Enhanced aridity and atmospheric high-pressure stability over the western Mediterranean during the North Atlantic cold events of the past 50 k.y.

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ABSTRACT

Multiproxy paleoenvironmental records (pollen and planktonic isotope) from Ocean Drilling Program Site 976 (Alboran Sea) document rapid ocean and climate variations during the last glacial that follow the Dansgaard-Oeschger climate oscillations seen in the Greenland ice core records, thus suggesting a close link of the Mediterranean climate swings with North Atlantic climates. Continental conditions rapidly oscillated through cold-arid and warm-wet conditions in the course of stadial-interstadial climate jumps. At the time of Heinrich events, i.e., maximum meltwater flux to the North Atlantic, western Mediterranean marine microflora and microfauna show rapid cooling correlated with increasing continental dryness. Enhanced aridity conceivably points to prolonged wintertime stability of atmospheric high-pressure systems over the southwestern Mediterranean in conjunction with cooling of the North Atlantic.

Keywords: Mediterranean, paleoenvironments, paleoclimate, last glacial, Heinrich event, aridity.

INTRODUCTION

Paleoclimatic records from polar ice cores and marine sediment cores provide compelling evidence that climatic conditions during the last glacial were highly variable (Johnsen et al., 1992; Broecker et al., 1992; Grootes et al., 1993; Bond et al., 1993; Grousset et al., 1993; Cortijo et al., 1995). Particularly striking are the millennial-scale Dansgaard-Oeschger (D-O) oscillations (Johnsen et al., 1992; Grootes et al., 1993; Meese et al., 1997) and the drastic cooling during the North Atlantic Heinrich events (Bond et al., 1993; Bond and Lotti, 1995; Cortijo et al., 1995; Vidal et al., 1997; Elliot et al., 1998). By contrast, there are few terrestrial paleoclimatic data from continental sediment cores that clearly indicate high cyclic variations of the vegetation cover in Europe (Watts et al., 1996; Allen et al., 1999) and North America (Grimm et al., 1993) during the last glacial. Attempts of correlation with the oceanic response, although indirect with such continental records, show that in Florida, moist periods occur during Henrich events (Grimm et al., 1993). Recent correlations between marine and continental proxy data in a core off Portugal show large development of dry climate–type vegetation in the west Iberian Peninsula, correlating to the ice-rafted detritus discharge and associated with North Atlantic cooling (Sanchez Goni et al., 2002).

Here we present a direct marine to continental climate correlation by using high-resolution multiproxy records from Ocean Drilling Program (ODP) Site 976 in the Alboran Sea, the westernmost section of the Mediterranean Sea (36°12N, 4°18W, 1108 m water depth) (Fig. 1). The records provide new insight into the evolution of marine and terrestrial paleoenvironments during the past 15 k.y., and enable a direct correlation with climates in the larger North Atlantic region; the records may help to resolve some discrepancies between previous marine and terrestrial results (Watts et al., 1996; Paterne et al., 1999).

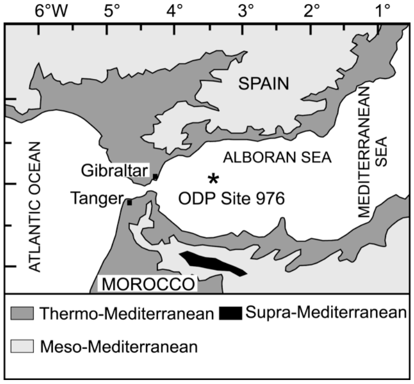

Figure 1. Location of Ocean Drilling Program (ODP) Site 976. Simplified vegetation map is after Ozenda (1975) and Rivas Martinez (1982).

METHODOLOGY

Isotope measurements were performed on a Finnigan MAT 252 mass spectrometer and Kiel CARBO II carbonate preparation device using 15–25 specimens of *Globigerinoides bulloides* from the size fraction 250–355 μm. Precision of the measurements was better than 0.06% (von Grafenstein et al., 1999). Micropaleontologic analyses were performed on the size fraction >125 μm, and more than 300 specimens were counted by samples. After drying, palynological samples were processed with 25% cold HCl, cold 70% HF, 50% cold HCl, and sieved on a 10 μm screen. Pollen grains and dinocysts were counted on the same slides (>100 grains except *Pinus* and >300 cysts were counted per sample). Paleoenvironmental interpretation of the downcore pollen assemblage fluctuations is based on the assumption that the primary pollen contribution to Alboran Sea sediments comes from western Mediterranean borderlands. Modern environments range from a thermo-Mediterranean belt, with *Olea*, *Pistacia*, and some steppe or semidesert representatives (*Artemisia*, Chenopodiaceae, *Ephedra*), to a meso-Mediterranean belt, represented by a sclerophyllous oak forest to a humid-temperate oak forest (mainly *Quercus* associated with Ericaceae), to a supra-Mediterranean belt with a cold-temperate coniferous forest (*Pinus*, *Abies*, *Cedrus*) at the higher altitudes (Ozenda, 1975; Rivas Martinez, 1982) (Fig. 1).

We identified 120 pollen taxa ranging from semidesert to mountain deciduous and coniferous forest. Their interpretation follows the modern climatic-plant relationships in Eurasia and northern Africa (e.g., Peyron et al., 1998). Here we present the variations of pollen percentages of two main associations: (1) the temperate association composed of European-

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TABLE 1. RADIOCARBON DATES AND ISOTOPIC EVENT USED FOR AGE MODEL OF OCEAN DRILLING PROGRAM SITE 976

Core, Hole, section, interval (cm)	Sample type	Depth (mcd**)	^{14}C age (yr B.P.)	Error	Calendar age (yr B.P.)
C 1H 1 60–62	*G. bulloides*	0.61	1710	± 40	1620§
C 1H 1 102–104	*G. bulloides*	1.03	3235	± 30	3460§
C 1H 2 63–65	*G. bulloides*	2.14	7010	± 50	7820§
C 1H 2 132–134	*G. bulloides*	2.83	8730	± 60	9700§
C 1H 3 60–62	*N. pachyderma*	3.61	10075	± 50	11 682§
C 1H 4 10–12	*G. bulloides*	4.61	9630	± 60	11 090†
C 1H 4 50–52	*G. bulloides*	5.01	11960	± 80	13 988§
D 2H 3 100–102	*G. bulloides*	5.51	12720	± 80	14 911§
D 2H 4 37–39	*N. pachyderma*	6.38	14330	± 90	16 856§
D 2H 5 2–4	*G. bulloides*	7.53	17220	± 120	20 309§
C 2H 3 55–57	*G. bulloides*	9.78	22420	−310 + 320	26 394§
C 2H 4 47–49	*N. pachyderma*	11.21	27140	−450 + 470	31 776#
C 2H 5 45–47	*N. pachyderma*	12.69	29930	−640 + 700	34 894#
C 2H 6 61–63	*G. bulloides*	14.35	33750	−610 + 660	39 087#
C 2H 6 75–77	*N. pachyderma*	14.49	34230	−1050 +1210	39 608#
D 3H 3 120–122	*G. bulloides*	15.40	35700	−750 + 820	41 194#
D 3H 4 18–20	*G. bulloides*	15.88	32270	−760 + 700	37 473†
Isotope stages	OIS ¾ transition	23.00			58 960*

Note: Accelerator mass spectrometry ^{14}C dates are corrected of the constant water reservoir age of 400 yr.
§ Converted to calendar years after Stuiver et al. (1998) and Bard et al. (1998).
# Converted to calendar years after Bard (1998) and Bard et al. (1998).
* Age after Martinson et al. (1987).
† Dates rejected as abnormally young.
**Meters composite depth.

Siberian trees such as *Quercus*, *Fagus*, *Carpinus*, *Corylus*, *Alnus*, *Betula*, *Tilia*, and *Ulmus* associated with Ericaceae, reflecting the warmer and moist climate characteristics of interstadials, and (2) the steppe to semidesert association, composed of *Artemisia*, Amaranthaceae-Chenopodiaceae, and *Ephedra*, which marks the dry and cold climatic conditions of stadials.

CHRONOLOGY

The chronology of Site 976 is based on 13 accelerator mass spectrometry (AMS) radiocarbon ages measured at the Leibniz-Labor of Kiel University on monospecific samples of *Globigerina bulloides* and *Neogloboquadrina pachyderma* (left coiling, l.c.) from the size fraction >125 μm (Table 1). All ^{14}C ages have been corrected by 400 yr to account for isotope fractionation during atmosphere-ocean carbon transfer (Bard, 1988; Siani et al., 2000). Conversions into calendar years use the calibrations of Bard et al. (1998) and Stuiver et al. (1998) for the ages younger than 24 ka and the method of Bard (1998) and Bard et al. (1998) for ages older than 24 ka. To complete our chronology for the base of the sequence, we considered the marine oxygen isotope stage (OIS) 3/4 event, deduced from the isotope chronology developed by von Grafenstein et al. (1999) (Table 1). Thus, according to this age model, our record spans the past 50 k.y. and time steps between samples vary between 300 and 800 yr (Fig. 2). The chronology is confirmed by the close correlation of our paleoclimatic records with the GISP2 (Greenland Ice Sheet Project 2) ice-core δ^{18}O record from Greenland (Grootes et al., 1993).

RESULTS AND DISCUSSION

The studied sequence displays a high-resolution continuous record from the last glacial through the Holocene (Fig. 2). High variability both in the continental (vegetation) and in the oceanic signals (δ^{18}O) is recorded during the last glacial. By contrast, the Holocene paleoenvironments are characterized by more stable conditions with much smaller amplitude variations.

Dansgaard-Oeschger (D-O) Oscillations

High-amplitude shifts during the last glacial are displayed in the pollen and δ^{18}O records,

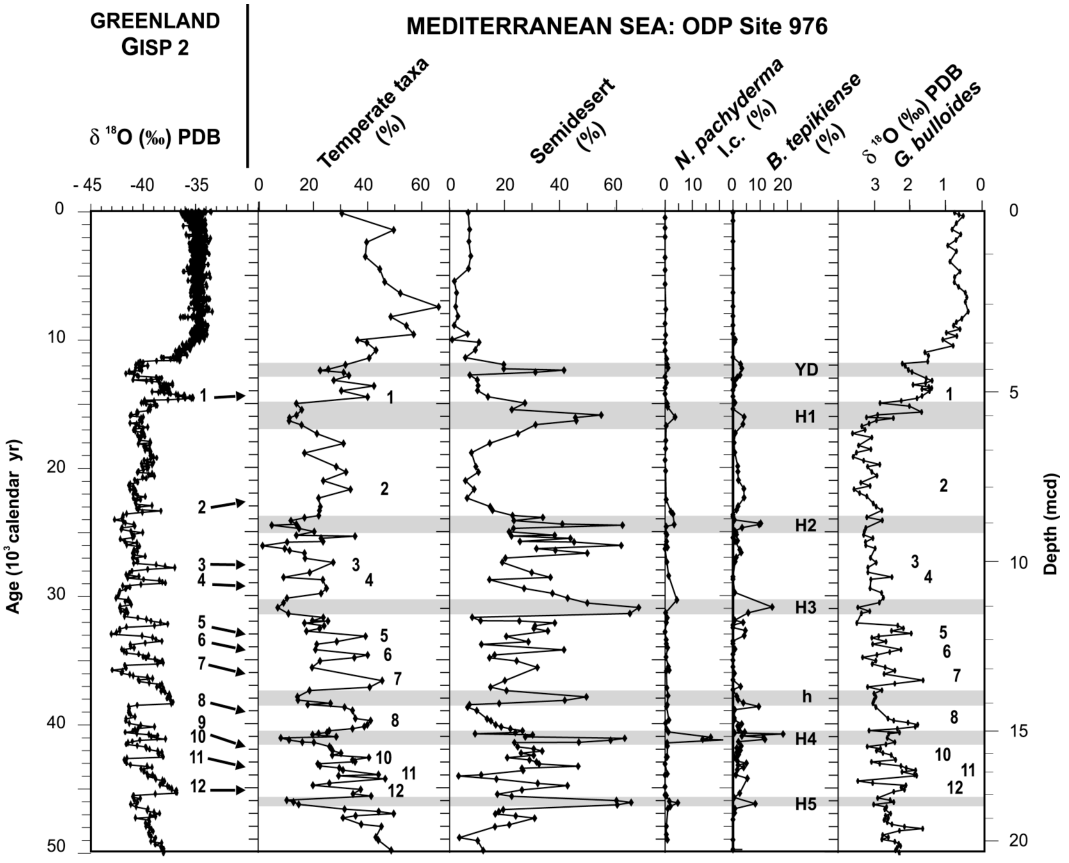

Figure 2. Comparison between GISP2 (Greenland Ice Sheet Project 2) record and paleoenvironmental reconstructions from Ocean Drilling Program (ODP) Site 976. GISP2 δ^{18}O record is shown along calendar-year time scale (Meese et al., 1997) (PDB is Peedee belemnite). Site 976 curves are plotted along calendar-year time scale (on left) and mcd (meter composite depth, on right); curves are for relative frequencies of temperate taxa and semidesert taxa, relative abundance of *N. pachyderma* (l.c.), relative abundance of *B. tepikiense*, and planktic δ^{18}O record. Dansgaard-Oeschger interstadials 1–12 are indicated along Site 976 records through graphical correlation with Greenland ice core record. At Site 976, Heinrich events H1–H5 are underlined by gray shading.

which indicate rapid oscillations of environmental conditions in the westernmost Mediterranean (Fig. 2). High downcore variability of pollen assemblages reflects repetitive alterations between temperate forest (mainly *Quercus*) very similar to today's vegetation in the mountains of the western Mediterranean to semidesert vegetation, as observed today in North Africa and southeastern Europe (Walter, 1974). These vegetation changes are indicative of very abrupt climatic changes in the Alboran Sea borderlands between warm-moist and cold-dry conditions. The pattern of temperate taxa shows 11 increases in temperate-vegetation abundance that correlate with the D-O interstadials 1–12 in the Greenland ice-core records (Johnsen et al., 1992; Grootes et al., 1993; Meese et al., 1997). The colder stadials are characterized by abundance increases in semidesert taxa. The abrupt and high-amplitude oscillations of marine and terrestrial climates recorded at Site 976 also correlate well with a record of sea-surface temperature (SST) changes, derived from a record of long-chain alkenone undersaturation, along core MD 952043 in the east Alboran Sea (Cacho et al., 1999).

Linking with North Atlantic Meltwater Events

Particularly striking are the five short-lived abundance maxima of polar planktic foraminifera *Neogloboquadrina pachyderma* (l.c.) that have also been observed in other Mediterranean sediment cores (Rohling et al., 1998; Cacho et al., 1999). In our core, coeval increases of the cold-water dinocysts *Bitectatodinium tepikiense* immediately prior to the abrupt warming events of D-O interstadials 1, 2, 4, 8, and 12 suggest a correlation with North Atlantic Heinrich events H1–H5 (Bond et al., 1993; Rasmussen et al., 1996; Elliot et al., 1998). Even if ice-rafted debris, the key indicator of Heinrich events in the North Atlantic, is not observed at Site 976, the *B. tepikiense* abundance peaks reflect the cold-water influxes associated with the Heinrich events. They occur at 16 118 calendar (cal.) yr BP (13 719 ^{14}C yr BP, 6.05 m composite depth or mcd), 24 419 cal. yr BP (20 732 ^{14}C yr BP, 9.05 mcd), 30 948 cal. yr BP (26 413 ^{14}C yr BP, 10.99 mcd), 41 115 cal. yr BP (35 627 ^{14}C yr BP, 15.35 mcd), and 46 223 cal. yr BP (18.33 mcd), which is very close to the established ages of Heinrich events H1–H4 (Elliot et al., 1998) and H5. The contention of abrupt cooling is confirmed by coeval increases in *N. pachyderma* (l.c.) abundances that, according to Rohling et al. (1998), reflect SST decreases of 5–8 °C below present-day SSTs. Such a decrease is comparable to the drop of $\sim$4 °C in SST derived from the alkenone proxy analyses during H1–H5 analyses in the Alboran Sea (Cacho et al., 1999). Synchronous with the *N. pachyderma* (l.c.) peaks in our core, increases of *B. tepikiense* imply a higher seasonal temperature contrast in the Alboran Sea surface waters at that time. In present-day environments, high abundances of this species, which is absent from the Mediterranean today, correspond to SSTs of $\sim$15 °C in summer and $\sim$1 °C in winter (Rochon et al., 1999). Comparison with modern SSTs in the Alboran Sea—maxima of 20 °C in summer and 15 °C in winter (Levitus, 1982)—implies that the enhanced temperature contrast indicated by the presence of *B. tepikiense* was induced by a winter SST decrease. Such cooling of the SSTs could be linked to cold-water advection from the Atlantic Ocean (Cacho et al., 1999) or to a regional cooling related to atmospheric conditions over the Mediterranean Sea. These marine climatic events are clearly correlated with continental cooling stadials from the same site that have the lowest occurrences of temperate taxa and, especially, the highest representation of semidesert (*Artemisia*, *Ephedra*, and Chenopodiaceae) taxa. Such associations are characteristic of cool steppe to cool desert (Tarasov et al., 1998), and thus suggest enhanced aridity on the adjacent westernmost Mediterranean borderlands during Heinrich events. This finding is consistent with the results obtained from sediment cores in the northeast Atlantic Ocean off Portugal, and the eastern Alboran Sea (Sanchez Goni et al., 2002), and notably, continental Mediterranean records (Watts et al., 1996; Allen et al., 1999). However, these implications contradict the contention that Mediterranean freshwater budgets during the Heinrich cold events were similar to modern ones in the area (Paterne et al., 1999). In contrast with North Atlantic records, no clear correlations with the δ^{18}O are seen in the ODP 976 core, presumably because salinity effects compensated for the effect of decreased temperature on δ^{18}O.

Weaker increases of *Artemisia* are seen during other cold phases and are sometimes correlated with small but significant increases in the percentages of cold-water *B. tepikiense*. One such event, between Heinrich events H4 and H3—immediately before interstadial 7 and at an interpolated age of 37 911 cal. yr BP (13.9 mcd)—may be related to the intermediate-cooling event ''h'' identified by Bond and Lotti (1995). Slight changes of the terrestrial vegetation are seen in response to other D-O stadials, whereas no significant changes are recorded in the marine microflora and microfauna. Such a difference in amplitude of the inferred climatic change between D-O stadials and Heinrich events is also seen in the nearby Alboran Sea alkenone SST record (Cacho et al., 1999), and shows a close connection between the response of the marine and continental paleoenvironments and the intensity of the ensuing climate changes.

Present-day Mediterranean climate is characterized by prolonged summer dryness and mild rainy winters (Walter et al., 1975). This climate is due to the displacement of the meteorological equator from north in summer to south in winter, which induces the southward trajectory of mobile polar highs, considered to be the conveyors of the intrahemispheric exchanges between polar and temperate latitudes (Leroux, 2000). We suggest that during the D-O interstadials, the atmospheric situation caused climatic conditions close to present-day ones. Within stadials, the meteorological equator probably did not shift southward during winters, which resulted in prolonged winter droughts over the western Mediterranean area. An atmospheric connection that involves changes in strength and position of the subtropical jet stream during winter has previously been called upon as a mechanism to explain the climatic changes recorded in the east Pacific and Arabian Sea during the last glacial (Sirocko et al., 1999). Likewise, enhanced winter dryness since 1980 in the Mediterranean has been linked to an increased stability of atmospheric high-pressure cells over southern Europe in response to the increase in the frequency and velocity of cold and dry mobile polar highs (Leroux, 2000). Moreover, during the same period, dryer and cooler conditions were also implied over the Mediterranean area by the high and positive North Atlantic oscillation (Hurell and Van Loon, 1997; Cullen et al., 2001). These observations lend credence to our interpretation that the increased aridity and desertification in the Mediterranean region during Heinrich events was caused by prolonged wintertime anticyclonic stability, likely combined with a positive North Atlantic Oscillation mode and cooling in the North Atlantic region. The enhanced aridity during these episodes resulted from increased winter dryness that enforced the detrimental effects of an already prolonged summer dryness on Mediterranean climates. Such drastic change in Northern Hemisphere atmospheric circulation is consistent with the changes in Greenland ice-core glaciochemical records that indicate a more vigorous atmospheric circulation during the cold stadial phases of the D-O oscillations and notably during the Heinrich events (Mayewsky et al., 1997).

CONCLUSIONS

The combined marine-terrestrial records at Site 976 show that during the last glacial, aridity increased noticeably in the westernmost Mediterranean borderlands far beyond its present state in association with a substantive cooling of the sea-surface waters. These episodes were tightly linked to millenial scale D-O climatic oscillations and especially to larger scale Heinrich cold events. By analogy with the recent climatic development in the area since 1980, we infer that intensified dryness in the Mediterranean region during Heinrich events has been caused by prolonged winter anticyclonic stability in conjunction with cooling in the North Atlantic region and, during these periods, the effects of the regular long summer dryness were further intensified by winter dryness.

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