Marine Geology 266 (2009) 182–197

Contents lists available at ScienceDirect

Marine Geology

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

Late Glacial–Holocene climate variability at the south-eastern margin of the Aegean Sea

M.V. Triantaphyllou [a,*], P. Ziveri [b,c], A. Gogou [d], G. Marino [c], V. Lykousis [d], I. Bouloubassi [e], K.-C. Emeis [f], K. Kouli [a], M. Dimiza [a], A. Rosell-Melé [c], M. Papanikolaou [g], G. Katsouras [d,h], N. Nunez [c]

[a] University of Athens, Faculty of Geology and Geoenvironment, Dept. of Historical Geology-Paleontology, Panepistimiopolis 15784, Athens, Greece
[b] Dept. of Paleoclimatology and Geomorphology, FALW, Vrije Universiteit Amsterdam, The Netherlands
[c] ICTA, Autonomous University of Barcelona (UAB) Edifici Cno-Campus UAB, 08193 Bellaterra, Spain
[d] Hellenic Centre for Marine Research, Inst. of Oceanography, 19013 Anavyssos, Greece
[e] Laboratoire d'Océanographie et du Climat: Expérimentation et Approche Numérique, Université Pierre et Marie Curie, Paris Cedex 05, France
[f] Institut für Biogeochemie und Meereschemie, Universitat Hamburg, Bundesstr. 55, 20146 Hamburg, Germany
[g] University of Cambridge, Department of Geography, Cambridge Quaternary, CB2 3EN Cambridge, UK
[h] University of the Aegean, Dept. of Marine Sciences, 81100 Lesvos, Greece

ARTICLE INFO

Article history:
Received 25 July 2008
Received in revised form 23 June 2009
Accepted 6 August 2009
Available online 15 August 2009

Communicated by G.J. de Lange

Keywords:
coccolithophores
pollen
benthic foraminifera
biomarkers
alkenone-based SST
sapropel S1
sapropel-like layer SMH

ABSTRACT

New micropaleontological, palynological, and geochemical results from a relatively shallow (~500 m) sediment core (NS-14) in the south-eastern Aegean Sea provide a detailed picture of the regional expression of sapropel S1 formation in this sub-basin of the eastern Mediterranean Sea. Specifically, freshwater input during ~10.6–10.0 ka BP has preceded the deposition of S1. Further decrease in surface water salinity is evidenced between 10.0 and 8.5 ka BP at the lower part of S1a, which in respect to S1b, is featured by warmer (~19.5 °C) and more productive surface waters associated with dysoxic bottom conditions. A series of coolings detected within the S1 depositional interval, may be linked to outbursts of cold northerly air masses and relevant pulses in the deep-intermediate water ventilation that caused the S1 interruption between 7.9 and 7.3 ka BP and culminated during the deposition of S1b, with the decline of deep chlorophyll maximum (DCM) at ~6.5 ka BP. The climate instability and the relevant absence of anoxia weakened the organic matter preservation in the shallow south-eastern Aegean margin during the S1 times. NS-14 record provides evidence for a distinct mid Holocene warm (up to ~25 °C) and wet phase associated with the deposition of the sapropel-like layer SMH (Sapropel Mid Holocene), between 5.4 and 4.3 ka BP. The SMH layer could represent evidence of on-going, albeit weak, African monsoon forcing, only expressed at the south-eastern edge of the Aegean Sea. Its end is associated with the 4.2 ka BP Northern Hemisphere mega-drought event and the termination of the African Humid Period at 3.8 ka BP.

1. Introduction

The eastern Mediterranean is an efficiently ventilated and highly evaporative semi-enclosed sea with surface waters depleted in phosphate, nitrate and silicate, and low biological production (Krom et al., 1992; Tselepides et al., 2000). However, the (quasi)periodic occurrence of organic-rich layers, so-called sapropels, throughout the sedimentary record of the last 13.5 million years (Hilgen et al., 2003), points to the development of dramatically different oceanographic and trophic conditions in the past (for extensive reviews see, e.g., Rohling, 1994; Cramp and O'Sullivan, 1999; Emeis et al., 2003). The accepted paradigm for sapropel formation dictates that these deposits formed under deep-sea anoxic/dysoxic conditions, which developed in concert with distinct minima in the orbital precession cycle, i.e., every ~21,000 years (Rossignol-Strick et al., 1982; Hilgen, 1991; Lourens et al., 1992, 1996). Briefly, the precession driven intensifications of the boreal African monsoon fuelled enhanced freshwater discharge along the North African margin of the eastern Mediterranean (e.g., Rohling et al., 2002a; Scrivner et al., 2004; Ehrmann et al., 2007). These positive shifts of the basin's freshwater budget – likely supplemented by contemporaneous increases in the freshwater supply from the southern European margin (Kotthoff et al., 2008) – inhibited the convective deep water formation processes, in turn, leading to oxygen starvation in the deep sea (Rohling, 1994; de Lange et al., 2008). Emeis et al. (2000, 2003) also emphasized the role of the sea surface warming during intervals of precession minima, which may have intensified the surface buoyancy gain, thereby contributing to weaken the deep water circulation. While there exists ample consensus on the enhanced preservation of organic matter under oxygen-deficient conditions of the eastern Mediterranean bottom waters

* Corresponding author. Tel.: +30 210 7274893.
E-mail address: mtriant@geol.uoa.gr (M.V. Triantaphyllou).

0025-3227/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.margeo.2009.08.005

(De Lange et al., 1999, 2008; Moodley et al., 2005), other studies emphasize that an increase in the export productivity from the pelagic layer may have played a critical role in the sapropel formation (e.g. De Lange and Ten Haven, 1983; Kemp et al., 1999; Mercone et al., 2001).

It has been found that the precession driven changes in the eastern Mediterranean water column have led to different sedimentary features in the individual sub-basins (Emeis et al., 2000). Much interest has recently been centred on the Aegean Sea (Rohling et al., 2002b; Casford et al., 2002, 2003, 2007; Ehrmann et al., 2007; Kuhnt et al., 2007; Marino et al., 2007), because it represents an important area of deep water formation for the entire eastern Mediterranean (Zervakis et al., 2004), which appears particularly sensitive to climate forcing today (Roether et al., 1996; Theocharis et al., 1999; Zervakis et al., 2000) as well as in the past (Kuhnt et al., 2007; Marino et al., 2007). Importantly, by virtue of its location, at the north-eastern sector of the Mediterranean, in winter the Aegean Sea is under the direct influence of northerly winds (Poulos et al., 1997), thereby holding great potential as key sedimentary archive to investigate the response of the regional climate to past high-latitude forced climate fluctuations. Indeed, several recently generated Aegean paleoceanographic records suggest that – during the Holocene – short-term cooling episodes, which are bound to the strengthening of northerly winds, are superimposed on the underlying subtropical/tropical control of the regional hydrography and ecosystems (Rohling et al., 2002b; Casford et al., 2003; Gogou et al., 2007; Marino, 2008). These findings suggest that during the Holocene the eastern Mediterranean climate was less stable than previously thought.

The present study investigates an expanded sediment record covering the last ~13 ka BP, from the shallow south-eastern margin of the Aegean Sea. We use a combined coccolithophore, pollen, benthic foraminifera, and organic geochemistry proxy data to address three main questions: (*1*) what is the fingerprint of the northern hemisphere climate variability on the south-eastern Aegean climate? (*2*) what is the interaction between primary production and organic matter preservation at intermediate depths during sapropel S1 deposition? (*3*) what are the major changes in sea surface temperature, hydrography, primary production, and in the regional moisture availability in the period immediately following the deposition of sapropel S1?

2. Basin location and oceanographic setting

The Aegean Sea, which is situated between Turkey and Greece (Fig. 1A), is connected with the Black and Marmara Seas through the Dardanelles Straits, and with the open eastern Mediterranean (Levantine Sea) through the Cretan Straits. The cooler (9–22 °C) and lower salinity (24–28 psu) Black Sea outflow waters flows along the east coast of Greece to reach the southwest Aegean Sea, and, due to their high nutrient contents, fuel productivity in the North Aegean Sea (Lykousis et al., 2002). The warm (16 °C in winter; 25 °C in summer) and saline (39.2–39.5 psu) Levantine surface waters flow northward along the eastern Aegean to the Dardanelles Straits (Zervakis et al., 2000, 2004). Several rivers discharge into the Aegean Sea, mostly from the north Hellenic coast and from the east coast of Turkey (Fig. 1A). Together, Black Sea outflow waters and river inputs both supply the Aegean with freshwater (Poulos et al., 1997; Roussakis et al., 2004).

Regarding the subsurface circulation, between 70 and 400 m depth, the Aegean is filled by the Levantine Intermediate Water mass (LIW). Between 400 and 900 m in the South Aegean can be identified a salinity minimum, which reflects the Transitional Mediterranean Water mass (TMW) (Lykousis et al., 2002). The development of deep convection takes place during the winter season due to favourable weather and hydrographic conditions, which are strongly affected by northerly outbreaks of cold and dry polar/continental air (Poulos et al., 1997; Theocharis et al., 1999). Deep convection leads to an increased oxygenation of the intermediate and deep layers. Overall, the distribution of oxygen (and nutrients) in the South Aegean Sea is influenced by the exchange of water masses through the Cretan Straits. In the Southern Aegean Sea sediments, oxygen penetration extends to about 3–5 cm (Lykousis et al., 2002). The South Aegean sub-basin is considered as a "typical oceanic margin" environment, characterised by very low export rates of organic matter from the euphotic zone (mean annual flux at 200 m: 5.6 mg m^{-2} d^{-1}; Stavrakakis et al., 2000) and organic — poor sediments, with mean total organic carbon values of 0.34% (Lykousis et al., 2002).

3. Material and age model

3.1. Core description

Core NS-14 was taken during the R/V Aegaeo-Cruise 1998, in western Kos basin (Fig. 1B), from a water depth of 505 m at 36°38′55″N and 27°00′28″E. Gray coarse sands with pebbles prevail from the core bottom (400 cm) to 300 cm. Between 300 cm and the core top the sediment mainly consists of gray hemipelagic mud (Fig. 2A). At 240 to 231 cm, we found a turbiditic layer (T) with graded bedding and abundant shallow benthic foraminiferal microfauna (mainly *Quinqueloculina* spp.). The dark gray to olive gray mud of sapropel S1, which occurrence is also confirmed by the total organic carbon (TOC) profile (see Section 5.1), extends from 120 to 55 cm. The S1 layer is divided into two sub-units (hereafter termed S1a and S1b, respectively), which are separated by an 11 cm thick (from 80 to 69 cm) lighter gray interval, here interpreted as the S1 interruption (Fig. 2A). Another dark olive gray mud sapropel-like layer, which we name Sapropel Mid Holocene (SMH); see Section 6.3) occurs between 40 and 25 cm. The most recent Z2 Santorini ash layer is positioned at 17 cm depth.

3.2. Chronology

Seven accelerator mass spectrometry (AMS) radiocarbon (^{14}C) datings (Table 1; Fig. 2B) were performed at the laboratories of Beta Analytic (USA) on cleaned, hand-picked mixed benthonic and planktonic foraminifera from core NS-14. Dating mono-specific planktonic assemblages was not possible due to relatively low amounts of planktonic foraminifera in core NS-14. However, due to the location of core NS-14, it is rather unlikely that this approach will considerably affect the precision of the chronology adopted in our study. In fact, the vigorous upwelling of intermediate waters to the surface along the south-eastern Aegean margin (Lascaratos, 1992; Yüce, 1995) imply a well homogenized water column and thus fairly small age offsets between surface and bottom waters in this sector of the basin.

Conventional ^{14}C ages have been calibrated using the program CALIB 5.0.2 (Stuiver and Reimer, 1993; Stuiver et al., 1998) with a regional reservoir age correction (ΔR) of 149 ± 30 years for sapropel interval (Facorellis et al., 1998) and 58 ± 85 outside the sapropel (Reimer and McCormac, 2002). In order to reduce the bias towards older ages produced by the contribution of old carbon (Casford et al., 2007) and by the presence of benthic foraminiferal shells in the dated material, we base the NS-14 chronology on the youngest ages of the age range provided by this calibration exercise.

AMS ^{14}C datings at 393 cm and 344 cm (Table 1) provided virtually identical ages. Taken at face value these dates would imply disproportionally high sedimentation rates in this segment of the record. However, the entire interval below 300 cm consists of olive gray coarse sands, which are likely reflective of a sediment gravity flow event at ~18 ^{14}C ka BP. Accordingly, these deposits either derive from a turbidite event during the early stages of the last deglaciation (Roussakis et al., 2004), or from seismically induced landslide phenomena (Papanikolaou and Nomikou, 2001). Hence, dating points at 393 and 344 cm were not considered here for chronological purposes. The Minoan Santorini ash layer (Z2 in Fig. 2A) was used as an additional time marker (3550–3577 yr cal. BP; Friedrich et al., 2006).