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Centennial- to millennial-scale climate oscillations in the Central-Eastern Mediterranean Sea between 20,000 and 70,000 years ago: evidence from a high-resolution geochemical and micropaleontological record

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ABSTRACT

Here we present a high-resolution faunal, floral and geochemical (stable isotopes and trace elements) record from the sediments of Ocean Drilling Program Site 963 (central Mediterranean basin), which shows centennial/millennial-scale resemblance to the high-northern latitude rapid temperature fluctuations documented in the Greenland ice cores between 20 and 70 kyr BP.

Oxygen and carbon isotopes, planktic foraminifera and calcareous nannofossil distributions suggest that Dansgaard–Oeschger (D/O) and Heinrich events (HE) are distinctly expressed in the Mediterranean climate record. Moreover, recurrent though subdued oscillations not previously identified in the Late-glacial Mediterranean sediments document a significant centennial-scale climate variability in the basin that is greater than previously thought.

Alternations between climate regimes dominated by polar outbreaks during D/O stadials and warm D/O interstadials, with associated intensification of continental runoff, are well expressed in the ODP Site 963. These place the Mediterranean basin as an often overlooked recorder of the interplay between large- and regional- scale climate controls at intermediate latitudes, and of the possible interactions between different components of the climate system. Significant changes in Ba/Ca values measured in *Globigerinoides ruber* shells from a number of D/O stadials and interstadials suggest enhanced freshwater input from the north-eastern Mediterranean borderland during the D/O interstadials. However, the short duration of 3D stratification events never led to complete oxygen consumption along the water column, but clear effects of sluggish 3D circulation in the basin are testified to by negative excursions in $\delta^{13}C$ measured in selected species of planktic and benthic foraminifera.

HEs are constantly associated with lightening in the $\delta^{18}O$ record of planktic foraminifera, possibly because of the impact of iceberg melting in the Iberian Margin on Mediterranean thermohaline circulation. Interestingly, in two cases in particular, HE2 and HE5, fresher water inputs also affected deeper horizons of intermediate waters, suggesting a basin-wide impact.

1. Introduction

Palaeoclimate studies have revealed the general high-frequency instability of Late Pleistocene climate on timescales of a few millennia, centuries or even decades (e.g., Broecker et al., 1992; Johnsen et al., 1992; Dansgaard et al., 1993; Grousset et al., 1993; Bender et al., 1994; Kotilainen and Shackleton, 1995; Porter and An, 1995; Behl and Kennett, 1996; Mayewski et al., 1996; Schulz et al., 1998; Cacho et al., 1999, 2000; Martrat et al., 2004; Sierro et al., 2005; Sprovieri et al., 2006; Frigola et al., 2008), with rapid cooling (stadials) and warming (interstadials) periods generally referred to as Dansgaard/Oeschger (D/O) millennial oscillations (Dansgaard et al., 1993; Bond and Lotti, 1995). Moreover, a number of massive ice-rafted detritus episodes, called Heinrich events (HE), occurred in the north Atlantic during some of the coldest stadials at

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the end of long-term cooling trends that include several D/O oscillations (Heinrich, 1988; Bond and Lotti, 1995).

The high sensitivity of the Mediterranean Sea to prompt recording of climate changes is related to the reduced volume of the basin, its restricted communication with the open ocean, the geographical position at the boundary between the subtropical/monsoon regime and the temperate westerlies. These characteristics render this area extremely attractive because it reliably and specifically documents the major climate changes influencing intermediate northern latitudes.

The key location of Ocean Drilling Program (ODP) Site 963 in the central part of the Sicilian Channel, with its documented very high sedimentation rate (Di Stefano, 1998; Böttcher et al., 2003; Sprovieri et al., 2006; Incarbona et al., 2008, 2009), provides the necessary resolution to analyze centennial/millennial-scale variability during the last glacial period.

The investigation was conducted at high resolution for oxygen and carbon isotope composition of selected species of planktic and benthic foraminifera along with quantitative analysis of the calcareous plankton (calcareous nannofossils and foraminifera) assemblages and Ba/Ca$_{G.\ ruber}$ measurements on a selected number of samples from stadial and interstadial intervals, so as to characterise Mediterranean surface and deeper layers during the Marine Isotope Stages (MIS) 3 and 4. Furthermore, comparison with results from the MD99-2343 high-resolution western Mediterranean sedimentary record (Cacho et al., 1999; Sierro et al., 2005; Frigola et al., 2008) allows discussion of the extent to which the particular zonal-latitudinal morphology of the basin can resolve gradients and discontinuities in global climate forcing.

2. Hydrology and climatology of the present Mediterranean

One of the crucial features of the Mediterranean is that the connection with the open oceans as well as the internal connections between Eastern and Western Mediterranean (EMED and WMED hereafter) are all shallow (from the 284 m of Gibraltar to the 560 m of the Sicilian Channel eastern sill), while there are particular sites in both basins where the coupling of circulation and atmospheric forcing causes intense buoyancy extraction and strong convective events to produce water that is sufficiently dense to reach the sea bottom, i.e. depths greater than 3000 m. The presence of shallow sills is thus a constraint to the direct exchange of deep water masses between the basins and with the open ocean.

The present Mediterranean is an evaporative basin, with evaporation exceeding the sum of precipitation and river runoff (e.g., Pinardi et al., 2004). The resulting negative freshwater budget is partially compensated by the Atlantic inflow at the Strait of Gibraltar, where a complex two-layer system is at work. The long-term equilibrium of both water and salt budgets brings about an outflow across the Strait of Gibraltar of 0.8–1.6 Sv (Bethoux, 1979; Hopkins, 1999), which, due to the shallow sills at the Strait of Gibraltar, involves mostly the intermediate layers. Buoyancy fluxes are enhanced in the present Mediterranean by the fact that irradiance over the area is about 20% greater than mean irradiance at similar latitudes (Bishop and Rossow, 1991). In addition, the latitudinal shift of the EMED with respect to the WMED results in a different insolation regime, which in turn provokes significant differences in the heat fluxes and seasonal dynamics of the mixed layer. All of the above, plus the presence of dry Etesian winds makes the Levantine basin one of the saltiest seas in the world, with salinity occasionally exceeding 39‰ and inducing the formation of Levantine Intermediate Water (LIW) (Lascaratos et al., 1999).

LIW is the main driver of a large thermohaline cell encompassing the whole Mediterranean, with inflow of Atlantic Water (AW) through the Strait of Gibraltar compensating for LIW outflow. Deep circulations in the two main sub-basins are decoupled and are composed of two minor thermoaline cells forced by dense water formation events: in the Gulf of Lion in the WMED and the South Adriatic in the EMED. In the latter, Bora bursts act on a permanent cyclonic structure, producing the source water for the Eastern Mediterranean Deep Water (EMDW), with the possible contribution of the Aegean Sea and the Rhodes Gyre.

As regards atmospheric forcing, the Mediterranean climate regime is primarily driven by its location on the transition between the climate conditions of the temperate westerlies that dominate over central and northern parts of Europe, and the subtropical high pressure belt over North Africa (Boucher, 1975; Lolis et al., 2002). When the summer subtropical cell of high pressure is displaced to the north, the SE part of the basin is characterised by drought. On the other hand, when the subtropical high pressures are displaced southward during winter, temperate westerlies with associated Atlantic depressions dominate the Mediterranean climate. Since both systems affect fundamentally different characteristics of the basin, with the subtropical/monsoon climate predominantly affecting the freshwater balance while the temperate westerly climate controls cooling in the northern part of the area, the Mediterranean is an excellent site for the study of the relative timing and impact of changes in these two major climatological systems. The important influence of tropical climate seems to strongly affect the inter-annual variability of the Mediterranean climate and its hydrological regime.

3. Materials

The ODP Site 963, Hole A, is located in the Sicilian Channel (central Mediterranean), between the Adventure Bank to the northwest and the Gela Basin to the southeast (37°02.148′N, 13°10.686′E; 480 m depth) (Fig. 1). Considering the water mass distributions outlined above, this depth corresponds to the lower layers of the IW flowing in the Channel. For this study only the segment between 9.48 and 31.24 m below the sea floor (mbsf) was analysed. This interval is included between two sedimentary sequences, cores 4H, 5H and 6H of Hole 963A and core 1H of Hole 963D, which were investigated in depth (Sprovieri et al., 2003, 2006; Incarbona et al., 2010a).

The material studied is characterised by homogeneous olive to grey nannofossil clays with disseminated pyrite. No lithologic evidence of sapropels, turbidites or resedimented layers is present, although a millimetric quartz sand horizon occurs in Section 5 of core 3H (Emeis and Robertson, 1996). The high sedimentation rate, over 20 cm/ka, allowed detailed reconstruction of high-frequency Quaternary climatic changes (Sprovieri et al., 2003, 2006; Incarbona et al., 2009, 2010a).

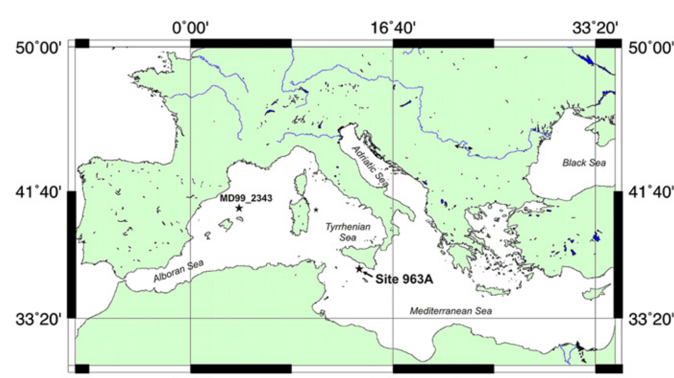

Fig. 1. Location map of the studied ODP Site 963A. The location of the MD99-2343 core is also shown.