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Calcareous plankton response to orbital and millennial-scale climate changes across the Middle Pleistocene in the western Mediterranean

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ABSTRACT

The paleoenvironmental conditions through MIS 15-9 at the Mediterranean Ocean Drilling Program (ODP) Site 975 were interpreted by high resolution study of calcareous plankton assemblages compared with available $\delta^{18}O$ and $\delta^{13}C$ records and high resolution paleoclimate proxies from the Atlantic Ocean. Sea Surface Temperatures (SSTs) have been estimated from planktonic foraminiferal assemblages using the artificial neural networks method. Calcareous plankton varied dominantly on a glacial–interglacial scale as testified by the SST record, foraminiferal diversity, total coccolith abundance and changes in warm-water calcareous nannofossil taxa. A general increase in foraminiferal diversity and of total coccolith abundance is observed during interglacials. Warmest SSTs are reached during MIS 11, while MIS 12 and MIS 10 represent the coldest intervals of the studied record. During MIS 12, one of the most extreme glacials of the last million years, occurrence of *Globorotalia inflata* and of neogloboquadrinids indicates a shoaling of the interface between Atlantic inflowing and Mediterranean outflowing waters. Among calcareous nannofossils the distribution of *Gephyrocapsa margereli–Gephyrocapsa muellerae* > 4 μm also supports a reduced Atlantic–Mediterranean exchange during MIS 12. Superimposed on glacial–interglacial variability, six short-term coolings are recognized during MIS 12 and 10, which appear comparable in their distribution and amplitude to the Heinrich-type events documented in the Atlantic Ocean in the same interval. During these H-type events, *Neogloboquadrina pachyderma* (s) and *G. margereli–G. muellerae* > 4 μm increase as a response to the enhanced inflow of cold Atlantic water into the Mediterranean via the Strait of Gibraltar. Mediterranean surface water hydrography appears to have been most severely affected at Termination V during the H-type event Ht4, possibly as a response to a large volume of Atlantic meltwater inflow via the Strait of Gibraltar and/or to freshwater/terrigenous input deriving from local mountain glaciers. Three additional SST coolings are recorded through MIS 14–16, but these are not well correlated with Heinrich-type events documented in the Atlantic Ocean in the same interval; during these cooling episodes only the subpolar *Turborotalita quinqueloba* increases. These results highlight the sensitive response of the Mediterranean basin to millennial-scale climate variations related to Northern Hemisphere ice-sheet instability and support the hypothesis that the tight connection between high latitude climate dynamics and Mediterranean sea surface water features can be traced through the Middle Pleistocene.

1. Introduction

During the last 700 ka the Earth experienced pronounced climate changes on orbital to millennial–submillenial time scales. The Quaternary Milankovitch forcing has been widely documented in deep-sea cores (e.g. Shackleton et al., 1990; Imbrie et al., 1992, 1993; Bassinot et al., 1994; Lisiecki and Raymo, 2005) and ice-core records (Petit et al., 1999; EPICA community members, 2004, 2006; Jouzel et al., 2007). In contrast, the signature in the geological records of millennial-scale variability has been extensively documented only in the last glacial period. Rapid warm-cold oscillations, now called Dansgaard–Oeschger (D–O) cycles were first observed in $\delta^{18}O$ profiles from Greenland ice cores (Dansgaard et al., 1982, 1993; Greenland Ice-core Project Members, 1993; Grootes et al., 1993) and later recognized in marine records of the nearby North Atlantic Ocean (Bond et al., 1993) and on a global scale (Voelker, 2002; Clement and Peterson, 2008). Prior to MIS 3, millennial-scale climate variability is known to occur (Oppo et al., 1998; Raymo et al., 1998; McManus et al., 1999) and seems important for modulating climate change on orbital time scales (Barker et al., 2011), but the spatial extent, synchronicity and frequency of individual events during older glacial cycles are much less understood.

In North Atlantic marine cores, some of the cold phases of the D–O cycles of the last glacial are associated with anomalous occurrences of ice-rafted detritus (IRD) resulting from massive discharges of icebergs from the Northern Hemisphere ice sheets (Heinrich, 1988; Bond et al., 1992, 1993; Broecker et al., 1992; Hemming, 2004), the so-called Heinrich events (HE) (Broecker et al., 1992). Peaks of the polar

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planktonic foraminifera *Neogloboquadrina pachyderma* sinistral (s), of magnetic susceptibility and signatures of sea surface temperature decrease are generally in phase with the HE (e.g. Bond and Lotti, 1995; Hemming, 2004). The HE were first detected in several North Atlantic deep-sea cores within the ice rafted detritus belt of Ruddiman (1977) between 40 and 50°N (e.g. Heinrich, 1988; Bond et al., 1992; Broecker et al., 1992; Grousset et al., 1993). Several paleoceanographic studies have however documented that climatic events, temporarily linked to HE, also occur beyond the Ruddiman IRD belt (e.g. Lebreiro et al., 1996; Zahn et al., 1997; Cayre et al., 1999; Bard et al., 2000; de Abreu et al., 2003) and as far south as the Gulf of Cadiz (Cacho et al., 2001; Voelker et al., 2006) during the last glacial. In previous glacial intervals of the Brunhes Chron, Heinrich-type ice-rafting events are documented through MIS 16-9 in the North Atlantic (McManus et al., 1999; Hodell et al., 2008; Ji et al., 2009; Stein et al., 2009) and on the Iberian margin (Voelker et al., 2009, 2010; Rodrigues et al., 2011). High resolution data from the Iberian margin (Rodrigues et al., 2011) show that the abrupt SST drops of about 4 °C–7 °C detected through MIS 15-9 and similar in their trends to the Heinrich events, lasted about 2.4 to 4.5/7 ky.

In the Mediterranean records, the imprint of millennial-scale events has been identified during the last glaciation (Cacho et al., 1999; Moreno et al., 2004), within MIS 5 (Sprovieri et al., 2006) and through MIS 7-1 (Martrat et al., 2004). In this region, despite being outside the direct influence of the melting icebergs, the climate and oceanographic impact of HE during the last glacial has been recognized in both marine (Rohling et al., 1998b; Cacho et al., 1999; Paterne et al., 1999; Cacho et al., 2000; Pérez-Folgado et al., 2003; Sierro et al., 2005; Melki et al., 2009) and terrestrial (Allen et al., 1999; Combourieu-Nebout et al., 2002; Sánchez Goñi et al., 2002) archives. Although IRD evidences are not documented so far in the Mediterranean sedimentary records, paleoceanographic studies support the hypothesis that during HE, iceberg-derived meltwater has entered the western Mediterranean where it reduced surface salinity and inhibited deepwater formation (Sierro et al., 2005). Abrupt cooling of surface water during HE has been related to polar Atlantic water inflow through the Strait of Gibraltar (Cacho et al., 1999, 2001) and/or to intensification of north-westerly winds over the Mediterranean (Rohling et al., 1998b; Cacho et al., 1999, 2001; Moreno et al., 2005). Evidence for tight coupling between rapid climate change in the North Atlantic and the Mediterranean is not limited to the last glacial cycle. The occurrence and the impact of rapid cooling events correlated to H-type events are documented back to MIS 6 (Martrat et al., 2004).

Until now, no long records of millennial-scale climate variability in the Mediterranean exist from earlier glacial cycles, straddling the Middle Pleistocene. This interval has been the subject of numerous high resolution studies in the Atlantic ocean (e.g. Oppo et al., 1998; McManus et al., 1999; Stein et al., 2009; Voelker et al., 2009, 2010; Alonso-Garcia et al., 2011; Rodrigues et al., 2011; Amore et al., 2012; Milker et al., 2013), which all document a persistent occurrence of rapid climate change events that appear analogous to the D–O and HE cycles of the last ice age. These events appear to be linked to a threshold size of the ice sheets and show a pattern where the strongest oscillations occur early in each glacial period. It remains unknown, whether the tight coupling between North Atlantic and Mediterranean rapid climate change events persisted across the Middle Pleistocene, how the events were manifested in the Mediterranean, how consistently individual events can be traced across the Strait of Gibraltar and whether the pattern of scaling seen in the North Atlantic applies to records in the indirectly affected semi-isolated Mediterranean Basin.

Encouraged by the first results presented by Tarantino et al. (2011) and Maiorano et al. (2013), we have carried out a quantitative study of planktonic foraminifera and calcareous nannofossil assemblages from the Mediterranean ODP Site 975, through MIS 15-9, with the aim to investigate the Mediterranean response to the Middle Pleistocene climate variability. The studied interval is interesting for studying long- and short-term climate changes. It includes MIS 12 which represents one of the most extreme glacials during the last million years, when sea level was probably lower than during the Last Glacial Maximum (Shackleton, 1987; Rohling et al., 1998a) and large phase of glaciation (Woodward et al., 2004; Hughes et al., 2006, 2007, 2010) as well as colder and drier climate conditions compared with the following cold stages (Tzedakis et al., 2003) affected the Mediterranean landmasses. In addition, the location of Site 975, which is in the Algero–Balearic Basin, represents an area affected by the Modified Atlantic Water (Fig. 1), and is therefore suitable to explore possible impact of abrupt coolings in the Atlantic Ocean on local sea surface temperature. Finally, the record from Site 975 can be tied to a high resolution North Atlantic chronological framework allowing direct assessment of the interaction of Mediterranean surface waters with events driven by Northern Hemisphere ice-sheet instability.

2. Material and methods

2.1. Studied core and oceanographical setting

Ocean Drilling Program Site 975 (Fig. 1) was drilled at a water depth of 2415 m on the Menorca Rise, between the South Balearic Basin and the Algerian Basin (38°53.8′N, 4°30.6′E) (Shipboard Scientific Party, 1996). Pleistocene sediments mainly consist of calcareous nannofossil clay and calcareous silty clay with nannofossil component dominating over foraminifer tests (Shipboard Scientific Party, 1996). Sedimentation rate was about 70 m/m.y. for the Pleistocene–Holocene interval according to Shipboard Scientific Party (1996); in detail it varied between about 6 and 9–10 cm/ky through MIS 15-8, according to the age model of Lourens (2004). The composite section based on Hole 975B cores 3–6 and Hole 975C cores 4–6 has been investigated. This interval provides a continuous sediment sequence from about 630 ka to 260 ka as revealed by isotope stratigraphy of Pierre et al. (1999).

At present, surface waters in the Algero–Balearic Basin, where the studied core is located, represent the Modified Atlantic Water (MAW) which forms by mixing between the Atlantic Water (AW) entering the Gibraltar Strait and Mediterranean Intermediate Water (Millot, 1999). The AW is a cold, lower salinity, nutrient-rich water mass and its transformation to MAW influences surface water gradients in the entire western Mediterranean. The MAW, which has higher temperatures (16 °C) and salinities (36.5‰) with respect to the AW (Tintoré et al., 1988; Heburn and La Violette, 1990), flows eastward (Morel and André, 1991; Millot, 1999) along the Algerian slope (Algerian Current—AC), while northward branches of MAW form various larger-scale cyclonic gyres reaching toward the Balearic Islands (Millot, 1999). Northwards, the MAW flows on both sides of Corsica joining to form the northern cyclonic gyre in the Gulf of Lions. The Northern Balearic Front in the Gulf of Lions separates the cold salty and old surface waters flowing along the north European coasts (Italy, French, Spain) in the southwest direction from the eddies originated in the warm, fresher and younger MAW. The deepest levels of the western Mediterranean Basin are filled by the Western Mediterranean Deep Water (WMDW), which is formed via deep convection in the Gulf of Lions during winter Mistral (Benzohra and Millot, 1995; Rohling et al., 1998b). Other oceanographic phenomena in the western Mediterranean arise from regional wind forcing (García Lafuente et al., 2002) as a consequence of atmospheric pressure differences in the Mediterranean area and Gulf of Cadiz. These processes influence the balance of eolian and river sediment input to both Alboran and Algero–Balearic seas. The Algero–Balearic Basin is considered an oligotrophic area with respect to the westernmost Mediterranean, however productivity varies seasonally as winter convection produces mesotrophic condition, while water column stratification and oligotrophic conditions occur in summer (Allen et al., 2002).

The intensity of the Atlantic–Mediterranean water exchange at the Gibraltar Strait varied during glacial–interglacial phases: during the Last Glacial Maximum (LGM) lower sea level (−120/125 m, Siddall