist herbs pollen percentages; **(g)** percentages of temperate and humid forest and deciduous *Quercus* (dashed line). **(B)** MIS 9 multiproxy record from the southwestern Iberian margin core MD01-2443 (Tzedakis et al., 2004; Martrat et al., 2007) including: **(a)** benthic $\delta^{18}O$; **(b)** benthic $\delta^{13}C$; **(c)** $C_{26}OH$ ratio; **(c)** planktonic $\delta^{18}O$; **(d)** U^{k}_{37}-SST (°C); **(e)** percentages of temperate forest (green) and Mediterranean plants (red). Note that an offset of 0.64 per mil between MD01-2443 and MD03-2697 benthic $\delta^{18}O$ records is the result of the adjustment of the isotopic values to *Uvigerina peregrina* in the SW Portuguese margin record while in core MD03-2697 isotopic measurements were performed on *Cibicides wuellerstorfi*. Dashed arrows underline cool/cold episodes. Marine isotope substages and forested intervals are shown by white and grey bands and colour bars, respectively. Iberian Margin Stadials (IMS) are indicating following Martrat et al. (2007). MD01-2443 data are plotted against their own chronologies originally described by Tzedakis et al. (2004) and modified by Martrat et al. (2007).

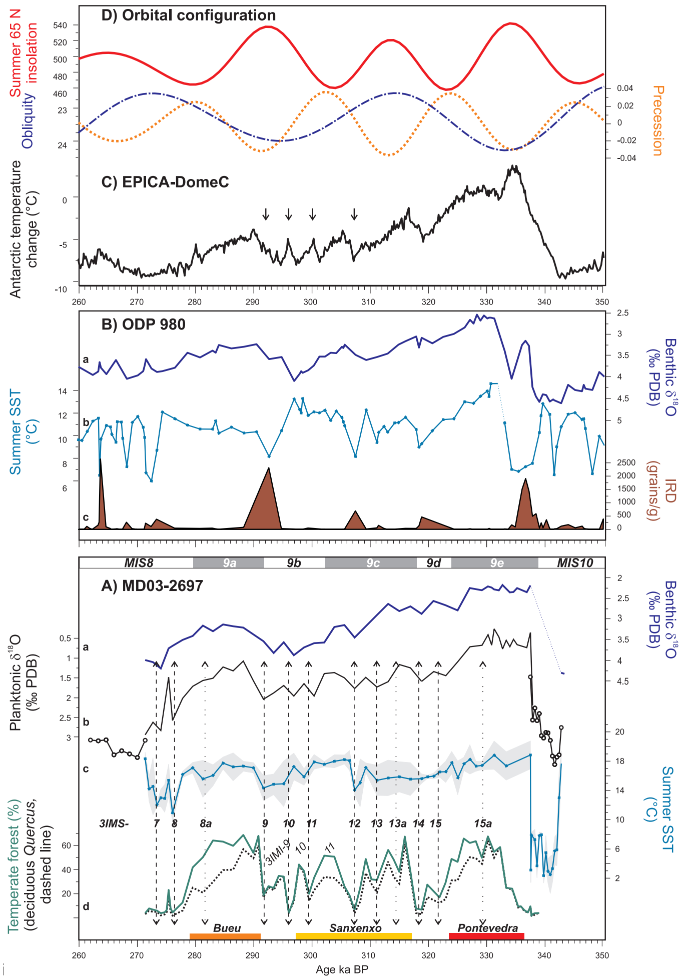

Fig. 5.

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Fig. 5. (A) Multi-proxy record of core MD03-2697 (as shown in Fig. 5) **(B)** ODP site 980 record composed of **(a)** benthic δ^{18}O, **(b)** SST derived from isotopic data; **(c)** ice rafted detritus (McManus et al., 2001, 1999). A new chronology for ODP site 980 MIS 9 interval was established by graphical correlation between the benthic δ^{18}O curves of ODP 980 and MD03-2697 cores. **(C)** EPICA-Dome C temperature estimates from deuterium data on EDC3 timescale (Jouzel et al., 2007) **(a)** D 65°N summer insolation (W/m^2), obliquity and precession index during MIS 9 (Berger, 1978).