Palaeogeography, Palaeoclimatology, Palaeoecology 459 (2016) 1–14

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Deep water circulation within the eastern Mediterranean Sea over the last 95 kyr: New insights from stable isotopes and benthic foraminiferal assemblages

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ARTICLE INFO

Article history:
Received 22 January 2016
Received in revised form 22 June 2016
Accepted 23 June 2016
Available online 25 June 2016

Keywords:
Mediterranean Sea
Benthic foraminifera
Sapropels
North Atlantic variability
Ventilation
Oxygenation

ABSTRACT

The response of eastern Mediterranean Sea (EMS) circulation to climate forcings over the last 95 kyr BP was studied using core MD04-2722, collected at 1780 m water depth within the Levantine Sea. Foraminiferal stable isotopes and benthic assemblages were combined in order to reconstruct deep water ventilation and oxygenation in relation to surface water freshening. Over the last deglaciation, benthic foraminiferal $\delta^{13}C$ values and oxygen index decreased, while the $\delta^{18}O$ gradient between benthic and planktonic foraminifera increased. The results, respectively, indicate slower ventilation, bottom water oxygen depletion, and stronger stratification prior to S1 sapropel deposition. A combination of deglacial sea level rise and fresher north Atlantic surface water contributions were determined to be a precondition for S1 formation within the Levantine Sea. Local Nile River freshwater supplied during the African Humid Period further strengthened water column stratification. As for S3 deposit, the central role of monsoonal precipitation was estimated. For the last glacial period, three events at around 53, 46 and 37 ka BP were marked by a deep water circulation reduction at the core location. Considering the influence of north Atlantic surface water salinity on Mediterranean Sea circulation, we propose that the 46 and 37 ka BP events are responses to Heinrich Events 4 and 5 that supplied fresher surface water to the Mediterranean Sea. Since the '53 ka event' was also characterized by the appearance of low oxygen benthic indicators as observed within the S1 and S3 layers, we tentatively attributed it to 'missing' sapropel S2. Our results indicate that intense stagnation within the EMS could occur when both the local freshwater supply and fresher north Atlantic surface water are contributors. The influence of north Atlantic conditions was significant to EMS circulation under warm and cold climate conditions.

1. Introduction

The Mediterranean Sea is located between the temperate westerlies of central and northern Europe and the subtropical high-pressure belt over northern Africa (Boucher, 1975; Lolis et al., 2002), and constitutes a semi-enclosed marginal sea with its own thermohaline circulation. Recently, a new deep water formation site that documents Mediterranean Sea sensitivity to on-going climate change was found within the eastern Mediterranean Sea (Roether et al., 1996; Klein et al., 1999; Schroder et al., 2006; Beuvier et al., 2010; Pinardi et al., 2015). Since model predictions for the twenty first century forecast a warmer and drier Mediterranean climate (Adloff et al., 2015), water circulation within the Mediterranean Sea is expected to change in the future, largely due to a dependence on near Atlantic Ocean surface water evolution (Adloff et al., 2015)].

In the past, massive freshwater influx during times of enhanced Northern Hemisphere monsoon precipitation over northern Africa (Rossignol-Strick et al., 1982), induced by maximum summer insolation (precession minima), led to circulation changes within the Mediterranean Sea. Perturbations of the hydrological cycle within the Eastern Mediterranean Sea (EMS) were initiated by a freshening of surface water (buoyancy gain) and a decline in deep water ventilation, leading to decreased deep water oxygenation (Rossignol-Strick et al., 1982). The main excesses in freshwater were estimated to originate from increased Nile River outflow (Rossignol-Strick et al., 1982), as well as enhanced winter precipitation over the Mediterranean Sea (Kallel et al., 2000) and its northern borderlands (Kotthoff et al., 2008; Roberts et al.,

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http://dx.doi.org/10.1016/j.palaeo.2016.06.038
0031-0182/

2011). During wetter periods, organic-rich layers called sapropels (organic carbon content >2%; Kidd et al., 1978) were deposited either due to a better preservation of organic matter or to increased surface biological productivity. Throughout sapropelic events, including the last sapropel S1, negative anomalies in stable oxygen isotopes, as obtained from planktonic foraminifera (Vergnaud-Grazzini et al., 1977), have been observed within the EMS, consistent with surface water freshening. Another reported characteristic is the absence of oxic species of benthic foraminifera (Mullineaux and Lohmann, 1981; Nolet and Corliss, 1990; Jorissen, 1999)]. In general, pre-sapropelic fauna indicate strong deep water oxygen depletion (Jorissen, 1999; Mercone et al., 2001; Schmiedl et al., 2003, 2010; Kuhnt et al., 2007].

New results for the S1 event indicate that the influence of remote forcing due to deglacial conditions may have contributed to sapropel formation within the Mediterranean basin (Grimm et al., 2015; Rohling et al., 2015; Grant et al., 2016). In addition to local climatic patterns, in particular Nile River runoff (Caley et al., 2011; Mojtahid et al., 2015; Revel et al., 2015), glacial preconditioning of deep water circulation over several thousand years was proposed for the formation of the last sapropel S1.

Superimposed on orbital variability, high frequency climatic variations characterized by rapid cooling (stadials) or warming (interstadials) are known to have occurred during the last glacial period (70–20 cal ka BP) and are referred to as Dansgaard/Oeschger (DO) millennial oscillations (Bond et al., 1993; Dansgaard et al., 1993). Abrupt cooling periods, known as Heinrich events (HEs), began at the end of some of the coldest stadials and were accompanied by massive iceberg discharges leading to ice-rafted detritus deposits within the north Atlantic Ocean (Heinrich, 1988; Bond et al., 1993). Such disturbances in the hydrological conditions of surface waters reduced deep water formation (Vidal et al., 1997) and, thus, modified Atlantic meridional overturning circulation. Heinrich events are not directly expressed in the Mediterranean Sea sedimentary record although several studies suggest that millennial-scale north Atlantic variability was transmitted to the Mediterranean Sea (Bar-Matthews et al., 1999; Cacho et al., 2000, 2006; Bartov et al., 2003; Sierro et al., 2005; Almogi-Labin et al., 2009; Sprovieri et al., 2012; Toucanne et al., 2012; Angue Minto'o et al., 2015). Both oceanic and atmospheric processes have been suggested as mechanisms for climatic teleconnections between high and mid-latitudes.

For the Western Mediterranean Sea (WMS), molecular biomarkers indicate surface water cooling during HEs (Cacho et al., 2000), whereas planktonic δ^{18}O values indicate lower surface salinities due to the input of fresher waters from iceberg melting (Sierro et al., 2005; Sprovieri et al., 2012). Enhanced intermediate (Toucanne et al., 2012) and deep water (Cacho et al., 2000) circulations have been deduced from benthic foraminifera oxygen and carbon isotopes during such time periods and have been attributed to more effective vertical mixing of water masses within the WMS due to the colder regime. On the other hand, Sierro et al. (2005) and Sprovieri et al. (2012) suggested that lower salinities within Mediterranean Sea surface waters resulted in a slowdown of western Mediterranean Sea deep water overturning during HEs. Thus far, transmission of the Atlantic Ocean signal to the EMS has not been clarified.

Here, we present a combination of benthic and planktonic foraminiferal stable isotopes (δ^{18}O and δ^{13}C) and benthic foraminiferal faunal assemblages from the eastern Levantine Sea MD04-2722 core (33°06′N, 33°30′E; 1780 m water depth; Fig. 1). The relatively high sedimentation rate of the core (around 8 cm/ka during MIS3) allowed us to investigate rapid climate variability. We compared our proxy record to previously published foraminiferal stable isotope records, as well as to faunal assemblages. In an attempt to clarify the behaviour of deep water circulation during sapropelic formation and HE periods, here, we focus on bottom water ventilation and oxygenation changes during sapropel S1, sapropel S3, and the last glacial period that are all well expressed in the benthic records.

2. Oceanographic settings

Present-day circulation within the Mediterranean Sea is characterized by an anti-estuarine pattern (Tomczak and Godfrey, 1994; Pinardi and Masetti, 2000). Atlantic surface water enters the WMS through the Strait of Gibraltar and flows into the EMS via the Strait of Sicily (Fig. 1). During this passage, salinity in the surface water increases due to excess evaporation over precipitation and runoff, leading to a salinity gradient between the western and eastern basins (Fig. 1b). This surface water is referred to as Modified Atlantic Water (MAW). Within the Levantine Sea, MAW forms a series of gyres and then flows around Cyprus (Pinardi and Masetti, 2000). Cold and dry air masses over the EMS during winter promote water mass mixing and the evaporation of surface water within the Levantine Sea in the vicinity of Cyprus-Rhodes, thus favoring vertical convection and the formation of Levantine Intermediate water (LIW). A mean temperature of 14 °C and a salinity of 38.7 (Tomczak and Godfrey, 1994) characterize this water mass which constitutes the major component of Mediterranean intermediate waters (Tomczak and Godfrey, 1994; Millot and Taupier-Letage, 2005). Since no intermediate formation site exists within the WMS, LIW flows between 200 and 500 m in water depth within the eastern and the western basins. Boreal winter winds cool Adriatic Sea surface water, facilitating mixing with LIW, and, consequently, the active formation of Eastern Mediterranean Deep Water (EMDW). With a mean temperature of 13 °C and a salinity of 38.6 (Wüst, 1961), EMDW flows below LIW (Tomczak and Godfrey, 1994). The Adriatic Sea has been considered the main source for EMDW (Pollak, 1951; Wüst, 1961; Malanotte-Rizzoli and Hecht, 1988; Robinson et al., 1992). However, due to a combination of high salinity waters intruding into the basin and strong winter cooling during 1991–1992 and 1992–1993, the Aegean Sea started to form unusually dense waters (Roether et al., 1996, 2014)]. This change in the main contributor to EMDW has become known as the Eastern Mediterranean Transient (Klein et al., 1999; Lascaratos et al., 1999; Malanotte-Rizzoli et al., 1999; Samuel et al., 1999). Deep water formation within the Aegean Sea peaked in 1993. At the core location, surface waters correspond to MAW and bottom waters to EMDW (Fig. 1).

3. Materials and methods

3.1. Core material

We studied core MD04–2722 (33°06′N, 33°30′E; 1780 m water depth; total core length of 36.96 m) collected south of Cyprus within the eastern Levantine Sea (Fig. 1a, b) during the VANIL cruise (R/V Marion Dufresne) in 2004. For this study, we investigated the first 745 cm of sediment within the core and sampled at every 2 to 10 cm (see Section 3.2).

The first 250 cm of core MD04-2722, spanning the last 23.6 kyr cal BP, is described in Tachikawa et al. (2015). From 745 to 250 cm, the interval is largely composed of bioturbated hemipelagic mud facies (Ducassou et al., 2009). The interval between 680.5 and 665.5 cm is marked by dark and slightly laminated sediments with some visible oxidation points or monosulphide spots (Ducassou, 2006; Ducassou et al., 2009). This observed feature is comparable with that of the S1 interval within the same core (Tachikawa et al., 2015).

3.2. Analytical methods

Stable isotope measurements (δ^{18}O and δ^{13}C) were performed on three species of benthic foraminifera (*Cibicidoides wuellerstorfi, Gyroidina orbicularis,* and *Gyroidina altiformis* - size fraction >250 μm) within the first 745 cm of the core at every 2 to 5 cm. For the 250–745 cm interval, isotopic analyses were carried out on the planktonic foraminifer *Globigerinoides ruber* picked from the 250–355 μm size fraction. Analyses were performed at CEREGE using a Finnigan Delta