

## PRELIMINARY RESULTS OF HIGH RESOLUTION PALEOCEANOGRAPHY AND PALEOCLIMATOLOGY DURING SAPROPEL S1 DEPOSITION (SOUTH LIMNOS BASIN, NORTH AEGEAN SEA)

Kostopoulou S.<sup>1</sup>, Triantaphyllou M.B.<sup>1</sup>, Dimiza M.D.<sup>1</sup>, Gogou A.<sup>2</sup>, Boulou-  
bassi I.<sup>3</sup>, Rousakis G.<sup>2</sup>, Parinos C.<sup>2</sup>, Diamantopoulou An.<sup>4</sup>, Geraga M.<sup>4</sup> and  
Lykousis V.<sup>2</sup>

<sup>1</sup>Faculty of Geology and Geoenvironment, National and Kapodistrian University of Athens,  
Panepistimiopolis 15784, Athens, kost.sofia@hotmail.com

<sup>2</sup> Hellenic Centre for Marine Research, Institute of Oceanography, 190 13 Anavyssos, Attiki

<sup>3</sup>Laboratoire d'Océanographie et du Climat, Expérimentation et Approche Numérique, Université  
Pierre et Marie Curie, Paris Cedex 05, France

<sup>4</sup>Faculty of Geology, University of Patras, 26100 Rio-Patra

### Abstract

*The paleoenvironmental conditions during the depositional interval of sapropel S1 in the northeastern Aegean (gravity core M-4, length 2.53 m; south Limnos basin) are studied based on quantitative micropaleontological (benthic and planktonic foraminifera) and geochemical (OC,  $\delta^{13}C_{org}$ ) analyses. Special feature of core M-4 is the thickness of S1 layer (96 cm). Our study points that sapropelic layer S1a has been deposited in more dysoxic and warmer conditions in respect to S1b. Both primary productivity and preservation of organic material are more intense during the lower part of S1. An interruption of the sapropelic conditions at 8.0 Ka BP which is mainly characterized by the increase of agglutinated foraminiferal forms confirms both higher oxygen bottom conditions and freshwater input.*

**Key words:** sapropel S1, foraminifera, geochemical indices, Aegean Sea.

### Περίληψη

*Οι παλαιοπεριβαλλοντικές συνθήκες κατά τη διάρκεια απόθεσης του σαπροπηλού S1 στο Βόρειο Αιγαίο (πυρήνας βαρύτητας M-4, μήκους 2,53 m, λεκάνης νότιας Λήμνου) προσδιορίζονται με βάση την ποσοτική ανάλυση μικροπαλαιοντολογικών (βενθονικά και πλαγκτονικά τρηματοφόρα) και γεωχημικών (OC,  $\delta^{13}C_{org}$ ) δεικτών. Χαρακτηριστικό του πυρήνα M-4 είναι η μεγάλη εμφάνιση του S1 που φτάνει το πάχος των 96 cm. Η μελέτη κατέδειξε ότι, το κατώτερο σαπροπηλικό στρώμα S1a αποτέθηκε σε θερμότερες συνθήκες, εντονότερης δυσοξίας, σε σχέση με το ανώτερο σαπροπηλικό στρώμα S1b.. Αύξηση της παραγωγικότητας και καλύτερη διατήρηση του οργανικού υλικού πιστοποιήθηκαν στο κατώτερο τμήμα του S1. Η διακοπή των σαπροπηλικών συνθηκών στα 8,0 Ka BP που χαρακτηρίζεται κυρίως από την αύξηση της σχετικής συχνότητας των συμφρυματοπαγών μορφών των βενθονικών τρηματοφόρων υποστηρίζει συνθήκες υψηλής οξυγόνωσης του πυθμένα και εισροή γλυκών υδάτων.*  
**Λέξεις κλειδιά:** σαπροπηλός S1, τρηματοφόρα, γεωχημικοί δείκτες, Αιγαίο.

## 1. Introduction

The Aegean Sea is located at the northern part of NE Mediterranean region, linked to the Black Sea through the Dardanelles and the Bosphorus Straits and to the eastern Mediterranean through the Cretan Straits, being recognized as a particularly important area for both regional and global climate changes. Numerous major rivers from the surrounding areas of the Balkans and Turkey flow into the Aegean Sea, providing the 75% of the North Aegean sediment influx (Lykousis et al., 2002; Roussakis et al., 2004; Ehrmann et al., 2007; Poulos, 2009), and they collectively constitute an important source of land-derived organic matter to the study area (e.g., Gogou et al., 2007). The Aegean receives low saline and cool BSW (Black Sea Water) through the Bosphorus Strait (between Black Sea and Marmara Sea) and the Dardanelles (between Marmara Sea and Aegean Sea). The cold (9 - 22 °C) and low saline (24 - 28‰) BSW flows along the eastern coast of Greece until it reaches the southwestern Aegean, and enhances the productivity in the northern Aegean Sea (Lykousis et al., 2002). The warm (16 - 25 °C) and saline (from 39.2 to 39.5‰) Levantine surface waters flow northward along the eastern Aegean Sea to the Dardanelles Straits (e.g., Zervakis et al., 2004). Especially for the basin of north Aegean Sea, it can be described as a «continental margin» ecosystem, and is characterized by generally cyclonic circulation (Lykousis et al., 2002).

The positive shift of the Aegean Sea's freshwater budget during sapropel deposition – possibly supplemented by enhanced freshwater inputs from the Southern European margin (Kotthoff et al., 2008) – weakened the basin's deepwater circulation and resulted in oxygen starved conditions at the seafloor. Recent paleoceanographic findings (e.g., Gogou et al., 2007; Triantaphyllou et al., 2009 a,b; Katsouras et al., 2010; Kouli et al., 2012) suggest that during the Holocene, a rather mild climatic period, between 10 and 6 kyr BP, appeared in the sediments through the deposition of the most recent sapropel layer S1. Besides the monsoonal system, precipitation and inflow of Black Sea waters may have also contributed in modifying the freshwater budget during times of S1 formation (e.g., Kuhnt et al., 2007). A centennial-scale cold event centered on 8.2 ka (Alley et al., 1997) coincides with the S1 interruption, and has been ascribed to a deepwater overturning reinforcement and reventilation.

In this study, we have performed micropaleontological (benthic and planktonic foraminifera) and geochemical (Organic Carbon; OC,  $\delta^{13}C_{org}$ ) analyses in sediments of core M-4 collected in the south Limnos basin, aiming to determine the paleoenvironmental changes during sapropel S1 deposition in north eastern Aegean Sea.

## 2. Materials and Methods

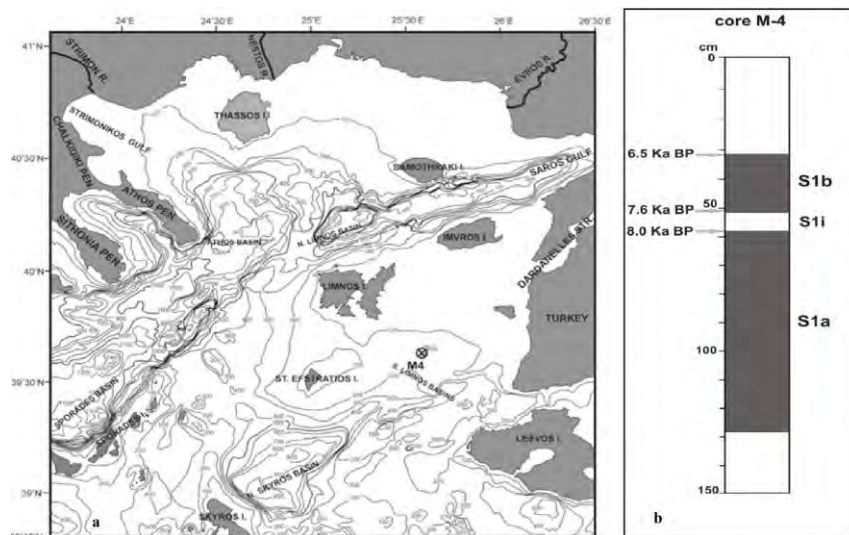
### 2.1. Core Description

Gravity core M-4 (length 2.53 m) has been recovered in south Limnos basin (Figure 1a) from water depth 216 m, at 39° 38.662'N 25° 35.165'E. Sapropel S1 is very well exposed in between 128-32 cm, with overall thickness reaching 96 cm. The uppermost 32 cm mainly consist of gray mud with shells (e.g., *Ostrea*) and shell debris. Based on sediment color and the concentration of OM, the S1 layer is divided into two sub-units (hereafter termed S1a and S1b, respectively), which are separated by an 8 cm thick (from 58 to 51 cm) lighter gray interval interpreted as the S1 interruption (Figure 1b). In this paper only the interval relative to sapropel S1 will be examined.

### 2.2. Chronology

Three accelerator mass spectrometry (AMS) radiocarbon  $^{14}C$  datings were performed at the laboratories of the oceanographic institute LOCEAN/Universite P.-M. Curie, on cleaned hand-picked planktonic foraminifera from core M-4. Conventional  $^{14}C$  ages have been calibrated by using Calib vs. 6.1.0 software (Stuiver et al., 1993) and the MARINE04 calibration dataset with a regional reservoir age correction ( $\Delta R$ ) of  $139 \pm 40$  (Facorellis et al., 1998). The age model of the core M-4

resulted from the linear interpolation between three calibrated datings. According to this model, S1a is deposited between 9.7-8.0 ka BP, whereas S1b spans 7.6-6.5 Ka BP. The age resolution between the samples is 38-163 years for S1b, 38-39 years for the interruption and 24-73 years for S1a.



**Figure 1 - (a) Location map of the study area in the north-eastern Aegean Sea, (b) Gravity core M-4 (the upper 150 cm).**

### 3. Methods

Two hundred and thirty samples were collected at 0.5 cm resolution for organic carbon (OC) content,  $\delta^{13}\text{C}_{\text{org}}$ . Analyses were performed using an automatic analyzer type "NA-1500 Nitrogen Analyzer". Stable carbon isotope ratios were expressed in terms of  $\delta^{13}\text{C}_{\text{org}}$  values against V-PDB for carbon, with overall analytical error based on duplicate measurements at  $\pm 0.2\%$ .

For benthic foraminiferal analyses, sixty four sediment samples of approximately 2 g dry weight each were wet sieved over 63  $\mu\text{m}$  sieve at resolution 0.5-3 cm. For each sample, a subset containing at least 300 benthic foraminifera were separated from the  $>125 \mu\text{m}$  fraction using a Leica APO S8 stereoscope. A scanning electron microscope analysis (SEM Jeol JSM 6360, Dept. of Hist. Geology-Paleontology) has been used for taxonomical purposes. Relative abundances of benthic foraminifera are presented and discussed in this study. Benthic foraminifera have been used as tracers for the nutrient content and oxygen concentration of the bottom water (e.g., Jorissen et al., 1995).

Forty six samples were used for planktonic foraminifera analysis. The mean sampling interval for the faunal analyses was 2 cm. The samples were disintegrated by hydrogen peroxide and then sieved through a 125- $\mu\text{m}$  mesh. The dry and weighed samples were split into separate aliquots. At least 200 planktonic specimens were identified and counted in each sample. Planktonic foraminifera have been proven useful in the reconstruction of palaeoceanographic and palaeoclimatic conditions (Bé & Tolderlund, 1971; Pujol & Vergnaud Grazzini, 1995). The sum of the percentages of species considered as indicative of warm waters versus the sum of those indicative of cool waters obtained as an index for the examination of the of the sea surface palaeotemperature and will be referred as PSST (Planktonic Sea Surface Temperature). *Globigerinoides ruber*, *Globigerinoides sacculifer*, *Orbulina univera* and *Globigerinella* spp. are considered warm-water indicators and *Turborotalita quinqueloba*, *Globigerinita glutinata* and *Globorotalia scitula* cold-water indicators (Thunell, 1978; Pujol & Vergnaud Grazzini, 1995).

## 4. Results

### 4.1. OC and $\delta^{13}\text{C}_{\text{org}}$

Higher OC values correspond to sapropel layers S1a and S1b (Figure 2). The maximum value of 1.94% is observed at 8.9 Ka BP during the deposition of S1a, whereas 1.67% is identified at 7.1 Ka BP. The interval of 8.0-7.6 Ka BP (S1 interruption) is characterized by a reduction of OC, however an increase to 1.26% exists at 7.7 Ka BP, just before the onset of S1b.  $\delta^{13}\text{C}_{\text{org}}$  values of range from -26.1 ‰ to -22.9 ‰ (Figure 2). The minimum values of  $\delta^{13}\text{C}_{\text{org}}$  were found during the interruption of sapropel S1 (7.7 Ka BP).

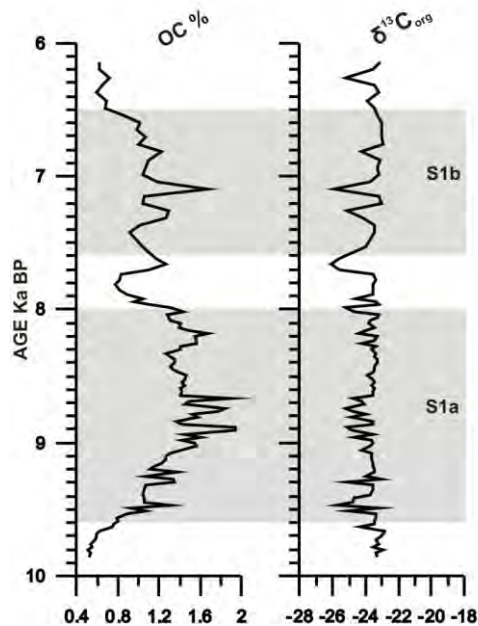


Figure 2 – Percentage concentration of organic carbon and vertical distribution of  $\delta^{13}\text{C}_{\text{org}}$  values of gravity core M-4.

### 4.2. Benthic Foraminifera

The presence of benthic foraminifera is continuous throughout the core M-4 (Figure 3). *Chilostomella mediterraneensis* is found in S1 lobes reaching almost 30% at 8.6 Ka BP during S1a and 25.4% at 6.8 Ka BP. *Bolivina striatula* peaks at 8.1 Ka BP (12.9%), decreases during the interruption of S1, but culminates again during the deposition of S1b. *Bolivina spathulata* displays low values during S1a; the highest abundance (29.9%) is observed at 7.8 Ka BP, followed by a gradual reduction during S1b. *Brizalina alata* is strongly fluctuating during S1 deposition, with abundances more pronounced within S1a. *Bulimina* spp. represents a significant component of sapropel microfauna, with an increasing trend in between 9-8.3 ka BP. The species *Globobulimina affinis* dominates the benthic assemblages of S1a, reaching 71.8% at 9 Ka BP. After 8 Ka BP, it is practically absent, with sporadic appearances, not exceeding 1 - 2%. *Cassidulinoides bradyi* is featured by a similar pattern, but with much lower abundance (max. 4.9% at 9.2 Ka BP). *Uvigerina mediterranea* reaches up to 24.2% at the beginning of layer S1a (9.6 Ka BP). Upwards it presents a gradual decrease, with another peak of 16.9% at the top of S1a (7.9 Ka BP); values are also increasing during S1b but to lesser degree. *Hyalinea balthica* increases significantly within S1b, showing a maximum of 16.7%, at 7 Ka BP whereas *Melonis barleeaanum*, agglutinants and miliolids occur in very low rates inside S1, but increase significantly outside the sapropel depositional interval.

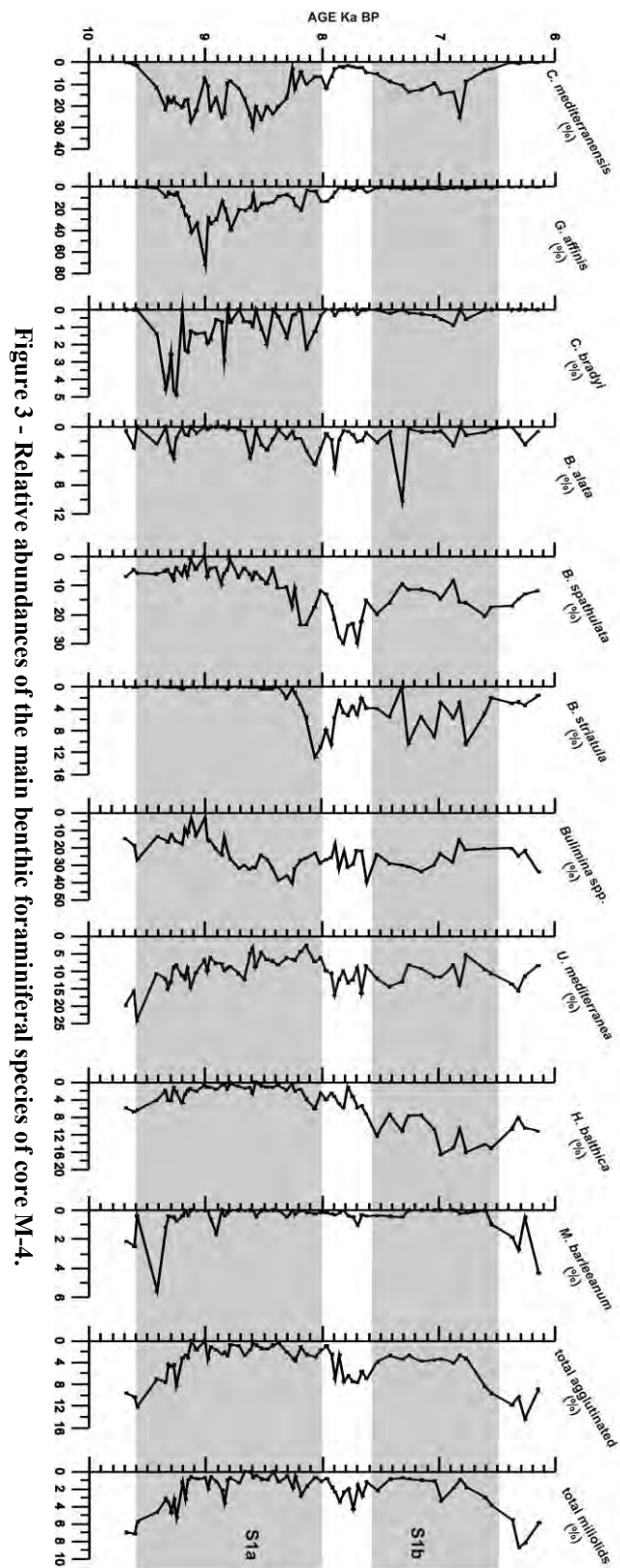


Figure 3 - Relative abundances of the main benthic foraminiferal species of core M-4.

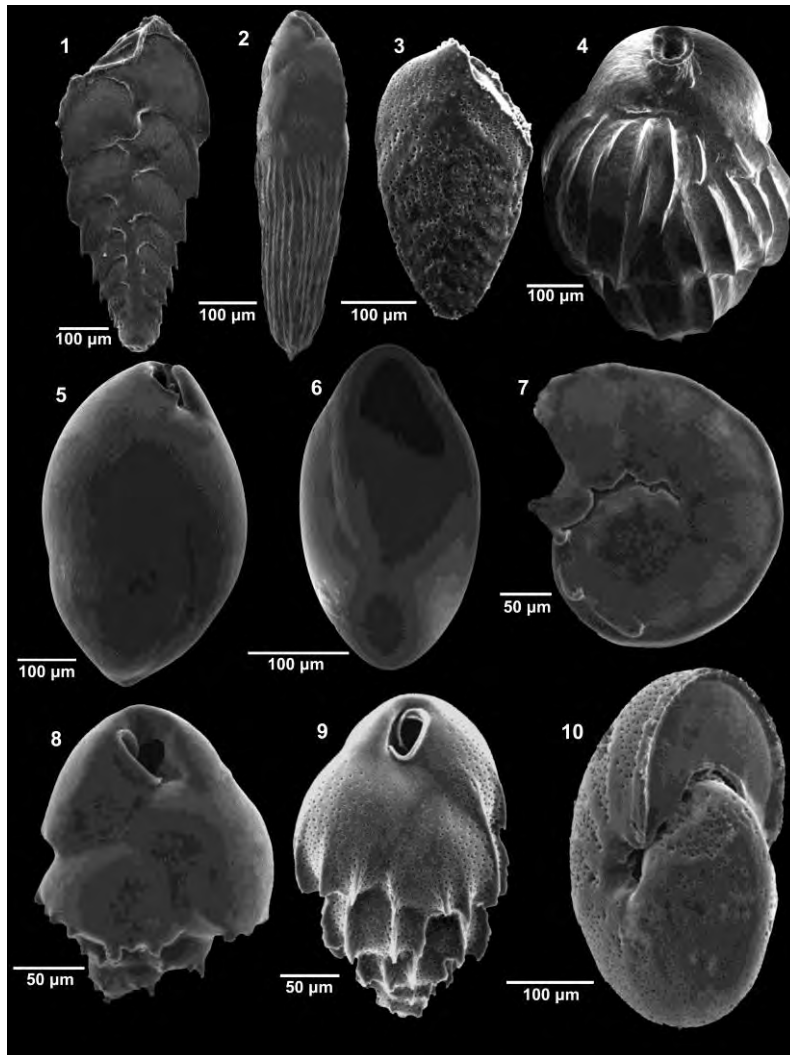
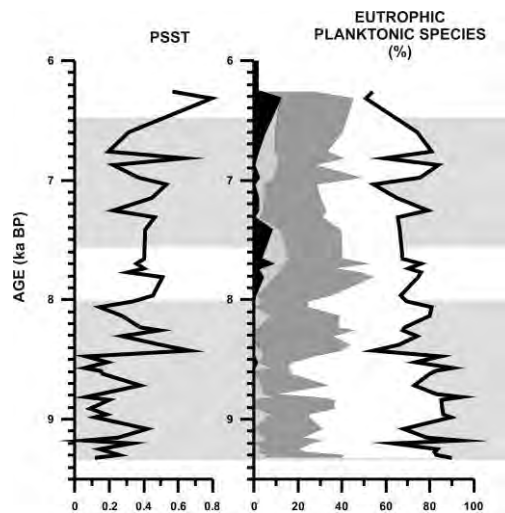


Plate I – 1. *Bolivina alata* (Seguenza), M-4, 88-88.5 cm 2. *Brizalina striatula* (Cushman), M-4, 38-38.5 cm 3. *Bolivina spathulata* (Williamson), M-4, 38-38.5 cm 4. *Uvigerina mediterranea* (Hofker), M-4, 33-33.5 cm 5. *Globobulimina affinis* (d'Orbigny), M-4, 63-63.5 cm 6. *Chilostomella mediterraneensis* (Cushman & Todd), M-4, 90-90.5 cm 7. *Hyalinea balthica* (Schröeter), M-4, 63-63.5 cm 8. *Bulimina marginata* (d'Orbigny), M-4, 38-38.5 cm 9. *Bulimina costata* (d'Orbigny), M-4, 88-88.5 cm 10. *Melonis barleeianum* (Williamson), M-4, 110-110.5 cm.

#### 4.3. Planktonic Foraminifera

Along the core sediments planktonic foraminifera assemblages are abundant and consist mainly of *Gs. ruber* (0–30%), *Gs. sacculifer* (0–13%), *Or. universa* (0-7%), *Globigerina bulloides* (5-45%), *T. quinqueloba* (5–75%), *G. glutinata* (0–5%), *Neogloboquadrina* spp. (0-13%) and *Globorotalia inflata* (0-12%). Similar is also the modern foraminiferal assemblages in the studied area (Thunell, 1978). The downcore variations of the PSST index presents an increasing trend upwards (Figure 4). The eutrophicated species have always high participation in the planktonic assemblages ranging about 60 to 90% of the total association, suggesting high eutrophicated levels throughout the deposition of S1. However the largest percentages occur during the deposition of S1a.



**Figure 4 – a. Downcore variation of the Planktonic Sea Surface Temperature (PSST) curve, b. Relative abundances of the eutrophic planktonic foraminifera species of core M-4 (colours: black: *Gr. inflata*; light gray: Neogloboquadrins; dark gray: *G. bulloides*; white: *T. quinqueloba*).**

## 5. Discussion and Conclusions

Sapropel S1a interval in south Limnos basin is characterized by the intense presence of anoxic/dysoxic benthic species (Figure 3), such as *C. mediterraneensis*, *G. affinis* and *C. bradyi* (e.g., Bernard & Sen Gupta, 1999; Fontanier et al., 2002; Kuhnt et al., 2007; Abu-Zied et al., 2008). In addition, *Bulimina* spp. (*B. aculeata*, *B. marginata* and *B. costata*), which are indices of extreme eutrophic and dysoxic conditions (e.g., Bernhard & Alve, 1996), along with the presence of *B. spathulata*, *B. striatula* and *B. alata* which are also living in low oxygen environments, and are relatively tolerant to non-oxic conditions (e.g., Jorissen et al., 1995) support dysoxic conditions within sapropelic layer S1a. However, S1a depositional interval is also featured by the presence of *U. mediterranea*, which has low tolerance to dysoxic conditions and prefers mesotrophic to eutrophic environments (e.g., Jorissen et al., 1995; Schmiedl et al., 2000). *H. balthica*, although in low abundances, indicates well oxygenated waters (e.g., Aksu et al., 1995; Morigi et al., 2001; Abu-Zied et al., 2008), while *Gyroidinoides* spp. also support higher oxygen conditions (e.g., Edelmann-Furstenberg et al., 2001). Therefore, there is ample evidence that less severe dysoxia has been developed in south Limnos basin during the deposition of layer S1a, in respect to what has been documented before for other Aegean basins (e.g., Kuhnt et al., 2007; Abu-Zied et al., 2008; Triantaphyllou et al., 2009a, b; Geraga et al., 2005, 2010).

Higher values of OC during the deposition of S1a than those of S1b indicate highest organic matter production and preservation in S1a, supporting previous results in the Aegean area (e.g., Gogou et al., 2007; Triantaphyllou et al., 2009b; Katsouras et al., 2010). The almost constant values of  $\delta^{13}\text{C}_{\text{org}}$  during S1a, confirm the hypothesis that the deposition of sapropel S1 depends on primary productivity and preservation of organic matter (Katsouras et al., 2010). During the depositions of S1a and S1b the dominant planktonic species are *T. quinqueloba* and *G. bulloides* (Figure 4). *T. quinqueloba* is indicative of cool waters, but is also tolerant to fairly low salinity and/or enhanced fertility in surficial waters (Rohling et al., 1997). High percentages of this taxon have been reported in the sediments of S1 in Aegean Sea. However, this pattern seems to be stronger in N. Aegean basins (Geraga et al., 2010) rather than in S. Aegean basins (e.g., Geraga et al., 2000; Triantaphyllou et al., 2009a). *G. bulloides* is indicative of sub-polar water masses highly dependent on enhanced food levels (upwelling, strong seasonal mixing or freshwater inputs, Lourens et al., 1994). The abundant presence of *G. bulloides* and *T. quinqueloba* suggests the development of a



low salinity surficial layer rich in nutrients over south Limnos basin during the deposition of S1a and S1b.

The interruption of sapropel S1 at 8.0 Ka BP can be associated with the north hemisphere cold event at 8.2 Ka BP. During the sapropel interruption interval, the increase of agglutinated forms confirms both higher oxygen bottom conditions and freshwater input (e.g., Alve, 1995). This is accompanied by decrease in OC and the presence of planktonic foraminifera assemblages which suggest stronger mixing of the water column at least during winter. The more negative values of  $\delta^{13}\text{C}_{\text{org}}$  identified at 7.7 Ka BP (-26.1 ‰) are indicative of terrigenous organic matter (e.g., Meyers & Arnaboldi, 2008; Katsouras et al., 2010) that may caused high value (1.26%) of OC, during the interruption interval.

Within the sapropelic layer S1b dysoxic foraminiferal species abundances are once more increased but to a lesser degree when comparing with S1a; in accordance with OC values and the relatively lower participation of the eutrophic planktonic assemblages. *U. mediterranea*, *H. balthica*, miliolids and agglutinants are increased, supporting even less dysoxia for S1b interval in respect to S1a, in south Limnos basin. Furthermore, the gradual increase of *H. balthica*, an indicator of cold environments (e.g., Aksu et al., 1995), during S1b confirms that this interval is featured by lower temperature conditions (e.g., Gogou et al., 2007; Triantaphyllou et al., 2009b). This fact is also supported by the increase of *U. mediterranea* (Figure 4), a species that occurs at the final stage or subsequently after cold events (Kuhnt et al., 2007).

Minimum values of the PSST have been obtained during the S1a deposition. Low PSST values are also recorded during the deposition of S1b. Both these intervals are associated with the high abundance of *T. quinqueloba*. This taxon is indicative of high fertility and cool waters but is also tolerant to fairly low salinity (Rohling et al., 1997). Therefore the low PSST values may have been partly misled from the prevalence of low salinity surface waters occurred in that time. However the establishment of cool surface waters during the deposition of S1 is in agreement with other relative studies (i.e. Aksu et al., 1995). Low PSST values occur also at the late stages of S1a in accordance to the prevalence of the cold event at 8.2 Ka (Alley et al., 1997).

An increase in the abundances of *Gr. inflata* and Neogloboquadrinds is obtained during the interruption of S1 and the late stages of the deposition of S1b. *Gr. inflata* is associated with cool and deep mixed waters (Thunell, 1978; Pujol & Vergnaud Grazzini, 1995; Casford et al., 2002) and Neogloboquadrinids of eutrophicated waters associated with the formation of a Deep Chlorophyll Maximum (DCM) layer (Fairbanks & Wiebe, 1980). Therefore their strong presence in these two intervals indicates less stratified waters in relation to those prevailed during the deposition of S1a and S1b.

All acquired data records present rapid simultaneous fluctuations, suggesting short term paleoceanographic and palaeoclimatic changes in the studied area. Rapid palaeoclimatic changes during the discussed interval have been also reported in pollen records from N. Aegean Sea (Kotthoff et al., 2008).

## 6. Acknowledgments

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