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Rapid climatic variability in the west Mediterranean during the last 25 000 years from high resolution pollen data

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Abstract

High-temporal resolution pollen record of Alboran Sea ODP Site 976 and pollen-based quantitative climate reconstruction shows that changes of Mediterranean vegetation have been clearly modulated by short and long term variability during the last 25 000 years. The western Mediterranean vegetation response appears nearly synchronous with North Atlantic variability during the last deglaciation as well as during the Holocene. High-resolution analyses of the ODP 976 pollen record allows to separate the Bölling/Alleröd period in two warm episodes that surround a cooling representative of the climatic succession of the Bölling, Older Dryas and Alleröd. A cooling trend is observed from Bölling to Alleröd. The ODP pollen record confirms that Mediterranean environments show rapid responses to the climatic fluctuations during the last termination, in particular that of all the climate oscillations associated with the successive steps of the deglaciation in the North Atlantic have been observed in the west Mediterranean region. Recurrent Holocene declines of the forest cover on the Alboran Sea borderlands indicate repetitive climate events that correlate well with several events of increased Mediterranean dryness observed on the continent and with alkenone SST showing Mediterranean Sea cooling. These events reflect clearly the response of to Mediterranean vegetation to North Atlantic Holocene cold events.

1 Introduction

In the context of future global warming, the Mediterranean region will clearly be one of the most sensitive to climate changes due to its intermediate geographical position just at the junction of the tropical and the polar influence. These predictive climate changes might have a large influence over its particular environments and dense population. Understanding the present and future environmental changes in Mediterranean includes discriminating natural global variability from human impact. Studying past environmental changes gives us a lot of information in order to draw the complex

picture of the climate changes. Numerous records have demonstrated that Mediterranean environments show rapid responses to the climatic fluctuation during the last climatic cycle (e.g. Allen et al., 2002; Bout-Roumazeilles et al., 2007; Brauer et al., 2007; Cacho et al., 1999, 2001; Combourieu-Nebout et al., 1999, 2002; Fletcher and Sanchez Goni, 2008; Sanchez Goni et al., 2002; Watts et al., 1996; Kotthoff et al., 2008). This is probably due to the climate specificity of the Mediterranean region that combines polar and tropical influences generating very sensitive environments strongly adapted to the summer dryness and mild winter, probably among the most reactive to climate changes. Some multiproxy records have demonstrated that Mediterranean environments have responded to short-term Holocene climatic events (e.g. Cacho et al., 2001; Frigola et al., 2007; Rohling et al., 1998, 2002). But rare pollen-based studies provide evidence of a clear response of the Mediterranean vegetation to these short-lived Holocene events (Allen et al., 2002; Jalut et al., 2000; Naughton et al., 2007). Several qualitative climate interpretations, mainly based on lacustrine records, have already been obtained for part of this period; however, they differ significantly, particularly regarding the Mediterranean area (e.g. Sadori and Narcisi, 2001; Antonioli et al., 2001; Marchal et al., 2002; Magny et al., 2007). This is mainly due to the scarcity of high resolution sequences covering the last 25 000 years in this region and also a lack of robust quantitative estimates of climate parameters in southern Europe and the Mediterranean for the last 25 000 years (Huntley and Prentice, 1988; Huntley et al., 1999; Allen et al., 2002, Cheddadi et al., 1997, 1998; Davis et al., 2003; Brewer et al., 2007; Fletcher et al., 2009; Dormoy et al., 2009).

In order to show the sensitivity of Mediterranean vegetation to last deglaciation and Holocene events, we present here high temporal resolution pollen analyses of the last 25 000 years from ODP Leg 161 Site 976. This very detailed study allows for the identification of centennial to millennial scale vegetation changes in the western Mediterranean and to reconstruct quantitative estimations of climatic parameters.

Consequently, our study aims to provide a new high resolution pollen analyses and also reliable picture of paleoclimatic variations in the Mediterranean region for the last

25 000 years BP in order to improve the state-of-the-art on environmental changes of the last deglaciation and Holocene (e.g. Allen et al., 2002; Cacho et al., 2001; Frigola et al., 2007; Naughton et al., 2007; Jalut et al., 2002; Björk et al., 1998; Bond et al., 1997; Lowe et al., 2008; Magny et al., 2006, 2007; Drescher-Schneider et al., 2007; Collombaroli et al., 2008; Rasmussen et al., 2007, 2008).

2 Location and environmental setting

ODP Leg 161 Site 976 was drilled in the Alboran Sea (36°12′ N, 4°18′ W) very close to the Gibraltar strait by the Joides resolution at 1108 m water depth (Fig. 1) (Comas et al., 1999). The Alboran Sea is bordered by the two Arc Mountains of Betic cordillera in Spain and Rif in Morocco. Climate is governed by the influence of the southern Azores anticyclone in summer and the mid-latitude atmospheric circulation in winter that results in a Mediterranean climate with long, dry summers (3 to more than 5 months) and mild, rainy winters (Walter et al., 1975; Quézel and Médail, 2003). Aridity reaches maximum along the southern Spanish coast, but peaks of precipitation occur in the Spanish hinterlands during spring and autumn. In northern Africa, rainfall is concentrated near the coast from autumn to spring and decreases decrease sharply southward (Walter et al., 1975) (Fig. 1). In both areas, the Atlantic influence is marked by increasing humidity in the western lands. The presence of the two Arc Mountains (Moroccan Rif and Betic Cordillera) implies increasing humidity and decreasing temperature and climate range from semi-aride near coast to wet climate at high elevations, which modifies the climate ombrothermic diagram pattern calculated for the Alboran Sea by New LocClim software (Fig. 1) (Grieser et al., 2006). Thus mean temperature of the coldest month varies from less than 10°C near the coast to values between −7° and 0°C at high altitude (above 2000 m) while mean temperature of the warmest month is generally greater than 20°C and mean annual temperature around 18°C. Annual precipitation ranges from less than 400 mm in the lowlands to more than 1400 mm in the Betic and Rif mountains (Quezel and Médail, 2003; Grieser et al., 2006). Such climatic and geographic conditions in

the Moroccan Rif and in the Betic Cordillera generate Mediterranean landscapes organised in altitudinal belts according to the ecologic and climatic requirements of the plants (Ozenda, 1975; Rivas Martinez, 1982; Polunin and Walter, 1985; Barbero et al., 1981; Benabib, 1982, 2000; Quezel, 2002; Quézel and Médail, 2003). Modern vegetation environments are divided into four classifications. A thermomediterranean belt is found in the lowlands with *Olea*/*Pistacia sclerophillous* schrubland and some associated steppe or semi-desert representatives (*Artemisia*, *Chenopodiaceae*, *Ephedra*). At mid-altitude both mesomediterranean belt, represented by the *sclerophyllous* oak forest, and humid-temperate oak forest (eurosiberian trees as *Quercus*, *Betula* ... and *Ericaceae*) are found. At higher altitude is a supramediterranean belt with a cold-temperate coniferous forest (*Pinus*, *Abies* and/or *Cedrus*, the latter living only in Morocco today at high elevation).

3 Methodology

3.1 Chronology

Our study concerns the uppermost 10 m of the ODP Site 976 core. The age model for this interval is based on ten ^{14}C AMS radiocarbon ages of monospecific samples of *Globigerina bulloides* and *Neogloboquadrina pachyderma* (left coiling) from the size fraction >125 µm (Fig. 2, Combourieu Nebout et al., 2002) and were performed at the Leibniz-Laboratory of Kiel University. All these ^{14}C ages have been corrected by 400 years to account for ^{14}C reservoir age of the modern Alboran Sea surface water, but being aware that some modifications of ^{14}C reservoir ages may have occurred during the studied interval (Bard, 1998; Siani et al., 2000, 2001). Conversion into calendar ages are based on recent calibrations (Calib software 5,02 version, Stuiver et al., 1993, 2005). According to this age model, our record spans the last 25 000 cal years (Fig. 2). The temporal resolution between samples varies from ~20 to 40 years for the abrupt events and 200 to 500 years elsewhere.

3.2 Pollen data

This core was sampled at 10 cm intervals and every 1–5 cm during the Bölling/Alleröd and the beginning of the Holocene. Pollen extractions followed classic protocol (Faegri and Iversen, 1964; Combourieu-Nebout et al., 2002): after drying, samples were processed with 25% cold HCl, cold 70% HF, 50% HCl and sieved on a 10 µm sift. Due to overrepresentation of *Pinus* pollen grains in marine sediments, at least 300 pollen grains (100 pollen grains excluding *Pinus*) were counted in each sample. *Pinus* pollen percents were calculated on the total pollen sum while other pollen percents were calculated on a sum excluding *Pinus*.

Pollen analysis yielded a rich microflora with 120 identified pollen taxa. Palynological interpretations are based on the assumption that pollen grains mainly originates from the borderlands of the Alboran Sea basin, essentially Morocco and Spain. The fossil pollen spectrum ranges from semi-desert to montane deciduous and coniferous forest allowing that the interpretation follows the modern climatic-plant relationships in Eurasia and northern Africa (Woodwards, 1987; Peyron et al., 1998).

3.3 Pollen-inferred climate reconstructions and biomisation

The Modern Analogues Technique (MAT), also called the best analogues method, first developed by Overpeck et al. (1985) and extended by Guiot (1990) to reconstruct climate parameters from fossil assemblages for past key periods has been applied to the ODP 976 pollen sequence. This method has been extensively used for the Late glacial and the Holocene climate reconstructions in Europe (e.g. Cheddadi et al., 1998; Davis et al., 2003; Peyron et al., 2005; Bordon et al., 2009; Magny et al., 2009; Kotthoff et al., 2008). The principle of this technique is (1) to compare, using a dissimilarity index, the fossil pollen assemblages with the modern pollen assemblages collected in a high-quality and taxonomically consistent modern pollen dataset, (2) and to select, for each fossil assemblage, several closest modern pollen assemblages (or best modern analogues). The selection of the best modern analogues (here 10) is based on the

calculation of a chord distance measured between each fossil and modern pollen assemblage (Guiot, 1990). The climatic values of each fossil assemblage are obtained as a weighted average of the climate parameters of the best analogues selected (Guiot, 1990). The climate parameters of each modern pollen record have been calculated and interpolated at each site using the high resolution database of climatic means of New et al. (2000). We have selected the mean temperature of the warmest month (Tsum) and coldest month (Twin), as these are important climate parameters controlling the plant distribution after Prentice et al. (1992), and also the mean annual temperature (TANN), mean monthly precipitation in summer (Psum) and mean monthly precipitation in winter (Pwin).

The MAT, like most of the approaches which aim to quantitatively reconstruct the past climate from fossil assemblages, is based on the present-day environments, and therefore requires high-quality, taxonomically consistent modern datasets. In this study, the method is based on an updated modern pollen-climate dataset which comprises 3530 pollen data sampled from a wide variety of biomes (Bordon et al., 2009). Among these 3530 samples, more than 2000 pollen spectra taken from mosses samples, soil or core samples are located in the Mediterranean basin (Spain, Morocco, Italia and Turkey). As *Pinus* is always overrepresented in marine sediments, we removed this taxon from the modern spectra as well as from the fossil spectra.

The character of past vegetation can be inferred from pollen analytical data in various ways, qualitative (pollen analyses and biomes) or more objective and quantitative (quantifications of climate parameters). In the present study, we have chosen to couple both approaches in order to reconstruct past vegetation changes by looking at the vegetation structure or biome. In Europe, 11 biomes are usually found in modern samples: tundra, cold deciduous forest, taiga, cool conifer forest, cold mixed forest, temperate deciduous forest, cool mixed forest, and more frequently in the Mediterranean area: warm mixed forest, xerophytic wood/shrub, steppes/temperate grassland, or desert. This approach allows the objective assignment of pollen taxa to plant functional types (PFTs) and to biomes on the basis of the modern plant ecology, bioclimatic toler-

ance, and phenology. We applied the biomisation technique described by Prentice et al. (1996), adapted by Peyron et al. (1998), Tarasov et al. (1999a, b), and largely used in Europe (Müller et al., 2008) and the Mediterranean (e.g. Allen et al., 2000; Huntley et al., 2003; Bordon et al., 2009) to each marine pollen assemblage. For each sample, the associated biome has been defined following the plant functional type-biome assignments procedure based on Prentice et al. (1996), and Peyron et al. (1998).

4 West Mediterranean vegetation and climate changes over the last 25 000 years BP

The reliability of pollen analyses in such sediments has already been clearly established thanks to several marine surface sediment studies (Heusser and Balsam, 1977; Hoghiemstra et al., 1992, 1995, 2006; Turon, 1984, Naughton et al., 2007).

The ODP pollen record shows a good correlation with other Alboran Sea cores (Fletcher and Sanchez Goni, 2008), Portuguese margin cores (Turon et al., 2003; Naughton et al., 2007) as well as with terrestrial sequences from southern Spain (Pons and Reille, 1988; Carrion et al., 2007) and northern Morocco (Cheddadi et al., 1998, 2009; Lamb et al., 1989). This demonstrates the reliability of our marine record to highlight the response of the Spanish and Moroccan vegetation to the successive climate events over the last 25 000 years (Table 1, Fig. 2).

If the main part of pollen flora of ODP record may originate from Spain as well as from Morocco, the presence of *Cedrus* in noticeable percentages marks without any doubt input from the south (Quézel and Médail, 2003; Quezel, 2002; Magri et al., 2002). This indicates that, in the Alboran area, pollen results correspond to the combination of north and south supplies (Bout-Roumazeilles et al., 2007), making our pollen record a reliable synthetic picture of the vegetation changes from the whole Alboran Sea area.

4.1 Late Pleniglacial

Between 25 000 and 23 000 years BP, the pollen associations reflect a broad extension of steppe or semi-desert with the dominance of *Artemisia* and *Chenopodiaceae*, in addition to reduced temperate forest as shown by very low percentages of deciduous *Quercus* (Table 1, Fig. 2). These vegetation assemblages are indicative of enhanced drought in the Alboran Sea borderlands that match the timing of the Heinrich 2 event (Elliot et al., 1998). Reconstructed biomes from pollen data correspond to an alternance of warm and cold steppe (Fig. 3). Pollen-inferred climatic parameters indicate that cold and dry conditions prevailed during H2 in the Alboran Sea (values in anomalies: −20°C in winter; −15 to −10°C in annual, −8°C in summer; −200 mm in winter, +100 in summer) (Fig. 3). The annual temperature (TANN) curve shows the same climate trend although with higher amplitude as the alkenone-based temperature record that indicates a decrease of about 3 degrees during Heinrich Event 2 (Cacho et al., 1999, 2001) (Fig. 4). The semi-desert phase is contemporaneous with a peak of Neoglobiquadrina pachyderma sinistra coiling and increasing abundance of the dinocyst Bitectatodinium tepikiense that both indicate a refreshment of Alboran Sea surface temperatures (Combourieu-Nebout et al., 2002). Such a synchronization between marine and continental changes during this time slice is also recorded in other Atlantic and Mediterranean cores (Combourieu Nebout et al., 1998, 2002; Sanchez Goni et al., 2002; Turon et al., 2003; Naughton et al., 2007, Fletcher et al., 2009) and allows correlation of this episode with Heinrich event 2. In the ODP record, this event is placed between 25 000 and 23 500 cal years BP, a time slice that corresponds well with the established ages (Bond et al., 1993; Elliot et al., 1998).

Between 23 000 and 19 000 years, a time-period that corresponds roughly to the LGM (Mix et al., 2001; Kucera et al., 2005), the vegetation becomes an open, herbaceous heath, associated with cedar forest (probably at altitude) after 20 000 years BP (Figs. 2 and 3). Such associations reflect that climate was more humid although cool, clearly different from the *Artemisia* semi-desert association recognized during Hein-

rich 2 that depicted a cold-arid climate. Reconstructed biomes are here dominated by warm steppe with rare cold steppe/temperate grassland and temperate deciduous forest samples. The quantitative climate reconstruction indicates high amplitude climate oscillations during this period characterised by a slightly moist climate with cool temperatures in agreement with the pollen assemblages. Results are presented in terms of anomalies regarding to present-day values: TANN anomalies around −5°C with Twin −10° to −15°C (Fig. 3). However our anomalies are slightly lower during the Last Glacial Maximum that during the H2 event and are similar to the SST anomalies deduced from quantitative reconstructions of foraminifer associations (Hayes et al., 2005; Kuhleman et al., 2008). These climate reconstructions are consistent with the LGM values reconstructed for the Mediterreanean region by Wu et al. (2007) with an other climate reconstruction method, the inverse vegetation modelling technique, and are 5°C higher than the values reconstructed by Peyron et al. (1998), with the plant functional type method. These values are also in better agreement with the recent atmosphere general circulation models simulations for the Last Glacial Maximum period (Kageyama et al., 2005; Jost et al., 2005; Ramstein et al., 2007).

Between 18 000 and 21 000 cal years BP, it is noteworth that some temperatures and precipitations reconstructed are clearly too warm and humid, therefore nearby present day ones. At the same time, it is surprising that the reconstructed biomes indicate the biome "temperate deciduous forest" whereas the pollen association lacks representatives of this biome (*Quercus* and others). This discrepancy is correlated with the high distances recorded all over this period between ODP samples and the MAT analogues and is probably due to a lack of good present-day analogues for the cedar/heath pollen association (Fig. 3).

4.2 Heinrich event 1

Between 17 000 and 15 000 years, a large development of *Artemisia*, *Chenopodiaceae*, *Ephedra* associated first with *Asteraceae* indicate an expansion of steppe or semi-desert (Table 1, Fig. 2). Such vegetation changes around 15 000 years BP has been

clearly evidenced and often attributed to the Oldest Dryas (GS-2) event, in the south-west as well as in other parts of the Mediterranean area (e.g. Pons and Reille, 1988; Watts et al., 1996; Combourieu Nebout et al., 1998, 2002; Allen et al., 2002; Penalba et al., 1997; Turon et al., 2003, Naughton et al., 2007; Fletcher and Sanchez Goni, 2008; Bordon et al., 2009). This corresponds with increased dryness over the Mediterranean and especially over the Alboran Sea borderlands. This semi-desert expansion is correlated in the marine environment with a peak in the foraminifer Neogloboquadrina pachyderma sinistral coiling that indicates a new cooling of the sea surface temperatures (Combourieu Nebout et al., 2002). This cold and dry event is consistent with the H1-Oldest Dryas event as recorded in other marine records in the same region (e.g. Fletcher and Sanchez Goni, 2008; Turon et al., 2003; Naughton et al., 2007). A maximum in the occurrence of Cedar reflects the altitudinal vegetation belt with a conifer forest at high elevation of the mountains that probably implies an increasing input from the south (Magri et al., 2002). As during H2, the reconstructed biomes from pollen data correspond to an alternance of warm and cold steppe/temperate grassland; while reconstructed annual temperature and precipitation show very cold conditions (Twin anomalies: around −20°C, Tsum anomalies: around −8°C, Pwin anomalies: −200 to −300 mm, Psum anomalies: 0 to 50 mm) (Fig. 3). The annual temperatures are colder than the sea surface temperature reconstructed in the Mediterranean (Kallel et al., 1997, Rohling et al., 1998); however, the annual temperature trend reconstructed here fits remarkably well with the alkenone SST record in the nearby MD 95-2043 marine core, although the ODP temperature values deduced from MAT pollen reconstruction are colder with an abrupt decrease of temperature values (Fig. 4).

4.3 Bölling-Alleröd

From 14 700 to 12 500 yr, the first large increase in deciduous (mainly *Quercus*) and Mediterranean forests corresponds to the Bölling-Alleröd interstadial (GI-1). During this period, *Cedrus* occurs regularly (15–20%), while, among the herbs, the *Cichoriodeae* remain present (15–20%) and semi-desert taxa such as *Artemisia* strongly decrease

(Table 1, Fig. 2). Such an association implies settling of the forest into altitudinal belts in the Betic and Rif Arc mountains with a likely enhanced wind input from the south (Magri and Parra, 2002; Bout Roumazeille et al., 2007). This development of Mediterranean oak forest at the expense of semi-desert formations is largely recognized in all the Mediterranean records. Our diagram may then be easily correlated to the well known Padul peat bog pollen diagram in the south of Spain (Pons and Reille, 1988). Nevertheless, Mediterranean taxa are less represented in marine than in continental records. This discrepancy is probably due to the location of the Padul peat bog at 785 m elevation in the altitudinal range of the *Quercus ilex sclerophyllous* forest (Barbero et al., 1992). Climatic reconstructions reveal temperature and precipitation values comparable to those depicted during the Holocene. The biome reconstructions clearly indicate temperate deciduous forest; however, some samples are still associated with a steppe biome (Fig. 3), and could indicate the occurrence of rapid and abrupt climate events during the Lateglacial. Two clear climate warmings with development of forest are depicted during this period from 14 800 to 14 120 yr and from 13 800 to 12 800 yr. They may be interpreted as the well-known Bölling and Alleröd warmings (Figs. 3 and 4) described in Europe and the Mediterranean (e.g. Magny et al., 2006; Drescher-Schneider et al., 2007). A rapid cold climate oscillation is depicted from 14 120 to 13 800 yr (Fig. 4, od event) with a weak decrease in forest recover that may be related to the Older Dryas or GI-1d event (Wohlfart, 1996; Bjork et al., 1998; Lowe et al., 2008). The chronology of site 976 is in accordance with both North GRIP and GISP chronozones GI-a to c, d and e (Table 2, Rasmussen et al., 2006, 2008; Lowe et al., 2008). Nevertheless, pollen record does not permit to easily distinguish GI-1a, b,c, although we clearly see biome changes from temperate deciduous to steppic during the Alleröd interstadial around 13 200 yr that may be related to GI-1b (Fig. 4). In our record, the Bölling interstadial appears slightly less warm as recorded by a weaker development of temperate forest than during the Alleröd interstadial (Fig. 4). It suggests a warming trend from Bölling to Alleröd as also evidenced in the oxygen isotope record based on stalagmites from southern France (Genty et al., 2006). Such a trend appears in opposition to the cool-

ing recorded in the North GRIP and GISP curves and in the Mid-European lake isotope signal which show a warmer Bölling followed by a regular trend decreasing intensity of the Alleröd warm events (Rasmussen et al., 2006, 2007; Lowe et al. 2008; NGrip members, 2004; Johnsen et al., 2001; von Grafenstein et al., 1999). Our results reinforce the evidence of a general north to south climatic trend during the Bölling/Alleröd period documented by the ice cores, lake and stalagmites records showing cooling in Greenland and northern Europe and climate stability or warming in the southern Europe and North Africa (Genty et al., 2006).

4.4 Younger dryas

Between 12 500 and 11 750 years, an increase of *Artemisia* and semi-desert taxa could indicate the return to cold conditions related to the Younger Dryas event (YD) (Table 1, Fig. 2). This event is recorded throughout the Mediterranean by many proxies from both continental and marines sites (e.g. Pons and Reille, 1988; Lamb et al., 1989; Watts et al., 1996; Combourieu Nebout et al., 1998, 2002; Allen et al., 1996, 2002; Penalba et al., 1997; Turon et al., 2003; Naughton et al., 2007; Fletcher and Sanchez Goni, 2008; Bordon et al., 2009). This period may be divided into two parts: a very dry period at the beginning (12 500 to 12 200 years) which corresponds to the increase of *Artemisia* and a more humid period (12 200 to 11 750) at least at mid to high elevation, indicated by correlative presence of *Artemisia* semi-desert and cedar forest together with a slight increase of *Quercus* forest (Fig. 3).

The biomisation indicates both steppe at the beginning of the YD and temperate deciduous forest during the second part. During the first *Artemisia* semi-desert phase, cold and dry conditions are first reconstructed for all climate parameters anomalies except for the Psum anomaly that slightly increases. This could imply that the seasonality during the Younger Dryas was different than today (Dormoy et al., 2009). Finally, Twin and Pwin increase at time of presence of cedar in vegetation. These results suggest storage of fresh water in continental ice sheet during the dry and cold phase of the Younger Dryas whereas the following humid period may reflect enhanced precipitation

possibly due to a more efficient hydrological cycle. Alternatively, it could also correspond to a latitudinal shift of the Westerlies northward during the early phase and to the south afterwards that may be linked to peculiar atmospheric configurations.

4.5 Holocene

The onset of the Holocene appears clearly after 11 750 years in the Alboran Sea by the large expansion of forest mainly composed of *deciduous Quercus* in association with Mediterranean *sclerophyllous* forest (mainly *Q. ilex* type and *Pistacia*) (Table 1, Fig. 2). Such a vegetation change is classically observed at the beginning of Holocene in the whole Mediterranean region (e.g. Pons and Reille 1988; Lamb et al., 1989; Watts et al., 1996; Combourieu-Nebout et al., 1998, 2002; Allen et al., 1996, 2002; Penalba et al., 1997; Turon et al., 2003; Naughton et al., 2006; Fletcher and Sanchez Goni, 2008; Bordon et al., 2009). This marks the progressive onset of present-day both altitudinal vegetation belts and Mediterranean climate. This forest expansion is correlated with the shift of the oxygen isotope curve towards low values which reflects the climate improvement at the beginning of Holocene in the marine environment (Combourieu-Nebout et al., 1998, 1999, 2002). This climate improvement reaches two maxima around 9000 and 7000 years BP that surround a forest decrease event around 8000 years. The maximum extension of *Quercus* forest marks the Holocene climate optimum. The biome assignment shows an alternance of temperate, deciduous forest and warm, mixed forest, especially around the 8.2 ka event, with rare steppe in the last millennia probably due to the anthopogenic impact. The climate reconstruction shows warm and humid conditions (Fig. 3), this last also depicted by the increase in fresh water *algae* input (Fig. 2). The annual temperature (between 0 and −5°C) and precipitation (between 0 and 100 mm) anomalies are consistent with the reconstructions obtained for southern Spain by the inverse modelling method for the mid-Holocene period (i.e. 6000 years BP ; Wu et al., 2007; Brewer et al., 2007).

After 7000 years, a large regressive trend occurs with a substantial decrease of the forest cover which marks the upper late Holocene cooling trend that is not clearly ex-

pressed with the climate parameters changes (Fig. 3). Between 4000 and 1500 years, rapid vegetation changes mark abrupt forest cover expansion/regression episodes. In the younger samples (younger than 500 years), *Artemisia* increases again, and suggests the changes in the recent times vegetation cover probably related to a slight anthopogenic impact.

The general warming then cooling trends of the Holocene are interrupted by several rapid oscillations depicted in the forest curves which may be interpreted as short-lived climate events at 11.95–11.4, 11–10.8, 10.5–9.8, 9.6–8.9, 8.5–7.9, 6–4.5, 3.7–3.1, 2.6–2.3 and 1.5–0.7 kyr that have been named ACP 1 to 8 (Tables 2 and 3, Fig. 4). Similar changes in the composition of vegetation during the Holocene have also been documented in the Italian Monticchio series (Allen et al., 2002) and in the Spanish Peninsula (Jalut et al., 2000). Even if no noticeable increase in steppic vegetation occurred during these events, some of them may be chronologically linked to the Holocene aridification episodes documented in the continental pollen records over southern Spain. Therefore APC 1, 2, 4, 5 and 7 may be correlated to the aridification events 6, 5, 3, 2 and 1 indicated by Jalut et al. (2000) (Table 3, Fig. 5).

These rapid and repetitive forest cover fluctuations do not imply abrupt changes in climate parameters as shown by the slight changes in MAT reconstructed temperature (TANN, Twin) and/or in precipitation (PANN, Pwin) anomalies (Fig. 4). This is particularly evidenced for the 8.2 kyr event, marked by a larger decrease in temperate, humid forest associated with increased *Cichoriodeae* and only represented by slight changes in reconstructed climate parameters (Fig. 3). Nevertheless, the strong decrease in temperate, humid forest that marks the 8.2 kyr event may be linked to a decrease in humidity (Dormoy et al., 2009) that correlates to the low lake-levels recorded in the same period in southern Spain and northern Morocco (Magny et al., 2003; Lamb et al., 1995.)

The variability of vegetation cover may also be correlated to the marine environmental changes recorded with the alkenone SST events in other cores located in the Gulf of Cadix, Alboran and Tyrrhenian Sea (Cacho et al., 2001) (Fig. 4) and with δ^{18}O

events evidenced in Balearic basin (Frigola et al., 2007) (Table 3). A tentative correlation between west Mediterranean vegetation events and these marine cold events is presented in Fig. 5. Taking into account the different chronological framework, each ODP forest event may correlate to west Mediterranean marine cold events. However, a comparison between the Alboran Sea pollen and alkenone records shows that more events are expressed on the continent (Fig. 4). Thus, ACP 6, 3 and 2 are absent in the Alboran Sea alkenone SST record. If we look only on the pollen-inferred TANN and SST alkenone curves, this discrepancy disappears (Fig. 4) and may be related to the precipitation effect that is combined with temperature influence in our vegetation record.

The nine pollen events depicted in ODP 976 may also be linked to the North Atlantic Holocene cold events (Bond et al., 1993, 2001). We present here a possible correlation (Fig. 5, Table 3). According to our chronology, ACP 1, 2 and 4 to 8 may be related to Bond events 1, 2 and 4 to 8. ACP 4 could include two Bond events, 3 and 4 probably, because, at the time of Bond event 3, only a very slight change appears in our record. In fact, this event corresponds here simultaneously with an increase in *Ericaceae* and the minimum representation of *Quercus* (Figs. 2 and 3) resulting only in a slight decrease in our temperate forest curve around 4500 yr (Fig. 4). During the Holocene, beside being represented on their own chronological scale, the timing of ACP events is very consistent with the North Atlantic Bond events (Bond et al., 1993, 2001) and Mediterranean similar climate events defined both in marine and continental series (Cacho et al., 2001; Frigola et al., 2008; Jalut et al., 2000, 2009). This suggests a very rapid response of Mediterranean vegetation to short-term climate forcing.

These repetitive short-lived events recorded in the ODP pollen data reveal the high variability of continental climate in the Mediterranean region during the Holocene and confirm the far-reaching impact of North Atlantic cold events on both marine data (Cacho et al., 2001; Frigola, 2007) and continental vegetation of the whole Mediterranean (this work; Allen et al., 2002; Jalut et al., 2000, 2009). Our results highlight the main control of precipitation on Mediterranean vegetation, that reflect the Ocean-

Atmosphere coupling through the apparent link between North Atlantic SSTs and atmospheric configuration (Cacho et al., 2001).

5 Conclusions

Mediterranean vegetation changes have been clearly modulated by short-term and long-term variability of North Atlantic. High-temporal resolution pollen record of Alboran Sea ODP Site 976 shows the synchronicity of western Mediterranean vegetation response to North Atlantic variability during the last deglaciation and Holocene. During the Bölling/Alleröd period, two warm episodes surround a cooling, representing the climatic succession of Bölling, Older Dryas and Alleröd with a cool trend from Bölling to Alleröd. Recurrent Holocene declines of forest cover on the Alboran Sea borderlands correlate with the SST coolings and are timely correlated to the North Atlantic cold events. That suggests the rapid response of Mediterranean vegetation to Holocene short-time climate events and reflects the large Ocean-Atmosphere coupling.

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Table 1. Chronostratigraphy, description of the ODP Site 976 pollen zones with their main representative biomes deduced from pollen association.

Chronostatigraphy	Pollen zone	Pollen signature	Main dominant biome
Holocene	ODP 976-6d	Increase in *Pinus* (30%), mediterranean forest (20%), *Ericaceae* (15%) and *Cichoriodeae* (25%) Peak in *Artemisia* (10%) Decrease in *Quercus* (<30%)	Warm mixed forest
	ODP 976-6c	Oscillations in *Quercus* (30–50%) Reappearance of *Artemisia* in low percentages, low percentages in *Cichoriodeae* (<10%) and *Ericaceae* lower than 10%	Warm mixed forest Temperate deciduous forest
	ODP 976-6b	Increase in *Ericaceae* (15%) and *Cichoriodeae* (25%) *Quercus* decrease (<30%)	Warm mixed forest Temperate deciduous forest
	ODP 976-6a	Regular decrease in *Pinus* (70→30%) and *Cedrus* (30→5–10%) Higher abundance of *Quercus* (40–60%) and increase in mediterranean forest (10–15%) Regular presence of *Pistacia* and *Olea* *Isoetes* regularly abundant	Warm mixed forest Temperate deciduous forest Climatic optimum
Younger Dryas	ODP 976-5b	*Pinus* (70%) Increase in *Cedrus* (30%) Low representation in *Quercus* (<20%) Decrease in *Artemisia* and *Chenopodiaceae* and persistance of *Ephedra* *Pteridophytae* (5–10%)	Temperate *deciduous* forest
	ODP 976-5a	*Pinus* (<50%) Increase in all semidesert taxa (*Artemisia* – 20%, *Ephedra* – 5%, *Chenopodiaceae* – 15%), Decrease in all trees (*Cedrus* <10%, *Quercus* <20%)	Temperate decodupus forest Steppe
Bölling/Alleröd Alleröd	ODP 976-4c	*Pinus* (40–60%) Increase in temperate (30%) and mediterranean forests (15%) Decrease in semi desert (<15%) *Isoetes* in low percentages (1–5%)	Temperate deciduous forest Warm mixed forest
Older Dryas	ODP 976-4b	*Pinus* (40–60%) Decrease in temperate Slight increase in semi desert (<15%)	Warm steppe
Bölling	ODP 976-4a	*Pinus* (40–60%) Increase in temperate (30%) and mediterranean forests (15%) Decrease in semi desert (<15%)	Temperate deciduous forest Warm mixed forest

Table 1. Continued.

Chronostatigraphy	Pollen zone	Pollen signature	Main dominant biome
Oldest Dryas – H1	ODP 976-3b	*Pinus* (70–80%) Low percentages in *Quercus* and temperate forest (<10%), presence of pioneers trees (Alnus) Decrease in *Ericaceae* (15→5%) Increase in semi desert associations (*Artemisia* 20–40%), *Chenopodiaceae* (10–20%), *Ephedra* (5–10%) *Cichoriodeae* decrease (20→<10%)	Steppe
	ODP 976-3a	*Pinus* (60–70%) *Cichoriodeae* abundant (25%), *Poaceae* (5–10%) Low percentages in temperate and mediterranean forest (<10%) *Ericaceae* decrease (20–10%) *Cedrus* decrease (20→<10%)	Warm steppe
Late pleniglacial	ODP 976-2b	*Pinus* (80%) Low percentages in temperate and mediterranean forest (<10%) *Cedrus* abundant (10–25%) *Ericaceae* abundant (15–25%) Semi desert elements in low representation (*Artemisia* <10%, *Ephedra* <5%, *Chenopodiaceae* <10%) *Cichoriodeae* (15%)	Temperate deciduous forest
	ODP 976-2a	*Pinus* (60%) *Cedrus* (<10%) Low percentages in temperate and mediterranean forest (<10%) *Ericaceae* abundant (15–25%) *Cichoriodeae* in high percentages (20–40%)	Steppe
H2	ODP 976-1	*Pinus* (35–60%) Low percentages in temperate and Mediterranean forests (<10%) *Ericaceae* (10–30%) semi desert taxa abundant (*Artemisia* 20–50%), *Chenopodiaceae* (5–15%), *Ephedra* (1–5%) *Cichoriodeae* (15–35%), *Poaceae* (5%)	Steppe

Table 2. Age comparison between Alboran Sea pollen event from ODP 976 record and Greenland records during the Bölling/Alleröd period. Ages are in kyr.

Ngrip and Grip*		Alboran Sea		
Events	Cal age in kyr	Pollen event**		Cal age in kyr
GS-1	12.896[a,b]–11.703[a,b]	Younger Dryas		12.8–11.75
GI-1a	13.099[b]–12.896[a,b]	Alleröd interstadial	Mpol 1a	13.8–12.8
GI-1b	13.311[b]–13.099[b]			
GI-1c	13.954[b]–13.311[b]			
GI-1d	14.075[a,b]–13.954[b]	Older dryas stadial	Mpol 1b	14.12–13.8
GI-1e	14.692[a,b]–14.075[a,b]	Bölling interstadial	Mpol 1c	14.8–14.12

*,a Rasmussen et al. (2006)
b Lowe et al. (2008)
** this work

Table 3. Age comparison between Alboran Sea pollen events from ODP 976 record, North Atlantic cold events (Bond et al., 1993), aridification events in the continental sites (Jalut et al., 2000), and with Mediterranean marine events from alkenone record in Adriatic Sea, Tyrrhenian Sea and Gulf of Cadix (Cacho et al., 2001) and from oxygen isotope record off Balearic islands (Frigola et al., 2007). Ages are in kyr.

North Atlantic Cold event[a]	Pollen events[b]	Aridification events[c]	Mediterranean			$d^{18}O$ events[e]
			Gulf of Cadix	SST events[d] Alboran Sea	Tyrrhenian Sea	Minorca
1 1.4	APC 1 0.7–1.5 (1.1)	6 0.75–1.3	–	AC1 1.01–1.9	TC1 1–1.91	M1 1.4–1.8
2 2.8	APC 2 2.3–2.6 (2.45)	5 1.7–2.8	–	–	TC2 2.5–3.45	M2 2.3–2.6
–	APC 3 3.14–3.77 (3.36)	4 3.4–4.3	–	–	–	M3 3.1–3.4
3 4.3	ACP 4 4.5–6 (5.2)		–	–	–	M4 4–4.2
4 5.9		3 4.2–5.3		AC2 4.75–5.94	TC3 5.28–6.58	M5 4.7–5.3
5 8.2	APC 5 7.9–8.5 (8.2)	2 7.6–8.4	CC1 7.8–8.25	AC3 7.56–9.08	–	M8 7.8–9
6 9.5	APC 6 9.6–8.9 (9.35)	? 9–9.5	–	–	TC4 9.13–9.62	–
7 10.3	APC 7 9.8–10.5 (10.35)	1 9.7–10.9	CC2 9.9–10.2	AC4 9.95–10.34	TC5 9.62–10.38	–
8 11.1	APC 8 10.8–11 (10.9)		–	AC5 10.95–11.21	–	–
–	APC 9-YD1 11.4–11.75 (11.57)		CC3 12.2–12.4	AC6 11.65–11.9	TC6 10.9–11.78	–
YD 12.5	YD2 11.75–12.8 (12.37)		CYD 12.6–12.9	AYD 12–13.1	TYD 12–13.09	–

[a] Bond et al. (1997)
[b] this work
[c] Jalut et al. (2002)
[d] Cacho et al. (2001)
[e] Frigola et al. (2007)

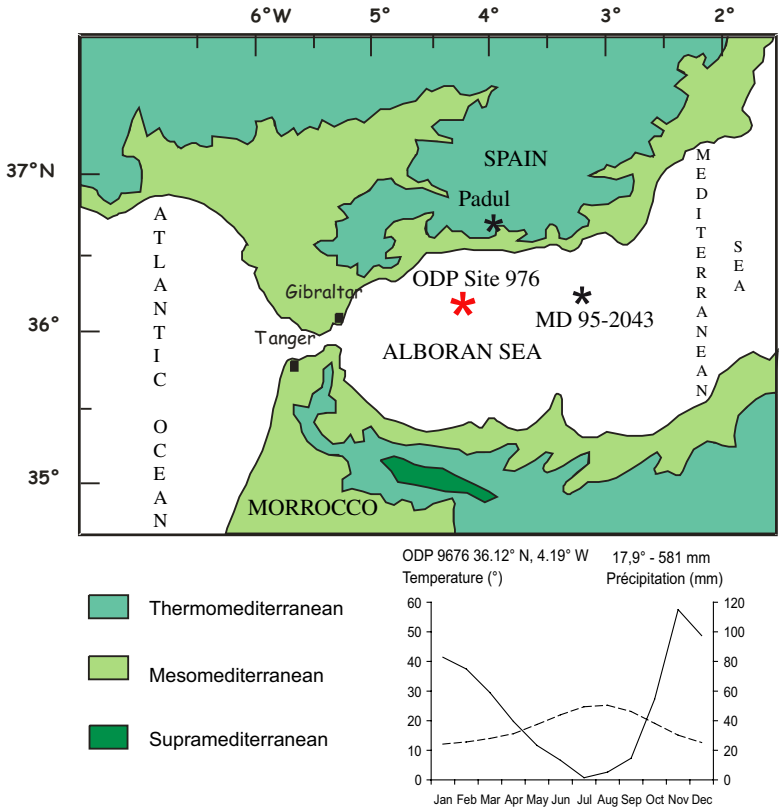

Fig. 1. Location map of the ODP Site 976. Climate diagram showing the present day climate (annual precipitation and temperature distribution) at site ODP Site 976 (at sea level) calculating with New Locclim software.

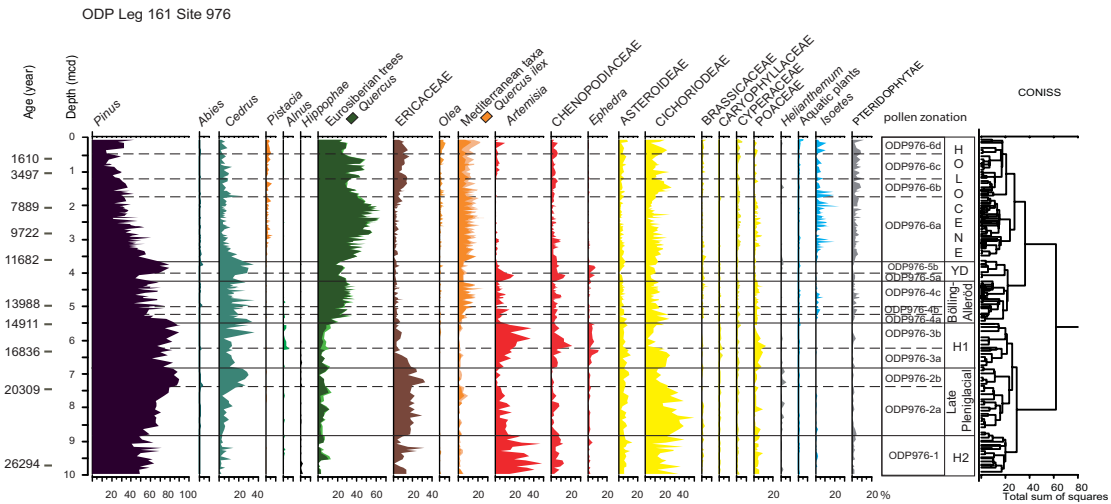

Fig. 2. Pollen percentages diagram. Percentages plotted against depth. Percentages have been calculated on a sum excluded *Pinus* except the *Pinus* curve calculated on the total sum of pollen. On the left, radiocarbon ages (in cal years) are plotted in depth. On the right, the pollen zones with their boundaries informed by analysis of the pollen data using CONISS (Grimm, 1986) and the resulting dendrogram.

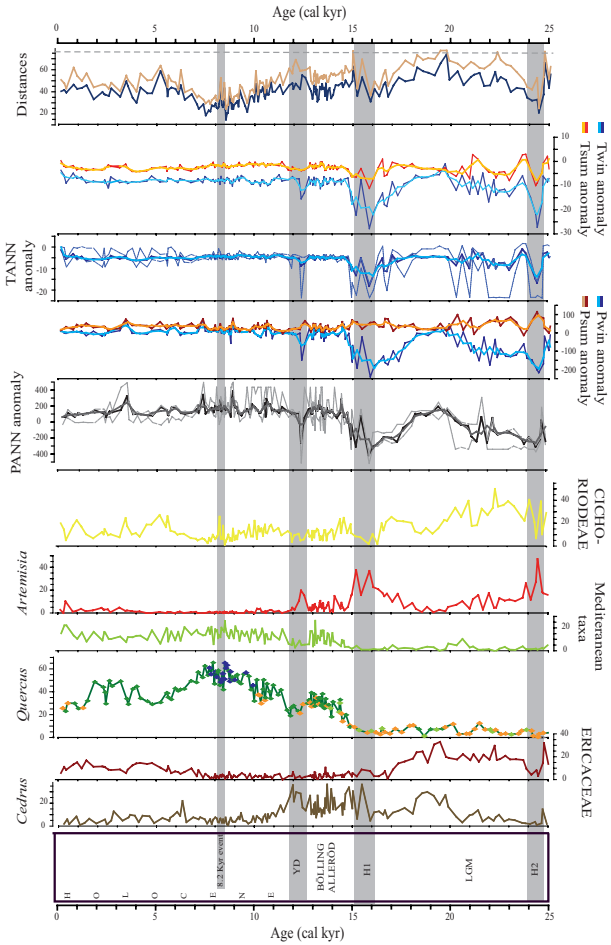

Fig. 3.

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Fig. 3. ODP Site 976 main pollen percentage curves (*Cedrus*, *Ericaceae*, *Quercus*, Mediterranean taxa, *Artemisia*, *Chenopodiaceae*, *Cichorioideae*).
ODP climate anomaly curves versus present day for PANN (annual precipitation), Pwin (winter precipitation) and Psum (summer precipitation), TANN (annual temperature), Tsum (mean temperature of the warmest month), Twin (mean temperature of the coldest month) from MAT method (dark colour curves present the MAT values and light colour curves the 3 point smoothed curves). The Dissimilarity index (Chord distance) measures the quality of the reconstruction through the modern analogues selection. On the right size are represented the calculated distances of the first (blue) and the last (orange) of the best analogues selected. The dotted line marks the threshold value (here 77,9) obtained from the Monte carlo method defined in Guiot et al. (1990).
Biomes deduced from MAT method are plotted on the *Quercus* percentage curve (warm mixed forest in dark blue, temperate deciduous forest in green, warm steppe in yellow-orange and cold steppe in olive green).

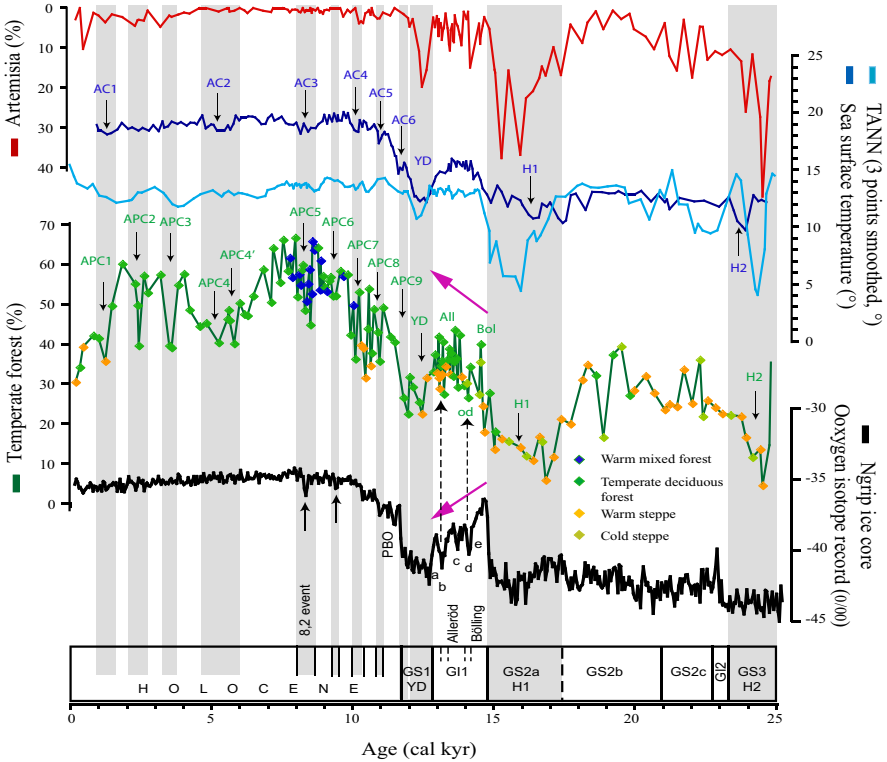

Fig. 4. Correlation between the climate events occurred during the Last Deglaciation and Holocene between Alboran Sea pollen record and associated TANN reconstruction (3point smoothed), Alboran Sea alkenone SST record from MD 95-2043 and Ice core record from Greenland. Events are underlined in grey and with black arrows.

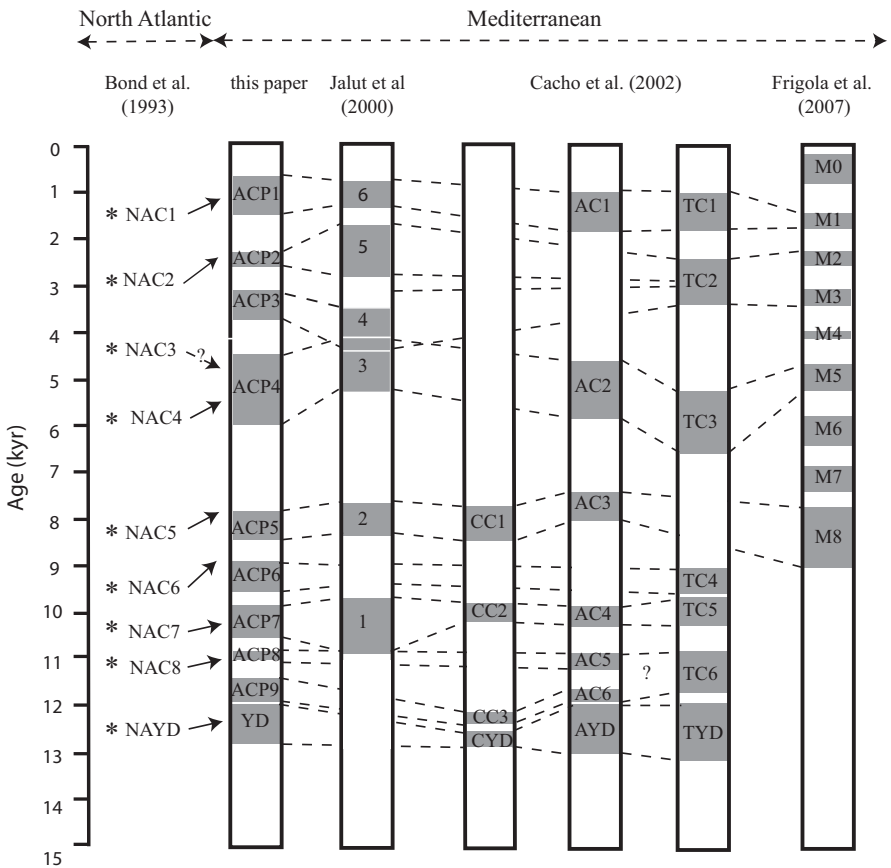

Fig. 5. Correlation between Alboran Sea pollen events from ODP 976 record, North Atlantic cold events (Bond et al., 1993), aridification events in the continental sites (Jalut et al., 2000), and Mediterranean marine events from alkenone record in Adriatic Sea, Tyrrhenian Sea and Gulf of Cadix (Cacho et al., 2001) and from oxygen isotope record off Balearic islands (Frigola et al., 2007).