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PLANKTON ECOSTRATIGRAPHY AND POLLEN ASSEMBLAGE ZONES OVER THE LAST 14 000 YEARS IN SE AEGEAN SEA (CORE NS-14)

Triantaphyllou M. V.[1], Antonarakou A.[1], Kouli K. [1], Dimiza M.[1], Kontakiotis G.[1], Ziveri P.[2], Mortyn G.[2], Lykousis V.[3], and Dermitzakis M. D.[1]

[1] *National and Kapodistrian University of Athens, Faculty of Geology and Geoenvironment, Department of Hist. Geology - Paleontology, Greece, mtriant@geol.uoa.gr, aantonar@geol.uoa.gr, akouli@geol.uoa.gr, mdimiza@geol.uoa.gr, gkontak@geol.uoa.gr*

[2] *ICTA Autonomous University of Barcelona (UAB) Edifici Cno-Campus UAB, 08193, Bellaterra, Spain, patrizia.ziveri@uab.es, graham.mortyn@uab.es*

[3] *Hellenic Centre for Marine Research, Inst. of Oceanography, 19013 Anavyssos, Greece, vlikou@ath.hcmr.gr*

Abstract

A quantitative analysis of coccolithophores, planktonic foraminifera and pollen assemblages was carried out on core NS-14 (SE Aegean Sea), recovered in the Western Kos Basin. Eleven coccolithophore (ACE1-11) and ten planktonic foraminifera (APFE1-10) ecozones have been recognized during the last 14 000 yrs using calcareous nannofossil and planktonic foraminifera abundances. Additionally eight pollen assemblage zones (PAZ1-8) have been recognised. The established high resolution ecozonal scheme allows a detailed paleoecological reconstruction for the Holocene archive in the SE Aegean Sea, defining two warm and humid phases (9300-8600 yr $_{cal}$BP and 7600-6400 yr $_{cal}$BP) associated with the deposition of S1 and a third one between 5200-4200 yr $_{cal}$BP.

Key words: *coccolithophores, planktonic foraminifera, pollen, ecozones, Holocene.*

Περίληψη

Η ποσοτική ανάλυση ασβεστολιθικών ναννοαπολιθωμάτων, πλαγκτονικών τρηματοφόρων και κόκκων γύρεως που πραγματοποιήθηκε στον πυρήνα NS-14 (ΝΑ Αιγαίο, Λεκάνη Δυτικής Κω), επέτρεψε τον καθορισμό έντεκα οικοζωνών κοκκολιθοφόρων (ACE1-11), δέκα οικοζωνών πλαγκτονικών τρηματοφόρων (APFE1-10) και οκτώ ζωνών συγκέντρωσης κόκκων γύρεως (PAZ1-8). Το υψηλής ανάλυσης οικοστρωματογραφικό σχήμα που αναπτύχθηκε επέτρεψε την λεπτομερή παλαιοικολογική ανασύσταση του Ολοκαίνου στην περιοχή του ΝΑ Αιγαίου και τον καθορισμό δύο θερμών και υγρών περιόδων (9300-8600 yr $_{cal}$BP and 7600-6400 yr $_{cal}$BP) που σχετίζονται με την απόθεση του σαπροπηλού S1 και μιας μεταγενέστερης μεταξύ 5200-4200 yr $_{cal}$ BP.

Λέξεις κλειδιά: *ασβεστολιθικά ναννοαπολιθώματα, πλαγκτονικά τρηματοφόρα, κόκκοι γύρεως, οικοζώνες, Ολόκαινο.*

1. Introduction

All the biochemical parameters of the euphotic zone, although relatively increased in the N. Aegean, clearly reflect the highly oligotrophic character of the Aegean Sea (Lykousis *et al.* 2002). Though the modern Aegean Sea is generally characterized by low primary productivity and organic deficient sediments, the late Pleistocene-Holocene deposition of sapropels (dark-coloured organic-rich sedimentary layers) demonstrates that dramatically different conditions periodically occurred and coincided with changes in global and regional climate (Rohling and Hilgen 1991) and / or water circulation and biogeochemical cycling (Anastasakis and Stanley 1986, Van Santvoort and de Lange 1997). The early Holocene sapropel S1 was deposited in the N. Aegean Sea between 9600-6400 yr_{nc} BP (Perissoratis and Piper 1992), in the SW Aegean Myrtoon Basin has lasted between 9000-6900 yr_{nc} BP (Geraga *et al.* 2000), while in the S. Aegean Geraga *et al.* (2005) provided an age of 9000-5500 yr_{nc} BP. Interruptions within sapropel S1, centred roughly at 7000 yr_{nc} BP, have been documented in the Adriatic (Rohling *et al.* 1997) and Aegean Sea (Perissoratis and Piper 1992, De Rijk *et al.* 1999, Geraga *et al.* 2000) and are interpreted as genuine events related to climatic deterioration (De Rijk *et al.* 1999).

The present study aims to high resolution paleoecological reconstruction of the Holocene SE Aegean archive in the shallow, very rapidly accumulated core NS-14 in the Western Kos Basin, SE Aegean. A special effort is being made towards to the detailed investigation of the remarkably thick S1 exposed at the core, and to the establishment of a refined ecostratigraphic scheme based on coccolithophore and planktonic foraminiferal patterns and pollen assemblages.

2. Materials and methods

The 400 cm-long NS-14 gravity core was recovered during the R/V Aegeo-Cruise 1998, in western Kos Basin (SE Aegean Sea; Fig. 1a), from a water depth of 505 m at $36^0 38' 55''$ N and $27^0 0' 28''$ E. A total of 156 samples were collected for coccolithophore analysis every 2 cm in the hemipelagic mud and every 1 cm in the sapropel intervals. Sample preparation followed standard smear slide techniques. Analyses were performed using a Leica DMSP optical polarising light microscope at 1250x magnification by counting at least 300 specimens per sample. Specimens resembling to *Reticulofenestra* spp. were assigned here to EHMC (*Emiliania huxleyi* Moderately Calcified morphotypes) of Crudeli *et al.* (2004, 2006). Additional counts of 15 fields of view (Negri and Giunta 2001) were performed for the species *Helicosphaera* spp., *Rhabdosphaera* spp., *Syracosphaera* spp., *Coronosphaera* spp., *Discosphaera tubifera*. The rare species *Braarudosphaera bigelowii* was counted in a fixed area of 150 fields of view. All results were converted in relative abundances (percentages) of selected species in order to avoid dilution effects such as the input of terrigenous matter.

Foraminiferal analyses were carried out on 67 samples. The sediment was washed through 150 μm mesh sieve and dried at 60° C. Quantitative analysis was carried out on each sample, subsampled into aliquots through a microsplitter, in order to obtain at least 300 specimens. Planktonic foraminifera specimens were identified and counted following the taxonomic concept of Hemleben *et al.* (1989). *Neogloboquadrina pachyderma* right and left coiling (d and s) and the two varieties of *Globigerinoides ruber alba* and *rosea* were counted and plotted separately. The species *Globigerinoides sacculifer* includes also *Globigerinoides trilobus*, according to Hemlemben *et al.* (1989) and the species *Globoturborotalita rubescens* and *Globoturborotalita tenella* were counted and plotted together (Capotondi *et al.* 1999). The identified species are expressed as percentages (%) of the total number of planktonic foraminifera. The paleoclimatic curve inferred from planktonic foraminifera assemblages was obtained by the formula (w-c)/(w+c)x100, where w represents the warm-water indicators and c the cold water indicators. *Globigerinoides trilobus-sacculifer*, *Globigerinoides ruber* var. *alba* and *rosea*, *Globoturborotalita rubescens*, *Globorotalia truncatulinoides*, *Orbulina universa* and *Globigerinella siphonifera* were considered warm water species, while *Globorotalia scitula*, *Globorotalia inflata*, *Turborotalita quinqueloba*, and *Globigerinita* *glutinata* were considered cold water indicators (Hemleben *et al.* 1989, Rohling *et al.* 1993, Pujol and Vergnaud Grazzini 1995).

Pollen analysis was performed on 134 samples of known weight. Samples were treated with 10 % HCl and 38 % HF and sieved over a 10 μm sieve, while *Lycopodium* spores were added in order to check the reliability of quantitative data. Samples were stored and mounted in silicone oil and a minimum of 150 pollen grains was counted in each sample excluding *Pinus*, Pteridophyte spores and aquatics. Percentage diagrams for selected pollen types were constructed, and pollen concentrations were calculated in grains/gram. As no major rivers are draining in western Kos Basin, the main pathway of pollen transport is assumed to be through wind (Muller 1959). Therefore pollen concentration in the sediments reflects changes in wind intensity and pollen production, while concentration of palynomorphs from taxa living in rivers and lakes (like *Sparganium*, *Pediastrum* and Zygnemantaceae) can be used as a proxy of river runoff into the basin (Targarona 1997).

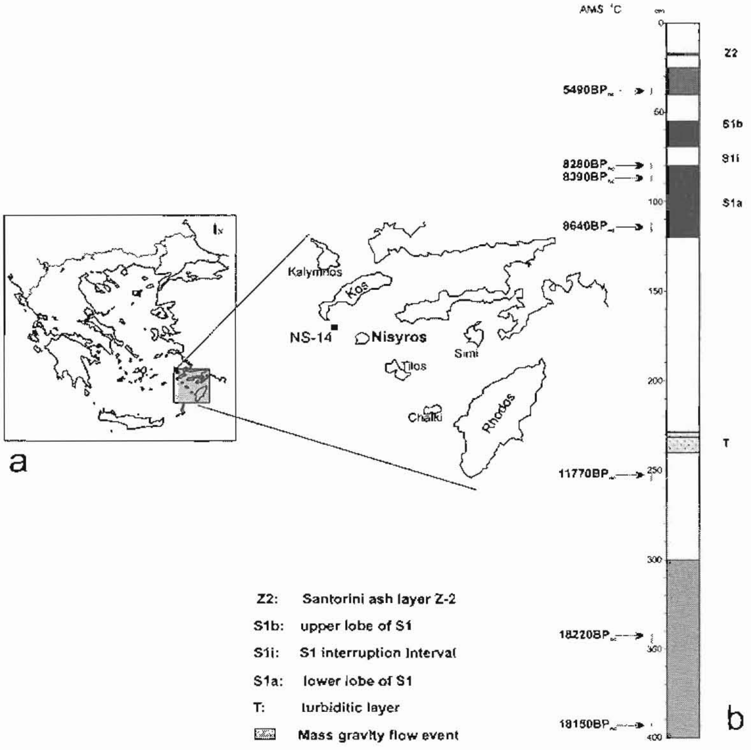

Figure 1 – a. Location of core NS-14 in SE Aegean Sea, b. Core NS-14 stratigraphy and performed AMS datings (after Triantaphyllou *et al.* subm.)

3. Results

3.1. General core lithology and age assessment

From the top to 300 cm, the core lithology mainly consists of grey hemipelagic mud, interrupted by a volcanic ash layer at 17 cm, which represents the most recent Z-2 Santorini ash layer. An additional dark interval is visually detected between 25 and 40 cm. Sapropel S1 is recognised from 55 to 120 cm and is distinctively divided in two units by a lighter grey coloured interval (69-80 cm). A turbiditic layer (T) is located between 231 and 240 cm. Grey clay with pebbles prevail from 300 cm to the bottom (Fig. 1b), representing a gravity flow event.

The base of S1(a) at 120 cm depth is considered to have an interpolated calendar age of 9300 yr $_{cal}$ BP (8800 yr $_{nc}$ BP), whereas the top of S1(a) at 80 cm, corresponds to an interpolated age of 8600 yr $_{cal}$ BP (8300 yr $_{nc}$ BP), (Triantaphyllou *et al.* 2006, Triantaphyllou *et al.* subm.). The top of S1 interruption at 69 cm is calibrated at 7600 yr $_{cal}$ BP (7300 yr $_{nc}$ BP) and the top of S1(b) at 55 cm has an interpolated age of 6400 yr $_{cal}$ BP (6100 yr $_{nc}$ BP). The estimated sedimentation rates (Triantaphyllou *et al.* subm.) indicate rapid accumulation of S1 (an average sedimentation rate of 57 cm/kyr in the lower S1(a) layer; 11 cm/kyr in the interruption and 11 cm/kyr in the upper S1(b) layer). The similar ages provided by AMS ^{14}C datings at 344 and 393 cm (Fig. 1b) indicate that the dark olive grey coarse sediments from 300 cm till the base of the core, represent a mass gravity flow event slightly younger than 18200 yr $_{nc}$ BP, mostly associated with possible seismic activity and landslide phenomena due to the active tectonism of the area (Papanikolaou and Nomikou 2001).

3.2. Coccolithophores

Coccolithophores are generally well preserved in all samples taken from the upper 300 cm of the sediment core. The frequency curves of the most indicative coccolithophore species are shown in Fig. 2a. From 300 cm up to 135 cm depth *E. huxleyi* abundances remain constant above 60 %. Above this level the abundances display a gradual decrease, with minimum values reaching 25 %, during S1 interruption interval. Relative abundances exceeding 60 % reappear from 30 cm towards core top. EHMC morphotypes are restricted mainly in the interval from 300 to 120 cm and reappear at 60 cm; showing the maximum abundance at 15 cm from the top. *F. profunda* shows more or less an inversed pattern to *E. huxleyi* with the highest abundance from 135 to 60 cm. A sharp decrease in the abundance of this species is recorded at 60 cm, during the formation of S1(b). A prominent frequency peak up to 52 % is also recorded at 32 cm. *Rhabdosphaera* spp. increase in relative abundance from 256 cm and upwards. *Syracosphaera* spp. and *Calciosolenia* spp. follow more or less the same trend. On the contrary, *Helicosphaera* spp. start to increase at 135 cm, peaking at the lower part of S1(a), between 120 and 100 cm. A second interval with high frequencies of *Helicosphaera* spp. occurs between 38 and 29 cm. *Gephyrocapsa oceanica* is mainly occuring between 60 and 29 cm with maximum abundance at the upper part of S1(b); outside this interval its presence is only sporadical. *B. bigelowii* is present at 170 cm and 78 cm, but increases at the upper part of S1(b) at 57-55 cm; it occurs with very few representatives up to 29 cm. *Calcidiscus* spp. and *Umbilicosphaera* spp. increase in abundance above 100 cm, but the highest frequencies are recorded above S1. The species *Umbellosphaera tenuis* presents higher values between 300 and 260 cm and above S1 up to 29 cm.

3.3. Planktonic foraminifera

The relative abundance data of 16 planktonic foraminifera species are presented in Fig. 3. *G. ruber alba* and *G. ruber rosea* abundance curves show maximum valnes at the interval 100-80 cm of the core. *G. ruber rosea* displays also a significant peak in abundance at 54 and 30 cm, whereas the species is almost absent in the lower part of the core. On the contrary *G. ruber alba* shows elevated percentages throughout the core. *G. trilobus/sacculifer* first appears at 130 cm, reaching maximnm abundance at the base of S1(a) and between 40-29 cm of the core. It almost disappears between 100-65 cm and then it appears again at 60-20 cm occurring up to the top in small percentages. *O. universa* shows several peaks in abundance during the deposition of S1, while it is almost absent in the lower part of the core. *Neogloboquadrina pachyderma* and *N. dutertrei* totally disappear within S1, existing only in the lower part of the core. However, *N. pachyderma* sinistrally coiled specimens, were found at 125, 80 and 10 cm. *G. bulloides* is continuously present in the core, slightly decreasing in the lower part of S1(a). At 50 cm from the core top the species displays a temporary disappearance but it reoccurs above this level reaching its maximum abundance. The abundance curve of *G. rubescens* and *G. siphonifera* shows a decrease at the interval 120-90 cm; both species are more abundant during 65-50 cm and they abruptly increase at 16-8 cm. *G. glutinata* presents a constant distribution in the core with a gradual decrease from the 54 cm to the top of the core. *T. quinqueloba* displays a sporadic distribution pattern being more abundant in the lower part of the core. The species is absent during S1. Among the minor species, *G. conglobatus*

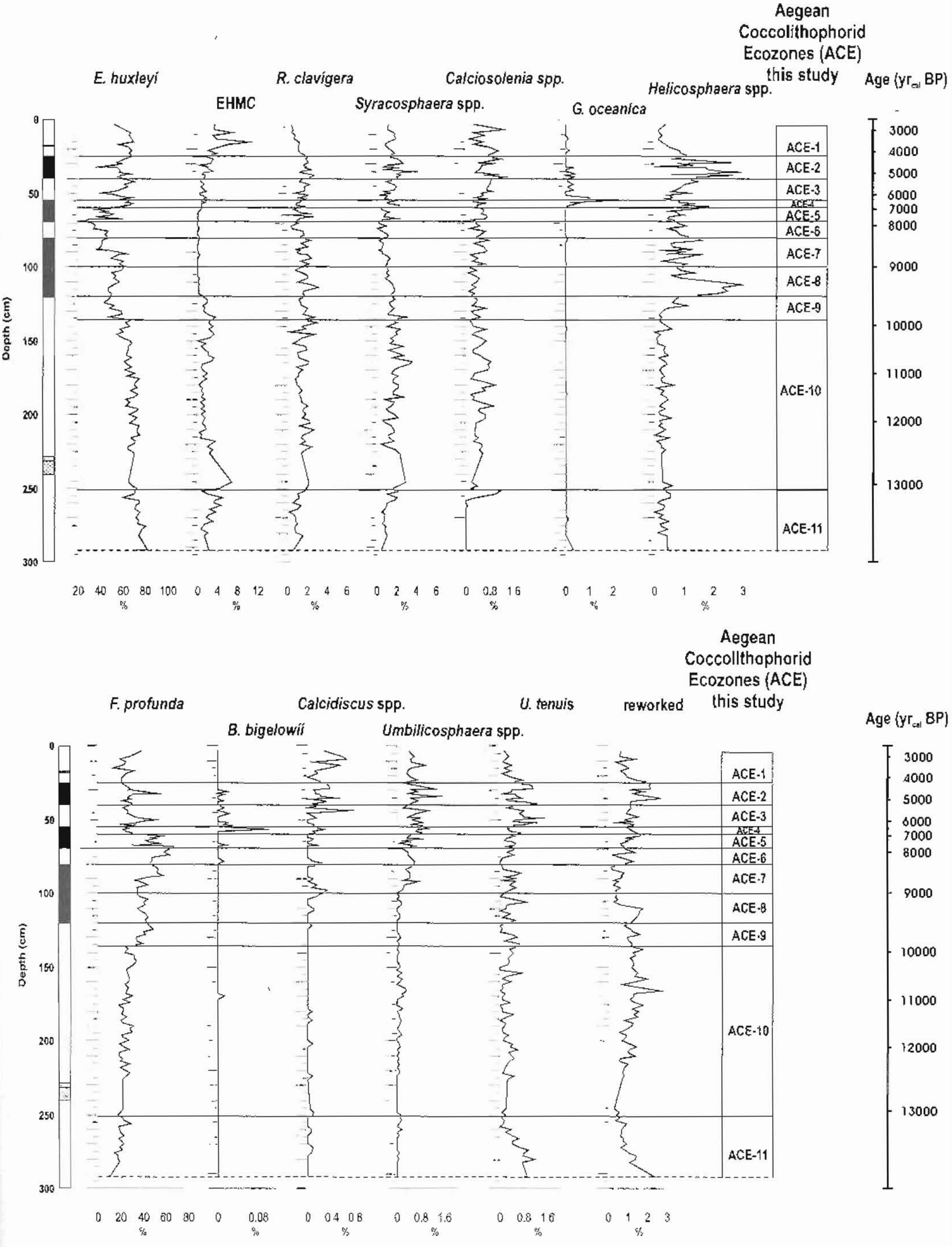

Figure 2 - Frequency curves of the most indicative coccolithophorid species in core NS-14. To the right the established coccolithophoris ecozones (ACE1-11)

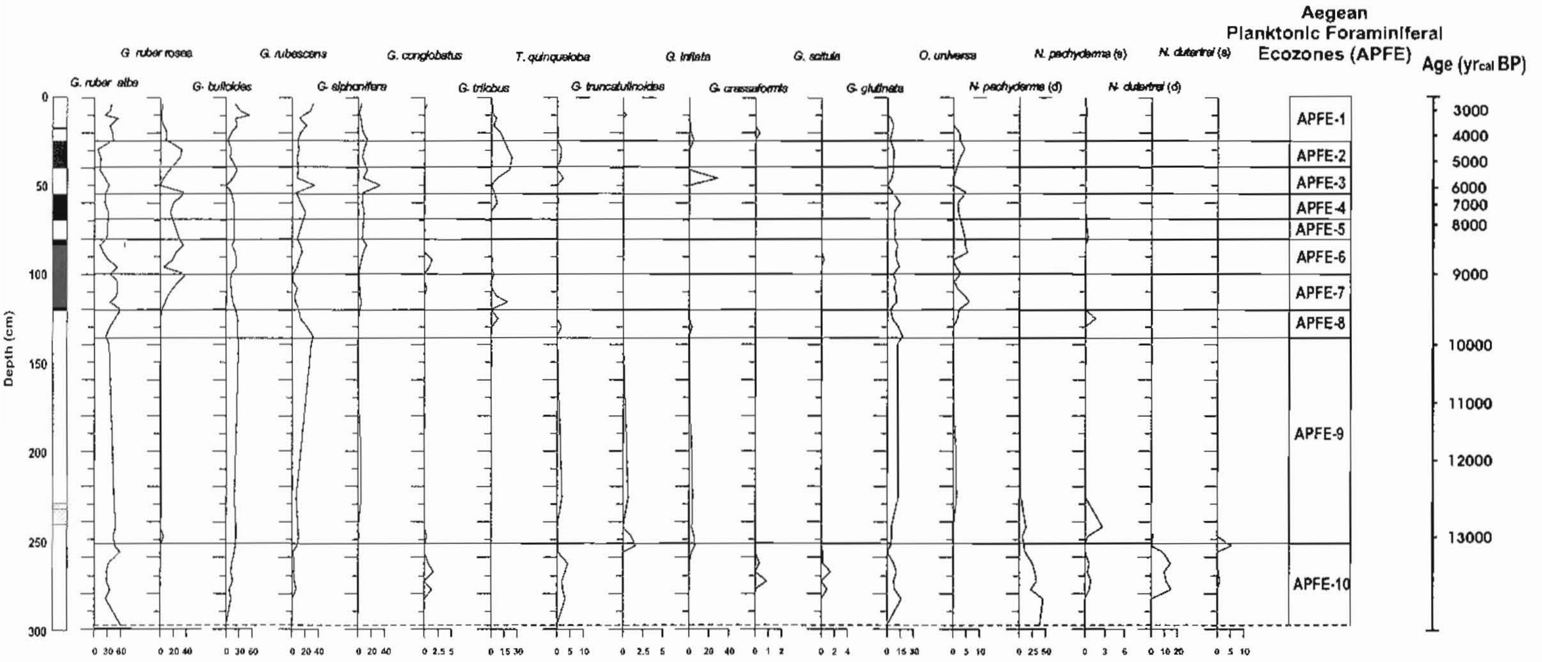

Figure 3 - Frequency curves of the most indicative planktonic foraminifera species in core NS-14. To the right the established planktonic foraminifera ecozones (APFE1-9)

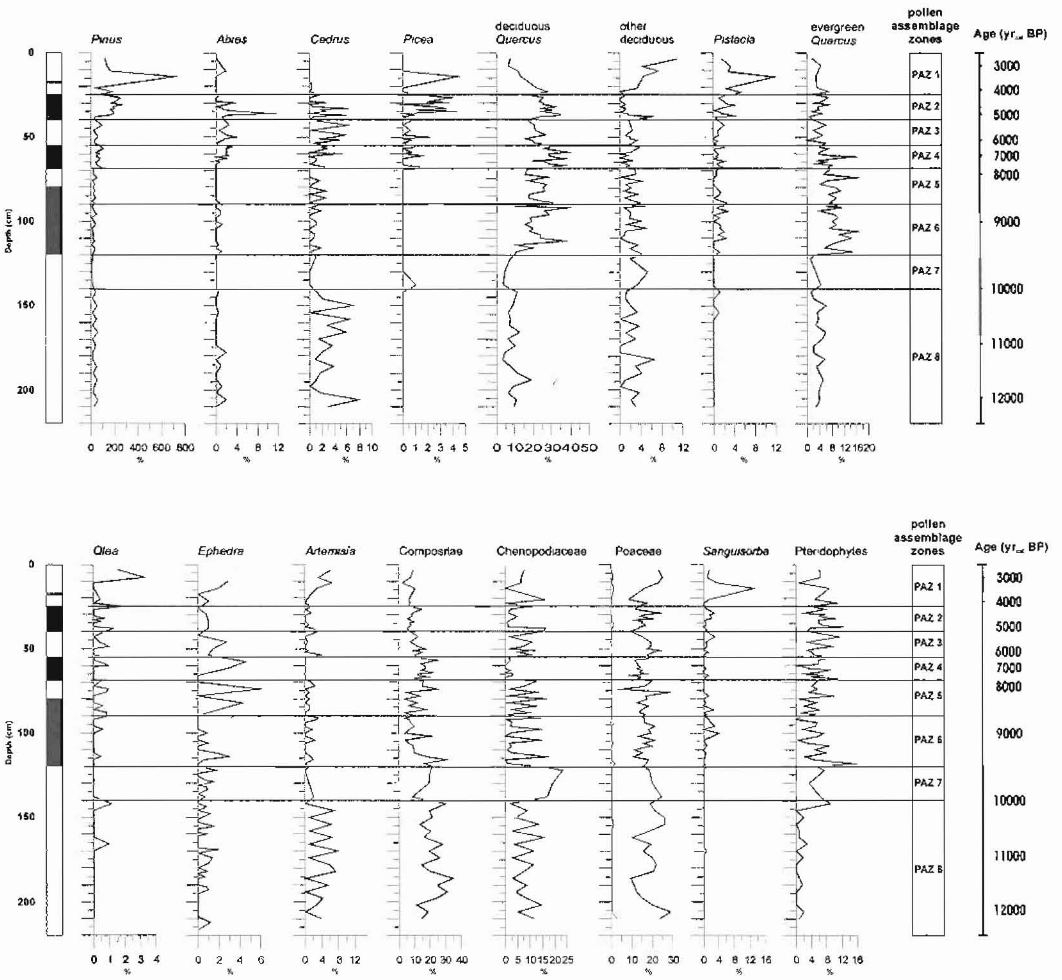

Figure 4 - Frequency curves of the most indicative pollen taxa in core NS-14. To the right the established pollen assemblage zones (PAZ1-8)

and *G. scitula* display the same distribution pattern, existing in small percentages in the lower part of the core; a slight influx is recorded in the upper part of S1(a). *G. inflata* is present in the lower part of the core. Upwards it occurs in low percentages just below S1(a), disappears within the sapropel, and reappears above it reaching its maximum abundance. *G. truncatulinoides* is mainly restricted at the lower part of the core.

3.4. Pollen

Pollen concentrations vary form 10 to 53.000 grains per gram of dry sediment, with the lower concentrations appearing in the lower horizons and the highest within the sapropel and in the 28-40 cm interval. The concentration of aquatic palynomorphs follows the same trend, increasing during the sapropel and showing maximum values in the 28-40 cm interval. No pollen diagram was constructed from 210 cm and downwards due to the extremely low pollen concentrations. Pollen spectra of core NS-14 reflect diversified vegetation ranging from steppe to semi-dessert (*Artemisia*, Chenopodiaceae), mountainous deciduous (*Quercus robur, Sorbus, Acer*) and coniferous forests (*Pinus*, *Abies* and *Cedrus*) representatives (Fig. 4). Arboreal taxa are continuously present in all spectra, though their abundances fluctuate. *Pinus* and *Cedrus* are continuously present while *Abies* appears less abundant and absent in many spectra and *Picea* is mainly represented on the upper 70 cm of the core. *Juniperus* and *Quercus* records continuous presence, the latter shows its highest abundance between 140 cm and 37 cm. Steppe vegetation elements as Compositae, Poaceae, Chenopodiaceae, occur in high values especially below 120 cm. In particular the curve of Chenopodiaceae shows a profound maximum in the 140-120 cm interval. The semi-desert taxa *Artemisia* and *Ephedra* though being almost continuously present in the spectra in low percentages, show relatively higher abundances from 140cm downwards. *Pistacia* appears continuously abundant from 120 cm upwards, becoming an important element of the Mediterranean forest.

4. Ecostratigraphy

4.1. Coccolithophore ecozones

The detailed coccolithophore analysis in the high sedimentation rate NS-14 core reveals a series of abundance fluctuations that permits the documentation and refinement of the regional E. Mediterranean ecostratigraphic scheme (Principato *et al.* 2003, Giunta *et al.* 2003), in particular during the interval of sapropel S1 deposition. Eleven coccolithophore ecozones (Aegean Coccolithophore Ecozones; ACE 1-11) are recognised, documenting the dramatic response of coccolithophore assemblages to environmental changes in SE Aegean (Fig. 2).

ACE-1 (= C1 of Principato *et al.* 2003). Interval: High abundance of *E. huxleyi* and EHCM (*E. huxleyi* moderately calcified morphotypes sensu Crudeli *et al.* 2004), decrease of *Helicosphaera* spp.

ACE-2 (= upper C2 of Principato *et al.* 2003). Top: last common occurrence of *B. bigelowii*. Interval: high abundance of *Helicosphaera* spp., increase of *Syracosphaera* spp., *F. profunda, U. tenuis*.

ACE-3 (= middle C2 of Principato *et al.* 2003). Top: abrupt increase of *Helicosphaera* spp. Interval: increase of *F. profunda*.

ACE-4 (= lower C2 of Principato *et al.* 2003). Top: distinct reduction of *B. bigelowii* and peak of *G. oceanica*. Interval: low abundance values of *Helicosphaera* spp. and *F. profunda*, peak of *B. bigelowii*.

ACE-5 (= C3 of Principato *et al.* 2003). Top: abrupt decrease in abundance of *F. profunda*, decrease of *Syracosphaera* spp. Interval: Peak in abundance of *Rhabdosphaera* spp., *Umbilicosphaera* spp., *Syracosphaera* spp., presence of *B. bigelowii*.

ACE-6 (= upper C4 of Principato *et al.* 2003). Top: peak in *F. profunda*. Interval: presence of *B. bigelowii*.

ACE-7 (= middle C4 of Principato *et al.* 2003). Top: decrease of *Syracospharea* spp. and *R. clavigera*. Interval: high abundance of *F.profunda* and *E. huxleyi*. EHCM morphotypes are absent.

ACE-8 (= middle C4 of Principato *et al.* 2003). Top: increase of *Umbilicosphaera* spp., decrease of *Helicosphaera* spp. Interval: very high abundance values of *Helicosphaera* spp. High values of *R. clavigera*. EHCM morphotypes are absent.

ACE-9 (= lower C4 of Principato *et al.* 2003). Top: increase of *Helicosphaera* spp., decrease of EHCM. Interval: gradual increase of *F. profunda* and *Helicosphaera* spp.

ACE-10 (= C5 of Principato *et al.* 2003). Top: peak in *Syracosphaera* spp., increase of *F. profunda*. Interval: high abundance of *E. huxleyi*, decreased values of *Helicosphaera* spp., peak of EHCM.

ACE-11 (= upper C6 of Principato *et al.* 2003). Top: increase in abundance of *R. clavigera*. Interval: increase of *E. huxleyi* and *U. tenuis*.

4.2. Planktonic foraminiferal ecozones

High resolution analyses performed on planktonic foraminiferal assemblages allowed the recognition of nine bioevents that are used to define ten Aegean Planktonic Foraminiferal Ecozones (APFE1-10), which are well comparable to the ecozones and biozones established in the central and eastern Mediterranean (Jorissen *et al.* 1993, Capotondi *et al.* 1999, Sbaffi *et al.* 2001, Principato *et al.* 2003). We summarise below the principal characters of each APFE in order to explain the high resolution ecostratigraphic scheme recorded in Fig. 3.

APFE-1 (=PF1 of Principato *et al.* 2003). Interval: significant presence of *G. ruber alba* and *G. bulloides*, decrease of *G. ruber rosea* and *O. universa*, presence of *G. trilobus/sacculifer* and *G. rubescens*, slight peak of *G. inflata*.

APFE-2 (=upper PF2 of Principato *et al.* 2003). Top: increase of *G. ruber alba*, decrease of *G. ruber rosea* and *O. universa* , disappearance of *T. quinueloba*. Interval: decrease of *G. ruber alba*, high abundance of *G. ruber rosea*, *G. trilobus/sacculifer* and *O. universa*, significant presence of *G. bulloides*, *G. glutinata* and *T. quinqueloba*.

APFE-3 (=middle PF2 of Principato *et al.* 2003). Top: disappearance of *G. inflata*. Interval: reappearance and maximum abundance of *G. inflata*, decrease of *G. ruber rosea*, presence of *G. trilobus/sacculifer* and N. *pachyderma*, high *G. ruber alba*.

APFE-4 (=middle PF2 of Principato *et al.* 2003). Top: High abundance of *G. ruber rosea* and *O. universa*, temporary disappearance of *G. trilobus/sacculifer*. Interval: decrease of *G. ruber alba*, positive trend of *G. ruber rosea*, presence of *G. trilobus/sacculifer* and *G. inflata*.

APFE-5 (=lower PF2 of Principato *et al.* 2003). Top: high abundance of *G. ruber alba*, positive trend of *G. ruber rosea*. Interval: decreasing trend of *G. ruber rosea*, *G. ruber alba* and *O. universa*, appearance of *N. pachyderma* (s) and *G. inflata*.

APFE-6 (=PF3 of Principato *et al.* 2003). Top: positive trend of *G. ruber alba* decrease of G. *ruber rosea*. Interval: significant increase of *G. ruber rosea* and high abundance of warm water species such as *O. universa*, *G. rubescens* and *G. siphonifera*, high abundance of *G. ruber alba* followed by a temporary negative trend, increase of *G. bulloides*.

APFE-7 (=upper PF4 of Principato *et al.* 2003). Top: decrease *G. ruber alba*, high abundance of *G. ruber rosea*, peak in abundance of *O. universa*, disappearance of *G. trilobus/sacculifer*. Interval: high abundance of *G. ruber alba* and *O. universa*, gradual increase of *G. ruber rosea* high abundance of *G. trilobus/sacculifer*.

APFE-8 (= lower PF4 of Principato *et al.* 2003). Top: high abundance of *G. ruber alba*, appearance of *G. ruber rosea*, temporary disappearance of *G. trilobus/sacculifer*, positive trend of *O. universa*. Interval: increasing trend of *G. ruber alba*, appearance of *G. trilobus/sacculifer*, presence of *G. inflata* and *N. pachyderma* (s).

APFE-9 (=PF5 of Principato *et al.* 2003). Top: positive trend of *G. ruber alba*. Interval: presence of *G. ruber rosea*, *G. truncatulinoides* and *G. inflata* decrease of *N. pachyderma* (d) and high abundance of *N. pachyderma* (s).

APFE-10 (=PF6 of Principato *et al.* 2003). Top: appearance of *G. inflata* and G. *truncatulinoides*, disappearance of *N. dutertrei* (d). Interval: decreasing trend in abundance of *G. ruber alba* following by an increase at the upper part, fluctuations of *G. scitula*, high abundance of *T. quinqueloba* and *G. glutinata*. The species *N. pachyderma* (d) and *N. dutertrei* (d) show significant abundance values.

4.3. Pollen assemblage zones

Pollen assemblages of NS-14 are organized in the following eight Pollen Assemblage Zones (PAZ 1-8), (Fig. 4).

PAZ-1: High abundance of Poaceae, Chenopodiaceae, *Artemisia, Olea, Pistacia* and *Sanguisorba*. Low values of *Quercus* and *Cedrus*.

PAZ-2: Increase of deciduous *Quercus, Abies, Picea, Pinus* and high pollen concentration. Drop in the values of Chenopodiaceae and *Artemisia*. Aquatic palynomorph concentration reaches its maximum values.

PAZ-3: Increase in steppic elements like Chenopodiaceae and Poaceae and conifers like *Cedrus*. Decrease in *Pistacia*, deciduous *Quercus* and *Picea* in an interval characterised by lower pollen concentration.

PAZ-4: Increase of deciduous *Quercus* and *Pinus*. Sharp decrease in Chenopodiaceae, Poaceae and absence of *Artemisia*. High pollen concentration.

PAZ-5: Increase of Chenopodiaceae, *Artemisia, Ephedra* and *Olea*. Decrease in deciduous *Quercus, Pistacia* and *Pinus*. Disappearance of *Abies* and *Picea* pollen.

PAZ-6: Increase of *Quercus* (both deciduous and evergreen), *Pistacia* and *Sanquisorba*, presence of *Abies*, decrease in Chenopodiaceae and high pollen concentration.

PAZ-7: Maximum expansion of Chenopodiaceae, increase in *Artemisia, Centaurea* and Poaceae, decrease in most arboreal pollen (*Quercus* deciduous and evergreen, *Abies, Olea*) and absence of *Pistacia*. Low pollen concentration.

PAZ-8: Further increase in abundances of *Artemisia* and Compositae and minor increase of deciduous *Quercus* and Conifers.

5. Paleoecological-paleoclimatic implications

The plankton and pollen abundance patterns and the climatic curve inferred from the planktonic foraminifera assemblages (Fig. 5) enhance the reconstruction of paleoecological-paleoclimatic conditions over the last 14 000 yrs in the SE Aegean Sea.

Warm period. Evidence of climatic fluctuations and seasonality (~14 000-13 100 yr$_{cal}$ BP)

Plankton ecozones ACE-11 and APFE-10 reflect generally warm conditions; the base of the ecozones cannot be defined due to the massive flow event recorded at core NS-14. ACE-11 is characterized by increased abundances of the upper-middle photic zone warm-water species *U. tenuis* (Winter *et al.* 1994) confirming the subtropical features of this interval. However several climatic fluctuations are recorded indicated by the paleoclimatic curve (Fig. 5). Cool and high fertility conditions are recorded by the abundance of *T. quinqueloba, G. glutinata* and *G. scitula* (Thunell 1978, Geraga *et al.* 2005) which dominate the assemblage as well as by neogloboquadriinids which confirm the presence of Deep Chlorophyll Maximum (DCM) and highly productive surface conditions probably due to increased terrestrial input. The warmer periods are reflected mainly by *G. ruber alba* and secondly by *G. rubescens* and *G. conglobatus*.

Temperature decrease. Deep winter mixing related to cooling (13 100-9900 yr$_{cal}$ BP)

The abundance peak of *Calciosolenia* spp. in ACE-10 indicates a shift to wetter period (Amore *et al.* 2004). The presence of *G. inflata* and *G. truncatulinoides* in APFE-9 reveal a well developed deep and cold mixed layer- deep winter mixing related to cooling (Pujol and Vergnaud Grazzini 1995). Peaks in abundance of *N. pachyderma* and *N. dutertrei* sinistral forms show high productivity and cool conditions (Thunell and Sautter 1992). Pollen assemblages are dominated by Gramineae, Compositae and *Artemisia* suggesting dry climatic conditions in PAZ-8 zone. How-

4.3. Pollen assemblage zones

Pollen assemblages of NS-14 are organized in the following eight Pollen Assemblage Zones (PAZ 1-8), (Fig. 4).

PAZ-1: High abundance of Poaceae, Chenopodiaceae, *Artemisia, Olea, Pistacia* and *Sanguisorba*. Low values of *Quercus* and *Cedrus*.

PAZ-2: Increase of deciduous *Quercus, Abies, Picea, Pinus* and high pollen concentration. Drop in the values of Chenopodiaceae and *Artemisia*. Aquatic palynomorph concentration reaches its maximum values.

PAZ-3: Increase in steppic elements like Chenopodiaceae and Poaceae and conifers like *Cedrus*. Decrease in *Pistacia*, deciduous *Quercus* and *Picea* in an interval characterised by lower pollen concentration.

PAZ-4: Increase of deciduous *Quercus* and *Pinus*. Sharp decrease in Chenopodiaceae, Poaceae and absence of *Artemisia*. High pollen concentration.

PAZ-5: Increase of Chenopodiaceae, *Artemisia, Ephedra* and *Olea*. Decrease in deciduous *Quercus*, *Pistacia* and *Pinus*. Disappearance of *Abies* and *Picea* pollen.

PAZ-6: Increase of *Quercus* (both deciduous and evergreen), *Pistacia* and *Sanquisorba*, presence of *Abies,* decrease in Chenopodiaceae and high pollen concentration.

PAZ-7: Maximum expansion of Chenopodiaceae, increase in *Artemisia*, *Centaurea* and Poaceae, decrease in most arboreal pollen (*Quercus* deciduous and evergreen, *Abies, Olea*) and absence of *Pistacia*. Low pollen concentration.

PAZ-8: Further increase in abundances of *Artemisia* and Compositae and minor increase of deciduous *Quercus* and Conifers.

5. Paleoecological-paleoclimatic implications

The plankton and pollen abundance patterns and the climatic curve inferred from the planktonic foraminifera assemblages (Fig. 5) enhance the reconstruction of paleoecological-paleoclimatic conditions over the last 14 000 yrs in the SE Aegean Sea.

Warm period. Evidence of climatic fluctuations and seasonality (~14 000-13 100 yr$_{\text{cal}}$ BP)

Plankton ecozones ACE-11 and APFE-10 reflect generally warm conditions; the base of the ecozones cannot be defined due to the massive flow event recorded at core NS-14. ACE-11 is characterized by increased abundances of the upper-middle pbotic zone warm-water species *U. tenuis* (Winter *et al.* 1994) confirming the subtropical features of this interval. However several climatic fluctuations are recorded indicated by the paleoclimatic curve (Fig. 5). Cool and high fertility conditions are recorded by the abundance of *T. quinqueloba, G. glutinata* and *G. scitula* (Thunell 1978, Geraga *et al.* 2005) which dominate the assemblage as well as by neogloboquadriinids which confirm the presence of Deep Chlorophyll Maximum (DCM) and highly productive surface conditions probably due to increased terrestrial input. The warmer periods are reflected mainly by *G. ruber alba* and secondly by *G. rubescens* and *G. conglobatus*.

Temperature decrease. Deep winter mixing related to cooling (13 100-9900 yr$_{\text{cal}}$ BP)

The abundance peak of *Calciosolenia* spp. in ACE-10 indicates a shift to wetter period (Amore *et al.* 2004). The presence of *G. inflata* and *G. truncatulinoides* in APFE-9 reveal a well developed deep and cold mixed layer- deep winter mixing related to cooling (Pujol and Vergnaud Grazzini 1995). Peaks in abundance of *N. pachyderma* and *N. dutertrei* sinistral forms show high productivity and cool conditions (Thunell and Sautter 1992). Pollen assemblages are dominated by Gramineae, Compositae and *Artemisia* suggesting dry climatic conditions in PAZ-8 zone. However the co-existence of deciduous *Quercus, Abies* and *Cedrus* indicate sufficient precipitation for the development of forest vegetation in favourable areas, while the sporadic presence of *Olea*, *Pistacia* and *Sanguisorba* after $10900yr_{cal}$ BP is indicative of frost-free winters.

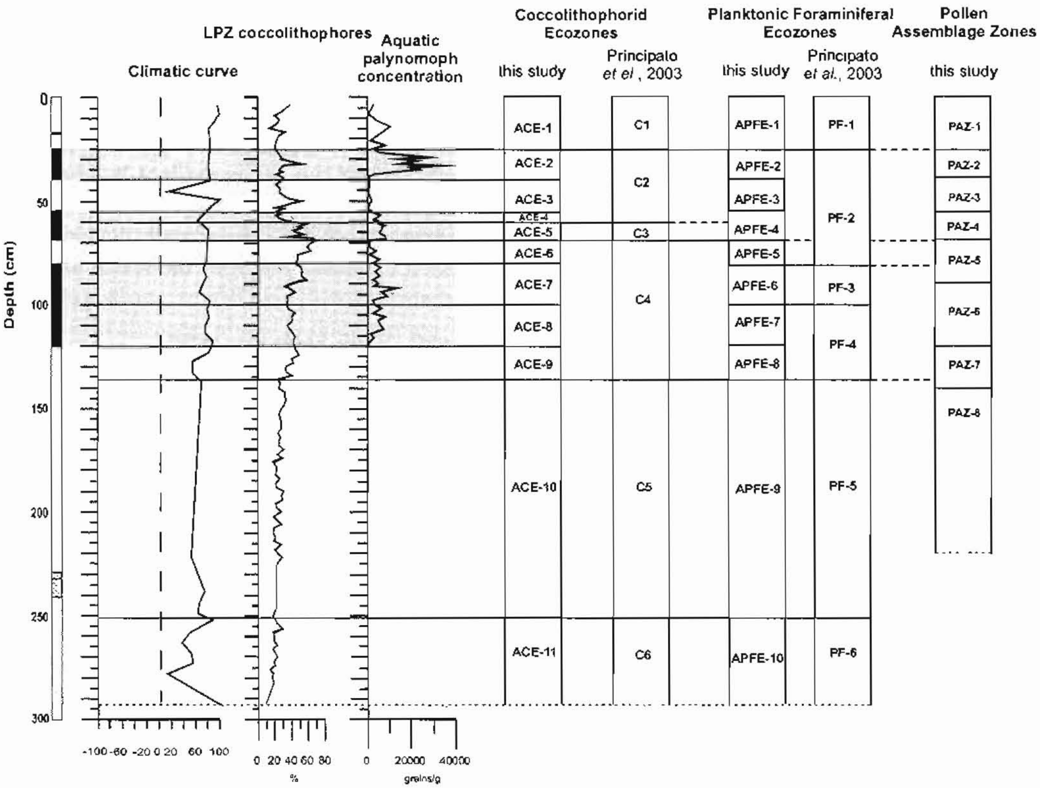

Figure 5 - Paleoclimatic curve inferred from planktonic foraminifera, LPZ coccolithophores relative abundance and aquatic palynomorph concentration and correlation scheme between the assemblage zones defined in SE Aegean Sea (core NS-14) and the correspondent intervals identified by Principato *et al.* (2003).

High primary productivity, increased run off, onset of stratification (9900-9300 yr_{cal} BP)

The gradual increase of *F. profunda* in ACE-9 coccolithophore ecozone supports the establishment of stratified conditions and the onset of nutrient-rich environment in the deep photic zone. Fresh water input and increase in productivity at depth is enhanced by the increase of *Helicosphaera* spp. and *Syracosphaera* spp. (Colmenero-Hidalgo *et al.* 2004, Amore *et al.* 2004). APFE-8 is marked by the appearance of *G. trilobus / sacculifer*, which indicates the occurrence of a shallow pycnocline (Fenton *et al.* 2000), possibly related to strong runoff periods (Rossignol-Strick 1985) and by the abundance of *N. pachyderma* sinistral forms indicating the development of DCM in the lower photic zone. *G. bulloides* is also indicative of high primary conditions and *G. ruber alba,* a warm oligotrophic surface dweller, shows a strong increasing trend indicative of the onset of stratification in the water column at the top of APFE-8. Lowering of SST as indicated by the paleoclimatic curve (Fig. 5) is due to the abundance of cool water indicators (*T. quinqueloba, G. inflata, G. glutinata)* just before the deposition of S1. The expansion of Chenopodiaceae in PAZ-7 zone may reflect the existence of a surrounding arid coastal zone (Geraga *et al.* 2000) and/or prevailing strong SE winds carrying them from the salt marshy areas of N. Africa (Rossignol-Strick 1999).

Increased fresh water input, warm and stratified water column (9300-9000 yr $_{cal}$ BP)

The very high values of *Helicosphaera* spp. followed by the abundance of tropical-subtropical *F. profunda* at the lower part of S1(a) confirm the development of a nutrient-rich environment in the middle-photic zone and further evidence to the lowering of salinity during ACE-8 ecozone. The increase of the paleoclimatic curve towards positive values is the main feature of APFE-7 ecozone due to the high abundance of warm water species (*G. ruber alba* and *O. universa*) as well as *G. ruber rosea* indicative of warmer conditions (Hemleben *et al.* 1989), which suggest enhanced stratification of the water column. Shallow pycnocline and strong run off is evident by the high abundance of G. *trilobus/sacculifer* as well as by the high aquatic palynomorph concentration. Moreover pollen assemblages that reflect the terrestrial response in PAZ-6 indicate the onset of forestation and the development of Mediterranean vegetation belts as a result of the warm and humid conditions.

Warm and stratified water column. Short cooler intervals (9000-8600 yr $_{cal}$ BP)

Warm conditions with negative shifts are suggested by the paleoclimatic curve and the faunal assemblages that prevail in APFE-6 ecozone during the upper part of S1(a). Strong warming of surface waters and stratification of the water column are related to the high values of *G. ruber rosea, G. rubescens* and *G. siphonifera*. Indications of cooler conditions are supported in ACE-7 by the gradual increase of *Umbilicosphaera* spp., a group that has a tendency towards eutrophic adaptation (Young, 1994) and is consistent with the nutrient redistribution in the surface waters (Principato *et al.* 2006).

Slight breaking of stratification, less saline surface waters, on-going productivity in the deep photic zone (8600-7600 yr $_{cal}$ BP)

The prevailing productivity during S1 interruption in the deep photic zone (high *F. profunda*; decreased only at the lower part of the interruption in the ACE-6 ecozone) is co-occurring with relatively less saline surface layer (moderate abundance of *Helicosphaera* spp., sporadic presence of *B. bigelowii* a species suggesting low salinity in surface waters (Negri and Giunta 2001, Giunta *et al.* 2003). A slight breaking of stratification can be attributed to the decrease of *G. ruber rosea*, dramatical reduction of *G. rubescens* and *O. universa* and the presence of *G. glutinata* and *N. pachyderma* dextral specimens in APFE-5 ecozone. The small expansion of steppe vegetation and the cocurrent drop of runoff proxies recorded in PAZ-5 zone indicate a drier period while the presence of *Ephedra* may reflect a drop in temperature (Mudie *et al.* 2002).

Humid conditions. Warm and stratified water column (7600-6900 yr $_{cal}$ BP)

B. bigelowii shows small but clear peak and together with relatively high abundances of *Helicosphaera* spp. and *F. profunda* suggest the constant presence of less saline surface waters and stratified conditions in ACE-5 coccolithophore ecozone during the lower part of S1(b). The expansion of mixed deciduous forests and the increase of aquatic palynomorph concentrations indicate a humid period in PAZ-4 zone. The increase in abundance of *G. ruber rosea*, *O. universa* and *G. rubescens* is indicative for the stratification of the water column in APFE-4 ecozone.

Wet and less warm period. Decline of DCM (6900-6400 yr $_{cal}$ BP)

F. profunda displays a distinct reduction in coccolithophore ecozone ACE-4 during the upper part of S1(b). Additionally an abrupt increase of hyposaline and relatively eutrophic species *B. bigelowii*, less saline *G. oceanica* (Di Stefano and Incarbona 2004) and high nutrient flourishing *E. huxleyi* (Young 1994) is recorded followed by the increase of eutrophic coccolithophore *Umbilicosphaera* spp. Our multiproxy data from NS-14 reveal a series of coolings that resulted to strong fresh water input and the breakage of stratification between 6900 and 6400 yr $_{cal}$ BP implying the decline of DCM at ~ 6500 yr $_{cal}$ BP, that predates the end of the S1 depositional conditions.

Decline of DCM, drop in precipitation (6400-5200 yr $_{cal}$ BP)

The warm and stratified waters continue to occur still for a short period in APFE-3 but they are immediately followed by remarkable vertical mixing as indicated by the peak in abundance of *G. inflata*. The lowering of SST as indicated by the paleoclimatic curve at this level is marked by the presence of cool water indicators (*T. quinqueloba* and *G. glutinata*). Expansion of coniferous forest in lower elevations reflects a temperature fall (Giunta *et al.* 2003) while expansion of steppic elements suggests a drop in precipitation in PAZ-3 zone.

Very humid and warm conditions (5200-4200 yr $_{cal}$ BP)

A warming phase is testified during APFE-2 ecozone by the significant increase of *G. ruber rosea* and *O. universa* and the temporary dissapearence of *G. inflata* (normal marine conditions), whereas strong runoff is evident through high abundance of G. *trilobus/sacculifer*. Moreover the intense fresh water input is documented by the sharp increase of *Helicosphaera* spp. followed by high abundance of *Calciosolenia* spp. and minor peaks of *B. bigelowii* in ACE-2 ecozone. The expansion of mixed deciduous forest together with the maxima of the runoff proxies indicates high precipitation in PAZ-2 zone. The presence of *Picea* in the area is indicative of strong north winds (Mudie *et al.* 2002).

Temperature decrease (4200-2500 yr $_{cal}$ BP)

A cool interval is recognised within coccolithophore ACE-1 due to the increase of *E. huxleyi* and the cool EHCM morphotypes (Crudeli *et al.* 2006). High primary productivity in a cold mixed layer is recorded by the occurrence of *G. bulloides*, *G. inflata* and *G. truncatulinoides,* whereas the presence of *G. glutinata* evidences cooling events in APFE-1 ecozone. PAZ-1 reflects a period with open vegetation cover and indications of human disturbed vegetation.

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