

BIOGEOCHEMICAL EVIDENCE FOR LATE CLIMATIC VARIABILITY IN THE AEGEAN SEA DURING THE FORMATION OF HOLOCENE SAPROPEL S1

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Introduction

During the last 20 kyr several millennial to centennial scale climatic events have been recorded in the northern hemisphere and worldwide, both cold as the Last Glacial Maximum (LGM), the Heinrich event 1 (H₁), the Younger Dryas (YD) and the 8.200 yr BP cooling event and warm like the Bolling-Allerød and the Holocene Climatic Optimum (HCO) events (Alley et al., 1997; Mayewski et al., 2004; McManus, 2004; Rohling & Pälike, 2005). Orbital cyclicity and North Atlantic circulation patterns (e.g. NAO) play a fundamental role in governing Earth's climate, as driving forces of the observed climate variability (Laskar et al., 1993; Visbeck et al., 2001; Dahl et al., 2005).

In the northeastern Mediterranean Sea, the Aegean marginal sea provides an ideal natural laboratory for the study of climatic changes in the temperate zone and for assessment of direct hydrographic responses to high-latitude climate variability (Fig. 1; Rohling et al., 2002; Gogou et al., 2007). Its hydrologic system is complex, with a strong inflow of water from Black Sea, riverine inputs, and intense air-sea exchanges, leading to episodic events of dense water formation (Zervakis et al., 2000). A distinct feature of biogeochemical records of the Aegean Sea during the HCO is the deposition of sapropel S₁, a sediment layer enriched in organic carbon. Sapropels deposition are related with 'precession minima' periodicity (Laskar et al., 1993; Meyers and Negri, 2003). During the Holocene precession minimum, monsoons intensification resulted in a widespread increase in humidity and concomitant increase of freshwater inputs to the Mediterranean Sea.

In order to search for evidence of millennial/centennial paleoclimatic variability in a regional scale, we study numerous organic biogeochemical proxies in three high-resolution cores collected in the north (152SL and MNB-3) and the southeastern (NS-14) Aegean Sea (Fig. 1). Continental environmental conditions have been inferred from land-plant biomarkers. Paleoproductivity patterns of diatoms, porynesiophytes, dinoflagellates, and nanoplankton were discerned from marine-derived biomarkers. Finally, alkenone U₃₇SST estimates revealed temperature variability in the Aegean Sea over the last 20 kyr.

Sampling and Analysis

The NS-14 (western Kos Basin-505m water depth) and MNB3 (N. Skyros Basin-800m water depth) gravity cores was recovered with R/V Agagao and achieved a centennial-scale sampling resolution. Foraminifera were handpicked and dated using AMS ¹⁴C at the laboratories of Beta Analytic (USA). The 152SL gravity core was recovered during the R/V Meteor-Cruise 2001, in Athos Basin, at 995m water depth. AMS ¹⁴C dating for 152SL took place in 8 intervals (4 cm-thick) in Kiel (Germany).

Age models were corrected using the program CALIB 5.0 (NS-14, 152SL) and CALIB 4.2 (MNB-3) with a regional reservoir age correction of 149 ± 30 years for the Aegean Sea (Facorelli et al., 1998). Total Organic Carbon (for NS-14, 152SL) was determined using a Thermo 1500 elemental analyzer and stable isotopes of ¹⁵N were determined using an ISODAT NT ConFlo III at the laboratories of GKSS (Germany). The TOC and ¹⁵N values on MNB-3 were determined on carbonate-free residues using a continuous-flow gas-ratio mass spectrometer (Finnigan Delta Plus XL) coupled to an elemental analyzer (Costech) in the Laboratory of Isotope Geochemistry, University of Arizona. Organic biomarkers (n-alkanes, sterols, alkanoids, keto-ols) analyzed using GC-FID and GC-MS in HCMR (Greece). GC-FID analyses have been performed in order to derive alkenone U₃₇ concentrations, in the Laboratoire d'Océanographie et du Climat, Paris. Sea surface temperatures (SST) are estimated by using the equation of Müller et al. (1998).

Fig. 3: Aegean U₃₇SST and GISP2 Temperature Record: Last 20 kyrs

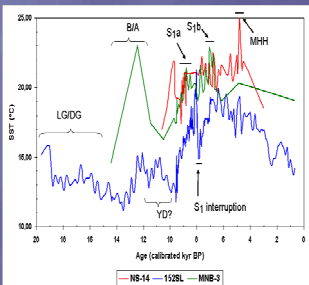


Fig 1: Sampling Area



Fig 4: TOC

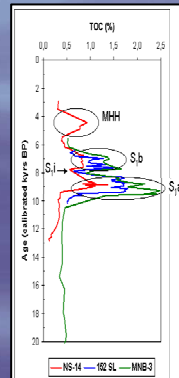


Fig 5: δ15N

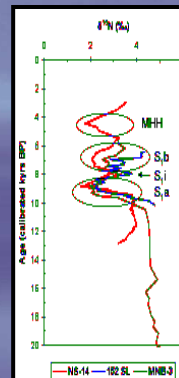


Fig 2: Chronological description and age assessment

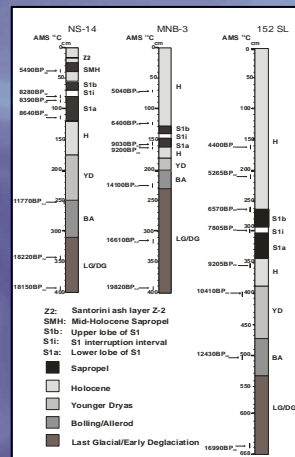
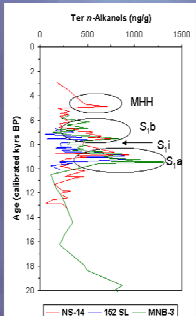


Fig 6: Terrestrial Biomarkers



Results and Discussion

Sea Surface Temperatures (SST) (Figure 3): Average SST in 152SL core is low during the last glacial and deglaciation periods (11-16°C). Minimum temperatures as low as 14.5°C (MNB-3) and 12.3°C (152SL) were recorded at 15-14 kyr BP, which predates a sharp increase to 22.9°C and 15.1°C at ca. 12.5 kyr BP respectively, that most likely corresponds to the Bolling/Allerød interstadial. Following this, a pronounced cooling of surface waters down to 16.2°C and 13.4°C at 10.5 kyr BP respectively, is probably related to the Younger Dryas cooling event. The period from the YD and through the whole S₁ sequence is marked by important fluctuations in SST. At the start of the Holocene, SST varies rapidly and increase to 17-19°C in all sites. During S₁ deposition, SST reaches values as high as 22°C (MNB-3), 21.2°C (152SL) and 22.4°C (NS-14) respectively. In all sites, S₁b is characterized by higher SST values compared to S₁a. Alkenone U₃₇SST records shows a pronounced centennial-scale cooling that culminates from 8.8 to 7.8 kyr BP, coeval to the N-Atlantic cooling event (Rohling and Pälike, 2005), causing an interruption in the deposition of S₁ in all sites. Finally, we observe important fluctuation of cool/warm intervals throughout the S₁ deposition period, more pronounced during S₁b, where their magnitude are often comparable to that of the S₁ interruption cooling event. These rapid coolings most likely provoked intermittent ventilation of Aegean deep waters, but they were rather short-lived and did not give rise to well-expressed 'interruptions' within S₁. Another cold event with ~6.2°C decrease marks the termination of MNB-3 S₁ deposition around 6.7 kyr BP, while in NS-14 a negative shift of ~1.5°C takes place at 6.9 kyr BP. Finally, U₃₇SSTs in NS-14 fluctuate between 5.2-4.2 kyr BP (MHH Phase expressed by the deposition of sapropel SMH; Triantaphyllou et al., subm.) with an average value of 22°C and a prominent peak at 4.8 kyr BP, indicating warm conditions that are also recorded, less pronouncedly, in the other two cores.

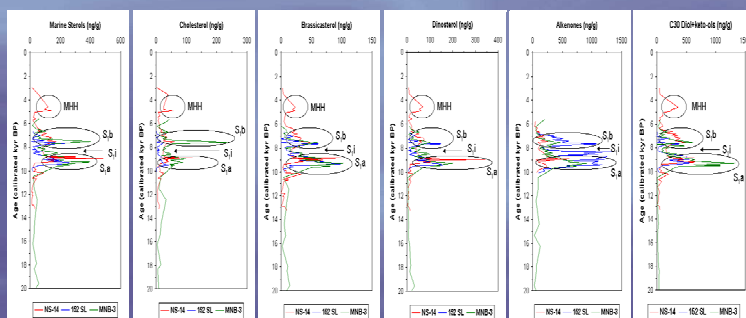
Total Organic Carbon (Figure 4): TOC concentrations remain low in the massive intervals below and above S₁ and increase within S₁. Higher OC contents are recorded in subliver S₁a compared to S₁b, indicating that the paleoceanographic conditions that encouraged higher marine productivity and/or enhanced preservation of OM were stronger before the S₁ interruption than after it. The cool interval of S₁ interruption is characterized by a marked decrease of TOC contents. In the Southern Aegean Sea (NS-14) high TOC values between 5.2-4.2 kyr BP suggest a relative increase in productivity and/or preservation corresponding to the MHH Phase.

Total Nitrogen Isotopes (Figure 5): δ¹⁵N exhibit higher values in the massive intervals above and below S₁ and decrease within S₁. Low δ¹⁵N values within sapropels likely reflect a significant contribution of N-fixing organisms, related probably to higher demand for nitrogen, after P regeneration and denitrification, due to the established dysoxia in the water column/sediment interface. The lower δ¹⁵N values within the S₁a layer suggest that salinity stratification was stronger at that time compared to S₁b. During the S₁ interruption, δ¹⁵N values increase, indicating a short-lived erosion of the stratification. In NS-14, low δ¹⁵N values at 5.2-4.2 kyr BP are probably associated with an event leading to low-oxygen conditions.

Terrestrial Biomarkers (Figure 6): Ter-alkanoles are characteristic of higher plant inputs. In the lower part of MNB-3 core we observe enhanced terrestrial inputs probably related to the rapid sea-level rise and an increase in supply of riverine inputs, corresponding to the late glacial/early deglaciation period from ca. 20 to 16.5 kyr BP. A peak at ~12.5 kyr BP is most likely linked to the beginning of a regional humidity increase known as the African Humid Phase and the onset of the Bolling/Allerød event. This state persisted until ~10.5 kyr BP, when low Ter-alkanoles (MNB-3, NS-14) reflect the cold and arid YD event. Holocene sapropel deposition exhibit higher values of Ter-alkanoles due to increased riverine inputs/continental runoff, characteristic of this warm and humid period (HCO). S₁ interruption is characterized by low terrestrial inputs, indicating cold and arid climatic conditions during this time.

Marine Biomarkers (Figure 7): Marine biomarkers exhibit low abundances before the S₁ deposition, reflecting low productivity/high diagenesis of biomarkers under well oxygenated conditions. Within S₁, significantly higher concentrations were recorded, with maxima at the S₁a period, indicating higher productivity and/or better preservation of marine OM, due to dysoxia. Among them, the high abundances of marine sterols (the sum of C₂₇, C₂₈-methyl and 4α-methyl compounds), alkenones and diols & keto-ols are typical of a productive marine system. An important decline in the abundance of all marine markers recorded in the cool interval of S₁ interruption compared to the sapropelic layers that can be related either to fluctuation in the supply of OM in our sampling sites and/or lower preservation of organic material due to bursts of ventilation to greater depths at this time. As for SST, an increase of marine markers abundance is recorded during the SMH event.

Fig 7: Marine Biomarkers



Synthesis

Our alkenone-SST and biomarkers distributions exhibit variability throughout the Aegean Late Glacial-Holocene climate, reflecting fluctuations in biogeochemical and climatic conditions in the eastern Mediterranean Sea during that time. More specifically:

> We observe a warming period related to the Bolling/Allerød at ~13 kyr BP followed by a pronounced cooling of surface waters at ~11.5 kyr BP most likely corresponds to the Younger Dryas event.

> Alkenone SST-records shows significant alterations of cool/warm intervals throughout S₁ deposition, suggesting important climate instability in the Aegean Sea during the Holocene Climatic Optimum. Those fluctuations were much more frequent within the latter part of S₁ deposition in the North Aegean Sea.

> Within N. Aegean cores 152 SL (S₁: 9.4-6.8 kyr BP) and MNB 3 (S₁: 9.6-6.7 kyr BP) the deposition of sapropel S₁ seems to start and finish earlier compare to shallower and southern Aegean core NS-14 (S₁: 9.3-6.4 kyr BP) indicating that maybe the dysoxia/anoxia in the Aegean sea started from the deeper and northern parts.

> During S₁ enhanced terrestrial loading and marine productivity/preservation of OM is confirmed by the increase in abundance of all terrestrial and marine markers. Higher values of TOC and all biomarkers within S₁a points that during this period the paleoceanographic conditions that encouraged greater productivity/preservation of OM were stronger compared to S₁b.

> A major cooling event recognized at around 8.2 kyr BP, indicating the presence of an interruption of S₁ in all sites. This cooling is well associated with the sudden cold event 8.2 years ago in North Atlantic and caused reventilation of Aegean deep waters.

> The S₁ interruption started earlier in core NS-14 (8.2 kyr BP) compare to cores 152 SL and MNB 3 (8.2 kyr BP) suggesting the persistence of local deep water formation in the northern Aegean Sea.

> Our records provide evidence for a distinct Mid-Holocene warm and wet phase between 5.2-4.2 kyr BP, associated probably with the 4.2 kyr BP Northern Hemisphere mega drought event and the termination of the African Humid Period at 3.8 kyr BP. (Triantaphyllou et al., submitted).

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