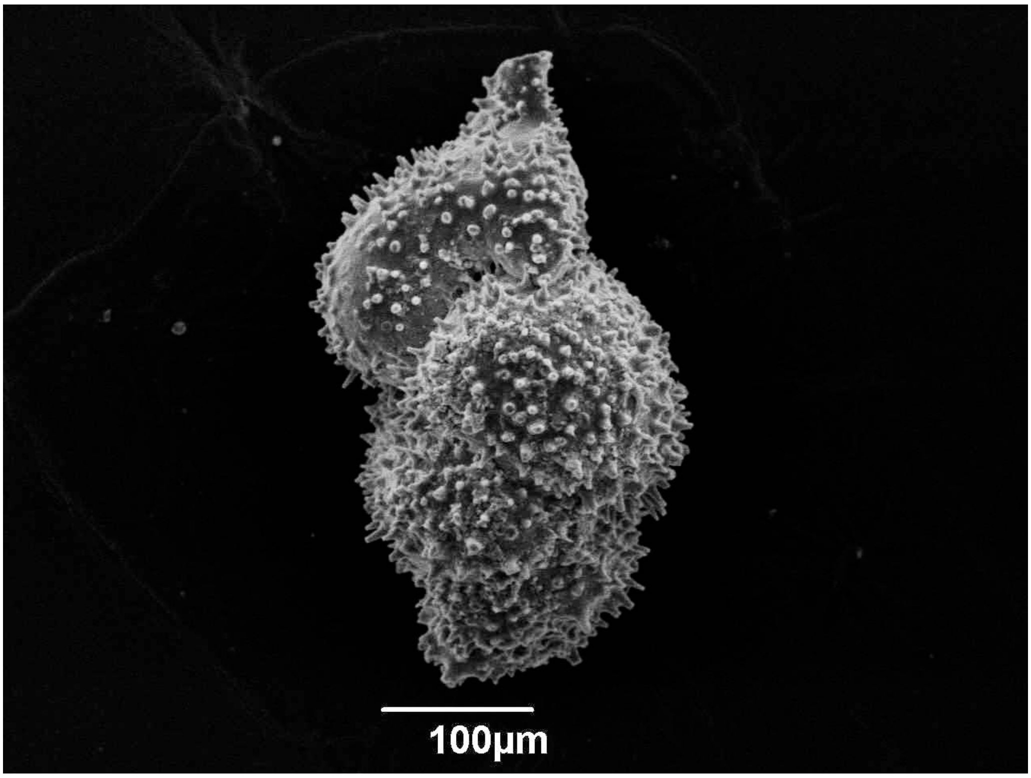
National Kapodistrian University of Athens – Dept. of Geology and Geoenvironment- Section of Historical Geology and Paleontology

Postgraduate Course of the Faculty of Geology and Geoenvironment
Specialization: Depositional Environments, Ecosystems and Geobioresources

Paleoenvironmental evolution of Pliocene sapropelic layers in the South Aegean Sea, NE Mediterranean

MSc Thesis



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Abstract

One of the most challenging features of the long-term Cenozoic climatic evolution, with some analog potential for present/ future global climate change, is the last sustained warm and high-atmospheric CO2 interval in Earth's history, which started after the end of the Messinian Salinity Crisis (5.971–5.332 Ma) in the Mediterranean Sea. The Messinian/ Pliocene boundary commonly includes a transitional organic-rich interval, followed by early Pliocene marine deposits. The early Pliocene is the most recent period in Earth history when the average global temperature (2.70–4.05 °C or 3–9 °C according to climatic models) and multi-proxy (e.g. Uk'37) paleothermometers and sea-level (5–70m) were higher than today. Moreover, the atmospheric carbon dioxide concentrations (pCO_2) were close to or slightly above modern values, between 330 and 400 ppm. The study of benthic foraminiferal assemblages is of high importance, as benthic foraminifera can be used as indicators for reconstructing environments of the past. The availability of more complete DSDP sedimentary successions containing well - preserved benthic assemblages of the Early Pliocene Cretan Basin, which were studied in order to determine the past environmental conditions, to observe the different foraminiferal assemblages and identify the existence of Early Pliocene potential sapropelic layers and the comparison of the conditions in which Early Pliocene potential sapropelic layers were deposited with the conditions that characterized the deposition of sapropel S1 during Holocene in the Aegean Sea and wether we can observe similar trends.

The study of the benthic foraminiferal assemblages of the Early Pliocene Cretan Basin indicates that the area was characterized by open marine conditions with periods of high organic flux and low oxygen rates. The benthic foraminiferal fauna of the area consists of normal-sized specimens with an increasing abundance of lower epibathyal fauna (i.e. *Bolivina spp., B. costata, U. pregrina*) and periodic occurences of some epiphytic taxa (i.e. *C. lobatulus, Neoconorbina sp., C. refulgens*) that are the product of in-basin transfer. Five potential sapropelic layers were observed through the micropaleontological study in the interval 4 – 437cm core depth. The potential sapropelic layers showcase low values of Benthic Foraminiferal Oxygen Index and Redeposition Index, indicating low oxic conditions with high values of infaunal species *Bolivina spp., B. costata* and *U. pregrina.* Additionally, 3 distinct Low Oxic events occurred in the interval 485 – 755cm core depth. During these low oxic events, BFOI values continue to indicate low oxic conditions, however there is major increase of oxic indicator species *C. pseudoungerianus* and *S. reticulata* that point to a better oxygenation of the sea floor.

The results that are acquired from this study can offer insight to the deposition trends of the Early Pliocene depositions that share similar characteristics with sapropelic layers and indicate that their formation conditions are similar to those of sapropel S1 (10.2–6.4 ka BP) during Holocene in the Aegean Sea. The Early Pliocene benthic foraminiferal assembladges are heavily impacted by organic flux and dissolved oxygen fluctuations and as a result are dominated by infaunal taxa that can tolerate low oxygen levels in the potential sapropelic layers and with higher abundances of oxic indicator species in the Low Oxic events, as in the case of sapropel S1, which is characterized by severe dysoxic conditions, interrupted with episodes of better oxygenation of bottom waters in the Aegean Sea.

Keywords: Paleoenvironment, benthic foraminifera, Pliocene, sapropels, Aegean Sea

Περίληψη

Η περίοδος που ακολούθησε μετά την κρίση αλατότητας του Μεσσηνίου (5.971–5.332 Ma) αποτελεί ένα από τα πιο αινιγματικά γεγονότα της γεωλογικής ιστορίας στο χώρο της Μεσογείου καθώς μπορεί να προσφέρει κλιματικά ανάλογα για το κλίμα του μέλλοντος στην Γη της κλιματικής αλλαγής. Το όριο Μειοκένου – Πλειοκαίνου, χαρακτηρίζεται από ένα μεταβατικό διάστημα με πλούσιες σε οργανικό υλικό αποθέσεις, που ακολουθούνται από θαλάσσιες αποθέσεις του Κατώτερου Πλειοκαίνου. Το Κατώτερο Πλειόκαινο, σύμφωνα με κλιματικά μοντέλα, είναι η πιο πρόσφατη περίοδος στην ιστορία της Γης όταν οι μέσες παγκόσμιες θερμοκρασίες ήταν υψηλότερες σε σχέση με σήμερα (2.70–4.05 °C) όπως και η στάθμη της θάλασσας (5–70m). Ταυτόχρονα, οι ατμοσφαιρικές συγκεντρώσεις διοξειδίου του άνθρακα (pCO2) ήταν κοντά ή ελαφρώς πάνω από τις σύγχρονες τιμές (330-400 ppm). Η μελέτη της βιοκοινωνίας βενθονικών τρηματοφόρων είναι πολύ σημαντική, καθώς τα βενθονικά τρηματοφόρα αποτελούν έναν χρήσιμο δείκτη για την ανακατασκευή παλαιοπεριβαλλόντων. Μέσα από τη μελέτη της ολοκληρωμένης βενθονικής πανίδας που είναι διαθέσιμη από τη γεώτρηση στη θέση 378A του προγράμματος DSDP (Deep Sea Drilling Project) η οποία περιέχει αναλυτικές πληροφορίες για την πανίδα των βενθονικών τρηματοφόρων, είναι δυνατή η μελέτη και ο εντοπισμός δυνητικών σαπροπηλικών στρωμάτων, περιοχών με χαμηλά επίπεδα οξυγόνου και περιβάλλον πλούσιο σε θρεπτικά συστατικά, για την περιοχή της λεκάνης του Κρητικού Πελάγους. Μέσα από αυτή τη μελέτη επιχειρείται να γίνει ένας προσδιορισμός των πιθανών αυτών στρωμάτων που φέρουν χαρακτηριστικά απόθεσης σαπροπηλικού στρώματος κατά το Κατώτερο Πλειόκαινο, η σύγκριση των συνθηκών απόθεσης με εκείνες του Ολοκαινικού σαπροπηλού S1 στην περιοχή του Αιγαίου Πελάγους και μια παλαιοπεριβαλλοντική ανακατασκευή της βενθονικής πανίδας και των ιδιαίτερων χαρακτηριστικών της στην λεκάνη της οπισθοτάφρου του Κρητικού Πελάγους.

Από τη μελέτη της βενθονικής πανίδας προκύπτει ότι η περιοχή χαρακτηρίζεται από συνθήκες τυπικού περιβάλλοντος ανοιχτής θάλασσας (απόλυτες συγκεντρώσεις με μέγιστο (55,3 f/g), με περιόδους υψηλής οργανικής ροής και χαμηλών συγκεντρώσεων οξυγόνου. Η πανίδα αποτελείται από δείγματα κανονικού μεγέθους με αυξημένη αφθονία ενδοπανιδικών ειδών (π.χ. *Bolivina spp., B. Costata, U. pregrina*) και περιοδικές εμφανίσεις κάποιων επιφυτικών ειδών (π.χ. C. *lobatulus, Neoconorbina sp ., C. refulgens*) που αποτελούν προϊόν μεταφοράς εντός λεκάνης.

Πέντε πιθανά σαπροπηλικά στρώματα παρατηρήθηκαν μέσω της μικροπαλαιοντολογικής μελέτης σε βάθος πυρήνα 4 - 437cm. Τα δυνητικά σαπροπηλικά στρώματα παρουσιάζουν χαμηλές τιμές BFOI (-20 – 24,4%) και R.I. (0, 6 – 25%) γεγονός που υποδηλώνει συνθήκες με χαμηλές συγκεντρώσεις διαλυμένου οξυγόνου και υψηλές τιμές σχετικής αφθονίας των ειδών ενδοπανίδας *Bolivina spp., B. costata και U. Pregrina.* Επιπλέον, εντοπίστηκαν 3 διακριτά γεγονότα με συνθήκες περιορισμένου οξυγόνου σε βάθος πυρήνα 485 - 755cm. Κατά τη διάρκεια αυτών των συμβάντων, οι τιμές BFOI (40,85 – 42,86%) συνεχίζουν να δείχνουν συνθήκες χαμηλής συγκέντρωσης διαλυμένου οξυγόνου, ωστόσο υπάρχει σημαντική αύξηση των ειδών – δεικτών οξικών συνθηκών *C. pseudoungerianus* και *S. reticulata* που δηλώνουν καλύτερη οξυγόνωση του θαλάσσιου πυθμένα.

Τα αποτελέσματα αυτής της μελέτης μπορούν να δώσουν μια εικόνα για τις συνθήκες των αποθέσεων που παρουσιάζουν παρόμοια χαρακτηριστικά με τα σαπροπηλικά στρώματα κατά το Κατώτερο Πλειόκαινο και δείχνουν ότι οι συνθήκες σχηματισμού τους είναι παρόμοιες με αυτές του Ολοκαινικού σαπροπηλού S1 (10.2-6.4 ka BP) στο Αιγαίο Πέλαγος. Οι συναθροίσεις των βενθονικών τρηματοφόρων του Κατώτερου Πλειοκαίνου στην λεκάνη του Κρητικού Πελάγους επηρεάζονται σε μεγάλο βαθμό από τις διακυμάνσεις της οργανικής ροής και του διαλυμένου οξυγόνου και ως αποτέλεσμα κυριαρχούν τα ενδοπανιδικά είδη που είναι ανεκτικά σε χαμηλά επίπεδα οξυγόνου στα δυνητικά σαπροπηλικά στρώματα, ενώ στα γεγονότα με χαμηλές συγκεντρώσεις οξυγόνου παρατηρούνται υψηλότερες σχετικές αφθονίες οξικών ειδών-δεικτών που δηλώνουν καλύτερη οξυγόνωση του πυθμένα σε σχέση με τις αποθέσεις πιθανών σαπροπηλικών στρωμάτων, όπως και στην περίπτωση του σαπροπηλού S1 που χαρακτηρίζεται από έντονα δυσοξικές συνθήκες με επεισοδιακά γεγονότα εμπλουτισμού σε οξυγόνο στην περιοχή του Αιγαίου Πελάγους.

Λέξεις-κλειδιά: Παλαιοπεριβάλλον, βενθονικά τρηματοφόρα, Πλειόκαινο, σαπροπηλός, Αιγαίο πέλαγος

Introduction

It is widely believed that if we manage to learn the climate of the past, we will be able to predict the climate of the future. Paleoenvironmental reconstructions are considered very important part of paleontology because of its numerous applications in the vast field of geosciences.

One of the most intriguing eras in Earth's geological history is that of the Messinian Salinity Crisis and the events that followed after. On account of their geographic ubiquity, their abundance in Mesozoic and Cenozoic deep - sea sediments and in Phanerozoic sediments and their utility as paleoenvironmental indicators, benthic foraminifera continue to be a main tool in paleoceanographic and paleoclimatic research and are used in this study to identify the paleoenvironmental evolution of the Early Pliocene sapropelic layers in the North Cretan Basin.

Site description and study area

The Aegean Sea

The Aegean Sea is an elongated embayment of the Mediterranean Sea located between the Greek and Anatolian peninsulas (Fig.1). The sea has an area of 215.000km^2 and in the North, it's connected to the Marmara Sea and the Black Sea by the straits of the Dardanelles and Bosporus. The Aegean Islands are located within the Aegean Sea and some bound it on its southern periphery, including Crete and Rhodes. The Aegean Sea is characterized by a number of inter-connected basins, with most of them reaching less than 2000m maximum depth. The main basins are the Cretan Basin, in a back-arc setting of late Neogene age; the Central Aegean Basin, where a number of islands belonging to discrete structural units are present; the Northern Aegean Basin, striking west-southwest to east-northeast which has been interpreted as a rifted basin (McKenzie, 1972) developed along the North Anatolian Fault which is also of probable late Neogene age.

The circulation in the Aegean (Fig.1) is dominated by an intensified rim current system that is consistent with the buoyancy introduced from the Dardanelles outflow and along axis wind forcing from the North. A cyclonic circulation across the basins with several sub-basin-scale gyres closely linked to the complex topography and an intense flow towards the South along the western land boundary characterizes the general circulation. The southern Aegean is the area were the basin is connected with the eastern Mediterranean general circulation. The influx of modified Leventine Intermediate Water which has high levels of salinity and temperature, along the eastern Aegean and at depths of about 100m is a known feature of the Aegean Sea circulation (Theoharis et al. 1993). The near-surface circulation also includes a northward drift along the eastern Aegean, which is particularly evident north of the Cyclades arc and is generally considered the boundary between the central and the southern Aegean.

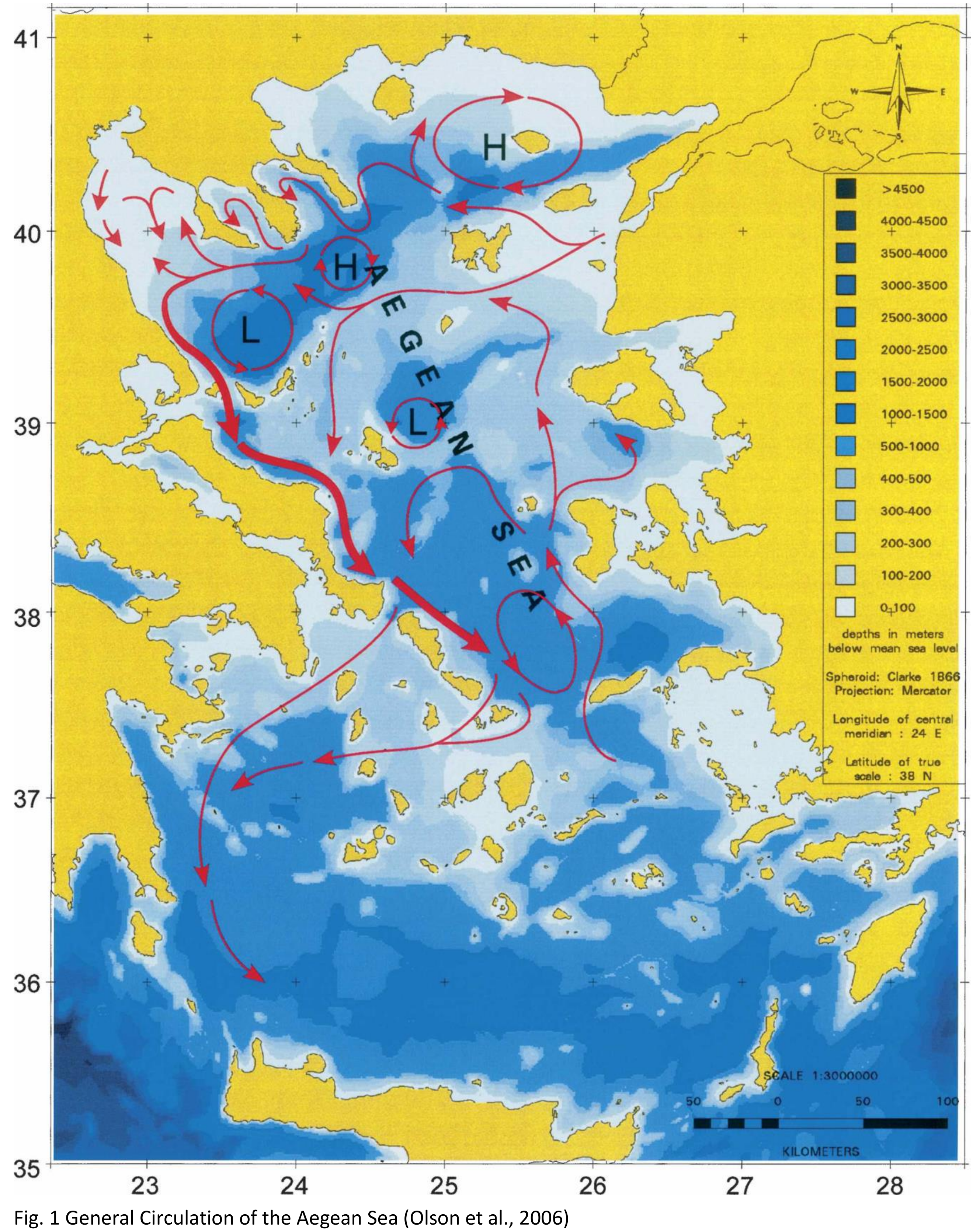

Fig. 1 General Circulation of the Aegean Sea (Olson et al., 2006)

The Cretan Basin

As mentioned above, the Cretan Basin (Fig.2) is one of the main basins located in the Aegean Sea and it is of late Neogene age (Van Hinsbergen, 2006) with its opening dating back to Middle Miocene (Papanikolaou & Vassilakis, 2010).

Fig. 2 Aegean Sea and Cretan Basin. In red is the area of interest.

The basin development history of Crete during the Neogene, could be explained by the combination of two different tectonic processes that include the formation of the South Aegean core complex as a result of N-S extension, followed by E-W, arc-parallel extension associated with the opening of the Aegean arc (Jolivet et al., 1996; ten Veen & Kleinspehn, 2003). According to Van Hinsbergen (2006), detailed paleobathymetry-based vertical motion reconstruction and stratigraphy, along with synthesis of various structural and sedimentological data acquired from literature, describe the basin's middle to early late Miocene history. The oldest deposits in the basin were uniquely derived during the Middle Miocene from the non-metamophic hanging wall of the Cretan detachment. Subsequent break-up of the hanging wall into extensional klippen resulted in the northward shift of the surface trace of the extensional detachment. This led to an east-to west running longitudinal sedimentary system.

Messinian salinity crisis and sapropel deposition

The Messinian salinity crisis (MSC) is considered one of the most dramatic episodes of oceanic change of the past 20 million years (Hsu et.al., 1978) and it is the result of a complex combination of tectonic and glacio-eustatic processes which gradually restricted and then isolated the Mediterranean Sea from the open ocean (Krijgsman et.al., 1999). This gradual process of change in the water exchange with the Atlantic caused important palaeoceanographic changes in the Mediterranean which are reflected with the alternations of open marine marls and sapropels, passes via diatomites into the Lower Evaporites and ends, above an erosional surface, with the Upper Evaporites and fresh to brackish water deposits of Lago Mare facies in the classic Messinian sequence of Sicily which started at 7.24Ma.

The deposition of Evaporites is controlled by astronomical precession (Fig.3). The precession cycle is related to the fact that the earth's rotational axis relative to the plane of the earth's orbit around the sun on the long term is not fixed in space. Changes in the direction of the axis in space affects the climate by causing a very slow shifting of the dates of the solstices and equinoxes along the orbit. A full cycle of precession takes 26.000 years (Fig.3). However, there are other complications in the earth-sun motions such as the entire earth orbit itself slowly rotates around the sun, about once for every four precession periods. As a result, the precession cycle manifests itself in the insolation onto the earth's surface in two dominant periodicities; a major one centered on 23.000 years and a minor one of 19.000 years.

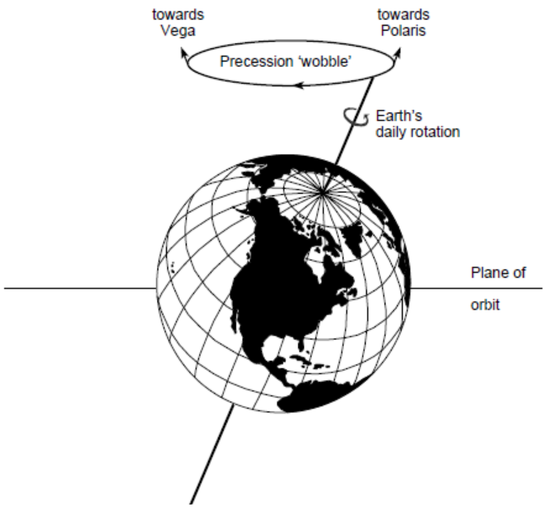

Fig.3 The earth's precession wobble. One revolution takes 23,000 years.

The total number of sedimentary cycles agrees with the total number of precession peaks, while time is insufficient for a 40kyr obliquity control, resulting in excluding the glacio-eustasy parameter as a probable cause of evaporites formation. Furthermore, the onset of the salinity crisis in the Mediterranean, correlating with a warming trend in the open ocean discounts the glacio-eustasy hypothesis (Cita and Ryan, 1979; Cita, 1979). Evaporite deposition occurred during precession maxima, in relatively dry periods when evaporation exceeded precipitation which in turn allowed the formation of a giant brine in the Mediterranean, when outflow of dense Mediterranean waters into the Atlantic was restricted or obstructed by shallow sills in the western Mediterranean gateways (Krijgsman et.al., 1999). During precession minima and relatively wet periods of climate, high freshwater runoff resulted in the deposition of sapropel-like sediments across the Mediterranean Sea.

The eastern Mediterranean Deep-sea sediments are characterized by the cyclic occurrence of dark sediment layers, called sapropels (Coolen et al., 2002). Sapropels are characterized by high total organic carbon (TOC ≥ 2%), S, and Fe content and significant enrichments in various trace elements (Calvert, 1983; Pruysers et al., 1991; Thomson et al., 1995). Sapropels have a cyclic nature of occurrence and are mainly defined by minima in the precessional index when perihelion occurred in the summer in northern hemisphere (Rossignol-Strick, 1983, 1985; Prell and Kutzbach, 1987; Hilgen, 1991). The transient distribution of sapropels of the Eastern Mediterranean correlates with maximum potential strength of the African monsoon where a function of orbital precession would result in maximum discharge from the Nile River (Rossignol – Strick, 1983). Rohling and Hilgen (1991) suggested that increased precipitation along the northern borderlands of the Eastern Mediterranean, could have been an additional precession-related factor for reduced salinities at sea surface during sapropel formation. During sapropel formation, surface water salinities must have been lower, according to $\delta^{18}O$ signatures of planktonic foraminifers (Williams and Thunell, 1979; Vergnaud-Grazzini et al., 1986).

DSDP expedition and available data

Apart from various geophysical surveys, the area in the North Cretan Basin was drilled during expedition 343 as part of the Deep Sea Drilling Project (DSDP). The Deep Sea Drilling Project (DSDP) was an ocean drilling project operated from 1968 to 1983. From this drilling in Site 378 (Fig.4) two different holes were drilled, which produced two cores 34,8 and 20m in length respectively. One of the specific objectives of DSDP Site 378 was to determine the stratigraphy of the ponded sediments and therefore the evolution of the Neogene tectonic movements of the region.

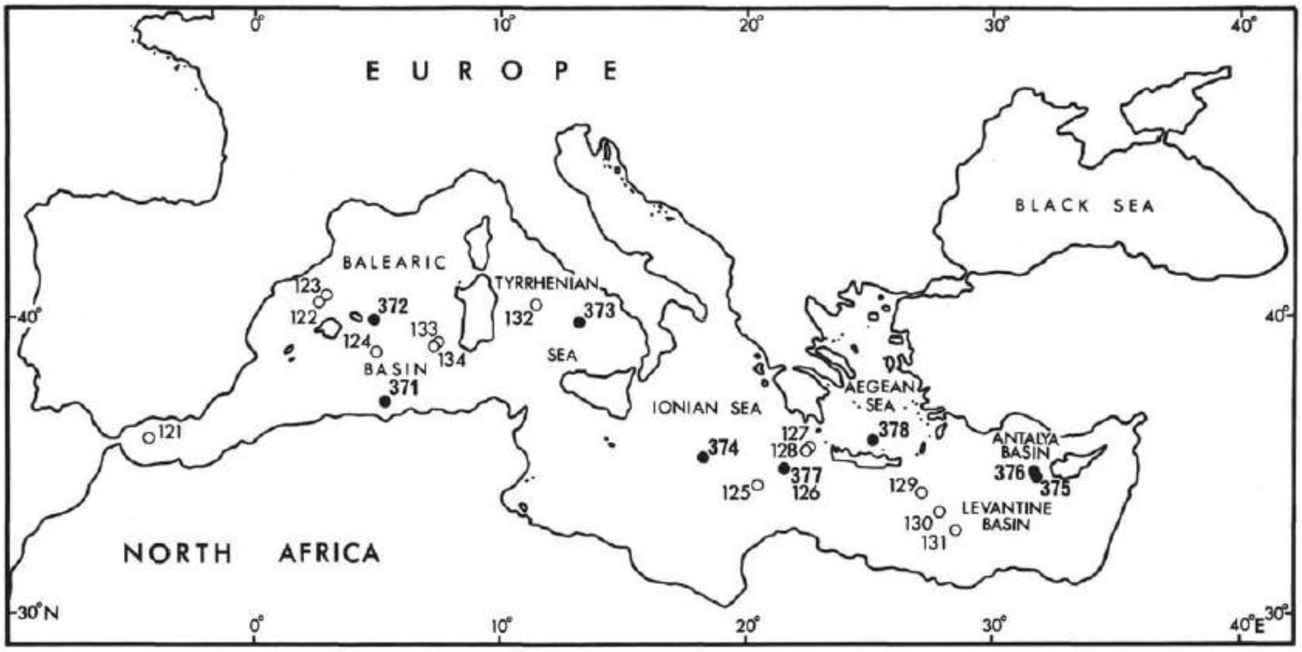

Fig. 4 DSDP Hole Locations

Study purpose

For this study, Hole 378A - Core 3A, located in the North Cretan Basin was sampled, in order to conduct foraminiferal research and observe the benthic foraminiferal assemblages that were deposited in the Cretan basin after the events of the Messinian Salinity Crisis. One of the most enigmatic features of long-term Cenozoic climatic evolution, with some analog potential for present and future global climate change, is the last sustained warm and high-atmospheric CO_2 interval in Earth's history, which started after the end of the Messinian Salinity Crisis in the Mediterranean Sea. The Messinian/Pliocene boundary commonly includes a transitional organic-rich interval, followed by early Pliocene marine deposits. The early Pliocene is the most recent period in Earth history when the average global temperature (2.70–4.05 °C or 3–9 °C according to climatic models) and multi-proxy paleothermometers and sea-level (5–70 m) were higher than today. Moreover, the atmospheric carbon dioxide concentrations (pCO_2) were close to or slightly above modern values, between 330 and 400 ppm. The study of benthic foraminiferal assemblages is of high importance, as benthic foraminifera can be used as indicators for reconstructing environments of the past. This availability of more complete DSDP sedimentary successions containing well - preserved benthic assemblages such as the ones from DSDP Site 378 aids:

- The study of the assemblages in order to determine the past environmental conditions in the Cretan Basin.
- The attempt to observe and define if the different foraminiferal assemblages can indicate the existence of Early Pliocene potential sapropelic layers.
- The comparison of the conditions in which Early Pliocene potential sapropelic layers were deposited with the conditions that characterized the deposition of sapropel S1 during Holocene in the Aegean Sea and whether we can observe similar trends.

Benthic Foraminifera

Foraminifera are testate protozoa, that possess granuloreticulose pseudopodia. They are considered a dominant deep-sea life form and are characterized by a life cycle that is often complex but typically involves an alternation of sexual and asexual generations (Holbourn et al., 2013). Benthic foraminifera can be found in every marine environment, from shallow waters to the deep sea (Corliss, 1980; Jorissen, 1999; Pawlowski and Holzmann, 2008). Due to their utility as paleoenvironmental indicators, benthic foraminifera continue to be a main tool in paleoceanographic and paleoclimatic research with numerous applications in fields such as biostratigraphy, paleobathymetry, paleoenvironmental and sea level reconstructions.

The classical definition of benthic foraminifera is based on three main characteristics. A test, composed of calcite secreted by the cell itself or consisting of mineral grains embedded in the organic test, a unique reproductive cycle with alternation of sexual and asexual generations and the presence of rhizopodia (Lee, 1990; Tendal, 1990; Bowser and Travis, 2002). Concerning their morphological classification, the main morphological characters that are taken into account are the wall structure of the test (agglutinated, porcelaneous, or hyaline), the number of chambers (monothalamous or polythalamous), and the test morphology (Hottinger, 2006). The wall structure can be categorized into three different types: hyaline perforate calcitic or aragonitic, imperforate porcelaneous, and agglutinated with either calcareous or organic cement (Wood, 1949).

The rhizopodia of the living cell, extend from a single or even multiple apertures and is the main tool that is used for feeding, test construction, signal transmission, locomotion, and anchoring to hard substrates (Travis and Bowser, 1991; Bowser and Travis, 2002; Murray, 2006). Depending on their mode of life, benthic foraminifera can be categorized as infaunal or epifaunal. Epifaunal species live to the bottom surface, while einfaunal species live in the sediment. Benthic foraminifera have been recorded to live up to 60 cm below the sediment surface (Goldstein et al., 1995), but in the majority of environments most live within the first few centimeters (Murray, 2006).

Deep - water benthic foraminifera are found across the oceans and their distribution inside the basin is mainly controlled by environmental parameters such as organic matter flux and carbonate dissolution (Altenbach et al., 1999; Jorissen et al., 2007; Pawlowski and Holzmann, 2008; Gooday and Jorissen, 2012). Deep - sea benthic foraminiferal population dynamics and changes in surface ocean productivity on various temporal scales are strongly linked (Gooday, 1988, 2002; Smart et al., 1994; Heinz et al., 2001). During eutrophic surface ocean conditions there is low diversity with blooms of opportunistic species in the deep sea (e.g., Ohga and Kitazato, 1997), while oligotrophic environments sustain low population density and promote high diversity with complex trophic relationships (Gooday, 1999).

Materials and Methods

Study Area – Core 42A

Deep Sea Drilling Program (DSDP) Site 378 (Holes 378 and 378A) is located in the north Cretan Basin (Fig.6). Its maximum penetration was 343.5 meters with termination in Messinian gypsum. The main objectives of this expedition were to study the close of evaporite deposition, the paleoceanography of the Plio-Quaternary, and the age of the last deformation of this marginal basin. For that reason, two separate holes were drilled, Hole 378 and 378A. In this study only Hole 378A was used and the samples that were studied were collected by Core 3A. Core 3A depth from drill floor is 2.138 – 2147,5m and depth below the sea floor is 243 – 302,5m.

Hole Lithology

The lithology of Hole 378A was divided by Hsu et.al (1978) in 4 different lithological Units. The upper three are hemipelagic calcareous units, all rich in nannofossils, and with drab colors. They are distinguished from one another by differences in age, physical coherence, and types and degree of burrowing. The 4th Unit includes the selenitic gypsum. The units' respected lithologies can be found on fig.5

Lithology at Hole 378A					
Unit	**Lithology**	**Core**	**Sub-bottom depth (m)**	**Est. Thickness (m)**	**Age**
1	(a) Nannofossil marl with interlayers of sapropelic marl and marl conglomerate		0-64	64	Quaternary
	(b) Nannofossil marl and ooze with sapropelic marl interlayers	1	64-131.5	67.5	Quaternary
2	Nannofossil marlstone with interlayered sapropelic marlstone		131.5-286	154.5	Late Pliocene
3	Nannofossil marlstone with abundant burrows and numerous sapropelic marlstone interlayers	3	286-308	22	Early Pliocene
4	Selenitic gypsum with minor limestone breccia	(6-2) 4-6		31.5	Late Miocene

Fig. 5 Hole 378A Lithology, after Hsu et al. (1978).

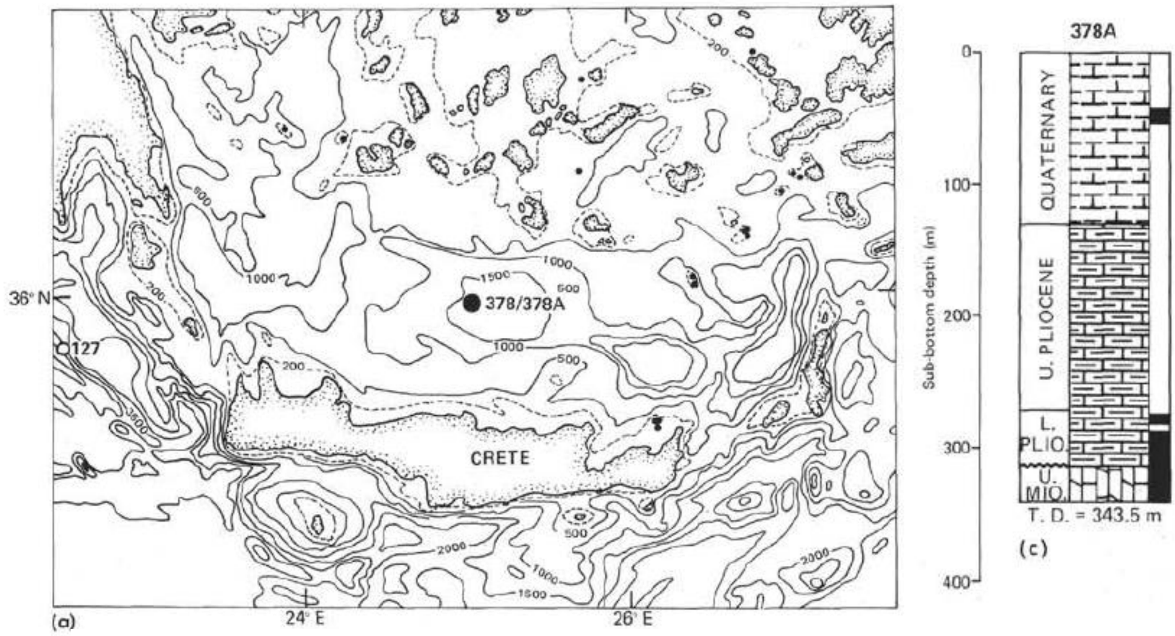

Fig. 6 Site and Core 378A (Hsu et al., 1978).

Sapropels of Core 3 and Biozones

According to Kidd et.al. (1978) Sapropels and sapropelic layers, ranging in color from black to very dark green and brown, were encountered in all of the eastern Mediterranean sites drilled during Leg 42A. In Core 3, 13 different sapropels were identified for sections 0 to 5. These layers were used as a basis for this study and can be found in Fig.7.

Sapropels and Sapropelic Layers of Core 3 in Hole 378A proposed by Kidd					
Section	**Top (cm)**	**Base (cm)**	**Nanno Zone**	**Foram Zone**	**Age**
0	34	43	CNPL3		
1	56	68			
2	0	16			
3	15	20			
3	52	60			
3	95	100			Early Pliocene (Zanclean)
4	16	25		MPI-3	
4	30	43	CNPL2		
4	70	83			
4	103	107			
5	72	85			
5	102	111			
5	130	142			

Fig. 7 Sapropels of Core 3

Core 3, according to Hsu et al., (1978) is identified to be in the *Discoaster asymmetricus* Zone (NN 14) in section 1 and sections 2-5 belong in the *Ceratolithus rugosus* Zone NN 13 (Martini, 1971). According to a more recent biozonation system (Fig.8) by Backman et al., (2012), section 1 belongs to Zone CNPL3 (*Discoaster asymmetricus/ Reticulofenestra pseudoumbilicus* Concurrent Range Zone) and sections 2-5 to Zone CNPL2 (*Sphenolitus neoabies* Partial Range Zone), placing them in Early Pliocene (Zanclean).

Sampling and sample preparation

For this study's purpose, 40 samples were collected from the DSDP Hole 378A, Core 3, located in the IODP repository, Marum, Bremen University, Germany (fig.8). The list of samples can be found on the Appendix. The core was sampled with high resolution from the undisturbed core sections' sediments, with samples taken from above centimeters, and bellow centimeters and inside each sapropel interval suggested by Hsu et. al. (1978) and each sample has a 2cm resolution. From each sample approximately 3g of material was used following the standard sample preparation. The preparation included extracting 3g of the material of each core sample and diluting it in a 2:1 hydrogen peroxide solution for 40 minutes. After the sample is diluted, a sieving process is followed using a 125μm sieve to keep the foraminifera and throw away the excess sediment. The remaining material was stored into Petri dishes and put in the oven at 60 degrees C until the sediment was dried completely.

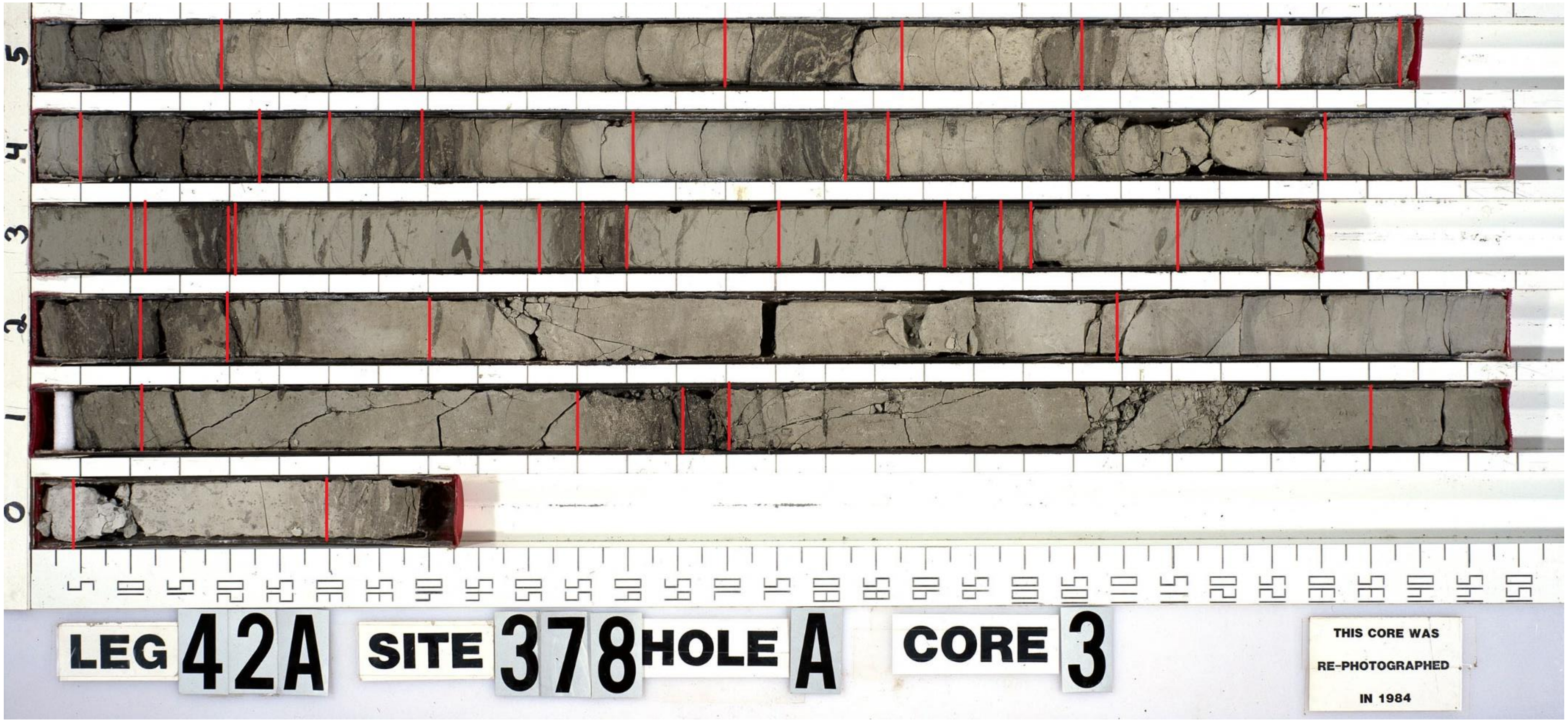

Fig. 8 Leg 42A Core 3 Sampling. The red lines indicate the location of samples.

Microscope study – Taxonomy

Each sample was put under the microscope for the foraminiferal study. Approximately, up to 150 benthic foraminiferal tests were picked from each cm and they were identified following the works of Cimerman et.al. (1991), Sgarrella et.al. (1993), Rasmussen et.al. (2005), Hayward et.al. (2012) according to the Loeblich & Tappan (1987) classification. After the identification process, the Redeposition index (RI) has been calculated from the concentration of redeposited benthic foraminiferal species. The R.I. was calculated by taking into account the re-deposited taxa that are considered as shelf-dwellers, comprising *Ammonia spp., Elphidium spp., Asterigerinata mamila, Astrononion sterligerum, Cibicides advenum, Cibicides refulgens, Cibicidoides Lobatulus, Neoconorbina spp., Reusella spinulosa, Valvulineria complanata and Miliolids (eg.* Sgarrella and Moncharmont Zei, 1993, Murray, 2006, Rasmussen et.al., 2005, Jorissen et.al., 1992). The presence of transported foraminifera was quantified by considering the specimens state (broken/ damaged specimens) and taxa expected to live at shallower water depths or/with an epiphytic mode of life. The Redeposition Index is calculated by the following formula:

RI%= 100 x [red. Total / (in situ Total + red Total)]

Where, red. Total = sum of redeposited benthic foraminiferal specimens; in situ Total = sum of in situ benthic foraminiferal specimens.

Additionally, the percentages of calcareous benthic foraminifera and agglutinated benthonic foraminifera and percentage of calcareous epifauna and infauna (paleoxygenation) were calculated and plotted in order to get a better view of the distribution of the various taxa in this study. The ratio of aerobic to anaerobic benthic foraminiferal forms can depict relative amounts of dissolved oxygen in deep oceanic waters (Kaiho, 1990). Kaiho (1994a) demonstrated that the BFOI derived from bathyal and abyssal Holocene assemblages correlates well with the dissolved-oxygen levels in overlying waters. The BFOI was subsequently employed to estimate global changes in dissolved oxygen within intermediate (200–1600 m) and deep (1600–4000 m) waters over the past 100 m.y. (Kaiho, 1991, 1994b). Therefore, the Benthic Foraminiferal Oxygen Index can be used for paleoenvironmental interpretations. It can be calculated by the following formulas:

$$BFOI = [a / (a + n) \times 100]$$

where a is the number of oxic species and n the number of dysoxic species.

When **a = 0 and n+s>0** (s is the number of suboxic indicators) BFOI value is given by

$$BFOI = [(s / (s+n)-1] \times 50.$$

Kaiho divided benthic foraminifera into **dysoxic** (0.1–0.3 mL/L), **suboxic** (0.3–1.2 mL/L), and **oxic** (>1.2 mL=L) indicators on the basis of relations between specific morphologic characters and oxygen levels and microhabitat. This study's list of the different categories is presented in Appendix B. The ranges of dissolved oxygen that can be recognized using the BFOI: 6.0C mL/L O_2) are shown in fig.9.

Dissolved oxygen conditions recognized using calcareous benthic foraminigera and their characters			
Oxygen condition	Oxygen level (mL/L)	Oxygen Index	Calcareous benthic foraminiferal characteristics
High oxic	3.0 - 6.0+	50 - 100	Dysoxic, suboxic and high ratios of oxic indicators
Low oxic	1.5 - 3.0	0 - 50	Dysoxic, suboxic and low ratios of oxic indicators
Suboxic	0.3 - 1.5	-40 - 0	Dysoxic and high ratios of suboxic indicators
Dysoxic	0.1 - 0.3	-50 - -40	Dysoxic and low ratios, or barren of, suboxic indicators
Anoxic	0.0 - 0.1	-55	Barren of calcareous benthic foraminifera

Fig. 9 BFOI dissolved oxygen ranges and values as suggested by Kaiho (1994).

Following the removal of the transferred epiphytic taxa from the assemblage and RI calculation, several Bioindices were calculated using the software Past, version 1.14, including total absolute abundances, relative and absolute abundances of foraminiferal species, species richness (S), Dominance (D) and Shannon–Wiener diversity (H) and plotted in graphs.

- Species richness (S) is the number of different species represented in each sample.
- Dominance (D) expresses the dominance of a species in the study population and is calculated by the formula of Simpson (1949):

$$D = \sum_{i=1}^{s} \left(\frac{ni}{N}\right)^2$$

Where: *s*: number of species

ni: total number of tests of species *i*

N: total number of all tests of all species

- The Shannon Wiener diversity index (H) refers to the number of different species and the relative frequency of individuals with which the species participates in the observation sample. It leads to conclusions about species interactions, which is not expressed by species abundance. The index is calculated by Shannon & Weaver's (1963) formula:

$$H = -\sum_{i=1}^{s} [\left(\frac{ni}{N}\right) x \ln \left(\frac{ni}{N}\right)]$$

Where: s: number of species

ni: total number of tests of species *i*

N: total number of all tests of all species

Scanning Electron Microscope

For the plate imaging, as well as defining several morphological features of the benthic foraminiferal tests multiple photos of various tests were taken by the use of Scanning Electron Microscope model Jeol JSM 6360 (fig.10), located at the Department of Geology and Geoenvironment in the Faculty of Historical Geology and Paleontology of the National and Kapodistrian University of Athens. The photographs (Appendix) helped to further distinguish morphological features of various benthic foraminiferal tests and facilitated the identification of species.

Fig. 10 Scanning Electron Microscope and Samples

Results

Systematic Taxonomy

In total, 66 benthic foraminifera species were recognized in Site 42A. All species that were identified, are listed in the Appendix.

Foraminiferal Study

Total Foraminiferal Abundance

The benthic foraminiferal assemblage from Core 3 is that of a typical open marine environment, with total absolute abundances reaching a maximum of 55,3 forams per gram (f/g) at 472cm depth (fig.11). According to the plotted diagram in fig.11 showing the total absolute abundances of samples, values reach at 50cm the number of 9,1 f/g. Values gradually rise at 94cm, equal to 53,4f/g and drop again at 110cm at 31,7f/g. There is a gradual decrease until 173cm, where there are 35,5f/g, followed by an increase until 199cm (48,5f/g). The values decrease gradually at 296cm depth with 7,7f/g and then increase to 35,9f/g at 346cm depth. There is a sharp decrease at 350cm and a sharp increase at 360cm with values reaching 29,6f/g and 54,5f/g respectively. The values continue to fluctuate with a decrease at 389cm (17,5 f/g) and increased values at 430cm (47,6f/g) and 472cm (55,3). The total absolute abundance falls at 553cm at 39f/g and then there is a series of increases at 571cm equal to 50,7f/g, at 635cm at 45f/g and at 755cm depth with values equal to 47f/g.

Redeposition Index

After the identification process, the Redeposition index (R.I.) has been calculated from the concentration of redeposited benthic foraminiferal species. The presence of transported foraminifera was quantified by considering the specimens state (broken/ damaged specimens) and taxa expected to live at shallower water depths or/with an epiphytic mode of life and the Redeposition Index was plotted in fig.11. The values are relatively low and follow a steady trend with some fluctuations across the core. At 29cm R.I value is equal to 1,59%, followed by an increase at 50cm depth equal to 3,23%. R.I. remains in steady values up until 110cm where it reaches 2,97% and at 173cm where values gradually increase at 9,38%. For the interval 206cm to 296cm, R.I. has steady values and then the value reaches 5,5% at 346cm depth. At 350cm, R.I. falls at 2,38% and the low values continue until 598cm where R.I.=11,73%. There is a gradual decrease in values at 635cm with R.I.= 3,6% and then R.I. follows a positive trend with the value increased at 13,3% at 686cm depth.

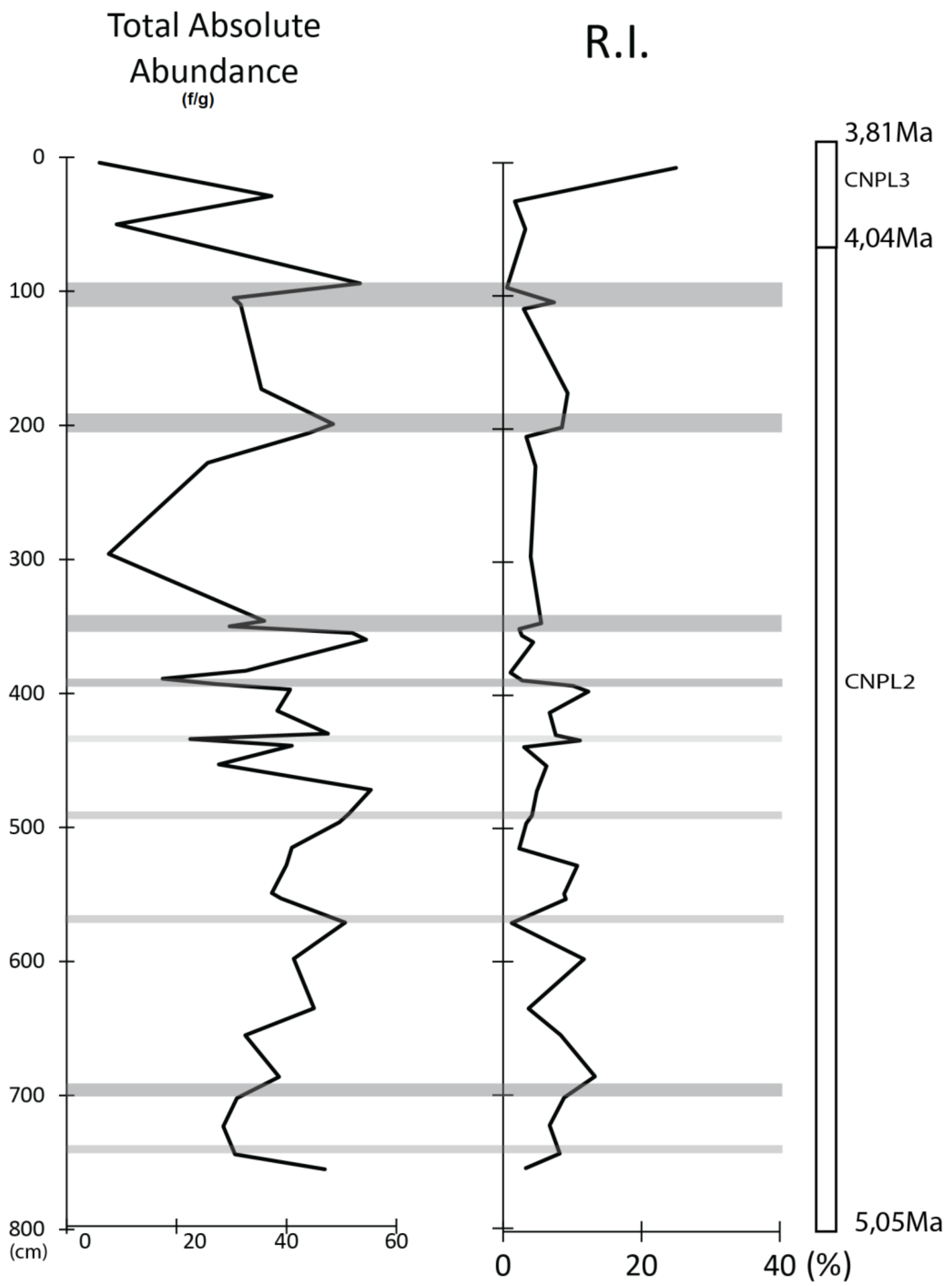

Fig. 11 Total absolute Abundance and Redeposition Index. Gray lines indicate potential sapropelic layers and Low Oxic events

Arenaceous to calcareous foraminifera and Epifaunal to Infaunal foraminifera percentages

In order to view the trends of the distribution of the various taxa and the differences in the occurrence of the epifaunal and the infaunal taxa, the percentages of Aglutinated to Calcareous foraminifera and Epifaunal to Infaunal foraminifera were calculated and plotted in fig.12 The foraminifera that constitute the epifaunal assemblage have significant percentages varying from 28,05% to 77,78% throughout core 3, with two intervals sharing increased values, at 206-346cm and at 496-528cm with the maximum values of those intervals being 62,5% and 73,23% respectively. The top part of the core, until 199cm depth, shows a series of increases and decreases at 94cm (37,35%), at 110cm (64,29%) at 173cm (33,72%) and at 199cm (29,25%). At 350cm depth, the epifauna sharply decreases to 28,05%, while the bottom part of the core from 389cm to 755cm also shows distinct fluctuations with the lower values at 430cm (47,65%), at 472cm (57,47%) and at 744cm (19,28%), indicating the higher values of infauna.

The agglutinated to calcareous foraminiferal percentages plotted in fig.12, have moderate values reaching 16,16% which indicates that agglutinated foraminifera are limited in the total assemblage. There are several sharp decreases in the percentages at 29cm (6,03%), at 173cm (1,15%) at 296cm (19,28%), at 360cm (5,88%), at 389cm (2,86%), at 397cm (4,9cm) and at 686cm (8,03%).

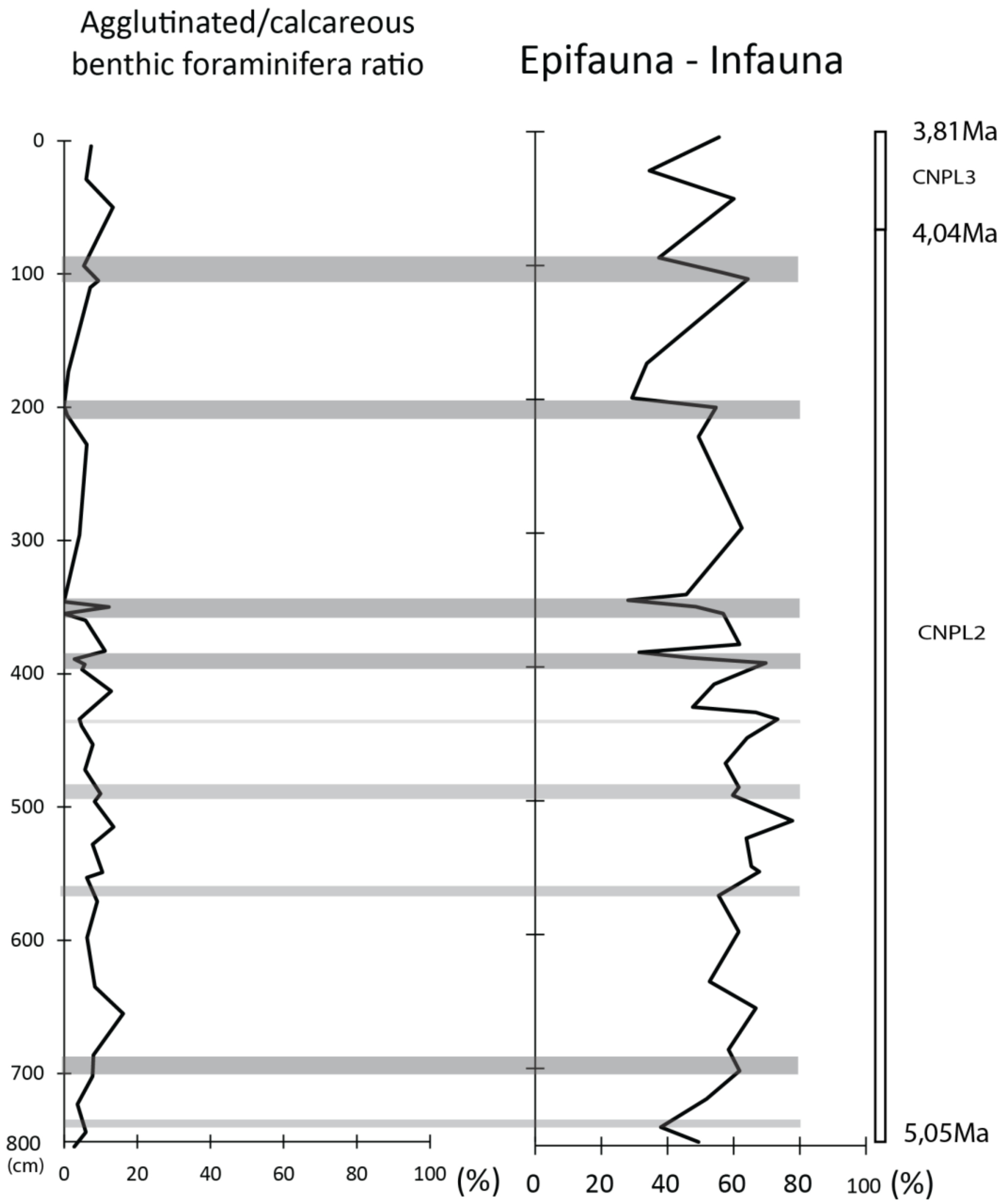

Fig. 12 Agglutinated to Calcareous Benthic foraminiferal ratio and Epifauna to Infauna ratio

Species richness varied from S=11 at 50cm to S=30 at 94 cm with an average of 22 species per sample. Dominance has low values, ranging from 0,06 at 413cm to 0,18 at 553cm and with many sharp increases in the interval 393cm-571cm, as shown in fig.13. The Dominance index presents an opposite trend in respect to the Shannon–Wiener index with H_{max}= 3,04 and H_{min}=2,15 (Fig.13). The Diversity indices values are shown in Appendix B.

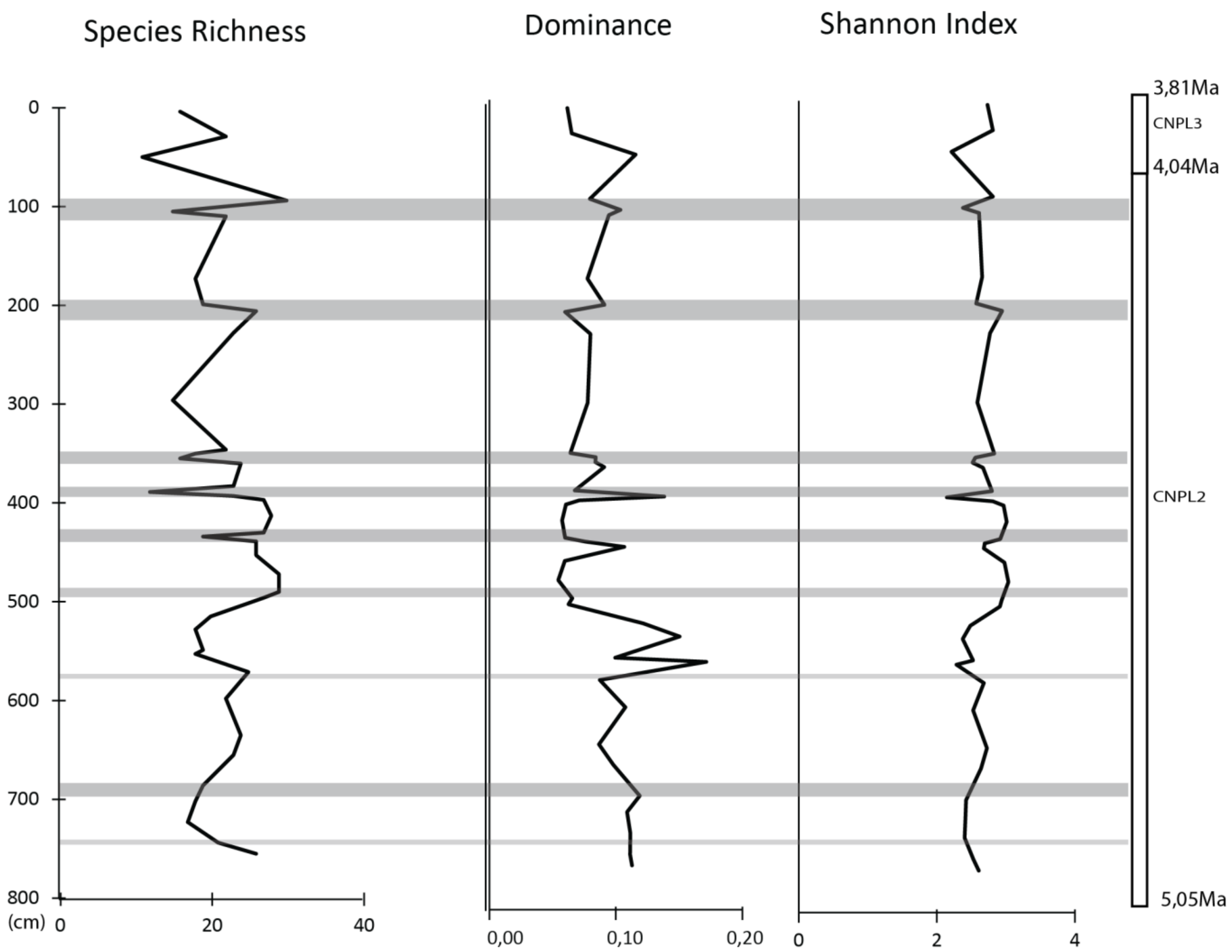

Fig. 13 Species richness, Dominance and Shannon Index.

In total, 8 taxa made up more than 5% of the total assemblage and therefore are statistically important. These are *Bolivina spp.* (includes: *Bolivina dilatata, Bolivina spathulata, Bolivina striatula and Bolivina pseudoplicata*), *Bulimina costata, Cibicidoides pseudoungerianus, Lenticulina spp, Melonis affinis, Planulina ariminensis, Siphonina reticulata* and *Uvigerina peregrina*.

***Bolivina spp**.* Is quite abundant throughout core 3 (on average 11,76% of the total assemblage), with the species reaching a maximum of 11,92f/g in 571 cm (figs.14,16). Relative abundance values showcase a maximum of 35,87% at 744cm depth. The species is represented throughout the core, with lower rates dominating 206-296cm and many sharp increases across depth. The species is highly represented as shown in fig…, with sharply increased values at 29cm (21,93%), 94cm (19,28%), 199cm (16,5%), 350cm (22,5%), 389cm (17,14%), 430cm (15,29%) 472cm (19,28%) 655cm (7,53%), 702cm (16,13%) and 744cm (35,87%).

Bulimina costata. made up on average 4,01% of the total assemblage, with total absolute abundance values reaching a maximum of 3,94f/g. The species has a maximum relative abundance at 12,5% at 350cm depth (figs.14,16). Relative abundance values show a constant representation of the species across the core, with values periodically showing sharp increases in 29cm at 21,93%, in 94cm at 7,23%, in 350cm at 12,7% and at 528cm at 7,26%. Sharp decreases in relative abundance values are observed at 110cm (2,11%), at 206cm (3,64%), at 296cm (min=0%), at 553cm (2,56%), at 655cm (1,08%) and at 744cm (3,26%).

The most abundant species was ***C. pseudougerianus*** (figs.14,16) throughout core 3, with it being on average 15,15% of the total assemblage and with maximum relative abundance equal to 39,32% at 553cm depth. The species is the dominant one with relative abundances fluctuating in high values as shown in fig. The interval 355-553cm is dominated by high values while the rest of the core has lower rates of relative abundance.

Lenticulina spp. made up on average 6,65% of the total assemblage with total absolute abundance values reaching a maximum of 6f/g. The species maximum relative abundance is equal to 20% at 110cm depth and is always present in moderate ammounts in the core, with relative abundance values varying from 1,79% to 20% (figs.14,16).

Melonis affinis constitutes on average 3,62% of the total assemblage with total absolute abundance values reaching a maximum of 8,96f/g. It is characteristic throughout the interval 346-553cm. Relative abundances fluctuate between 0% - 37,8% (figs. 14,16).

Planulina ariminensis made up on average 4,15% of the total assemblage (figs.15,16), with total absolute abundance values reaching a maximum of 5f/g. Relative abundance shows low rates throughout the core, with values between 0% and 15,79%, showing various fluctuations and a steady values interval at 571-686cm.

Siphonina reticulata made up on average 2,8% of the total assemblage, with total absolute abundance values reaching a maximum of 3,57f/g. Relative abundance shows low rates throughout the core, with values between 0% and 9,09%, showing various fluctuations from 360cm to 571 cm depth (figs. 15,16).

Uvigerina peregrina (figs. 15,16) made up on average 5,62% of the total assemblage, with total absolute abundance values reaching a maximum of 21,5f/g and being one of the most abundant species. Its maximum relative abundance value is 31,43% at 389cm depth and the values have sharp increases across the core with the higher values at 105 cm (24,29%) and at 199cm (28,87%). The species is only absent at 4cm.

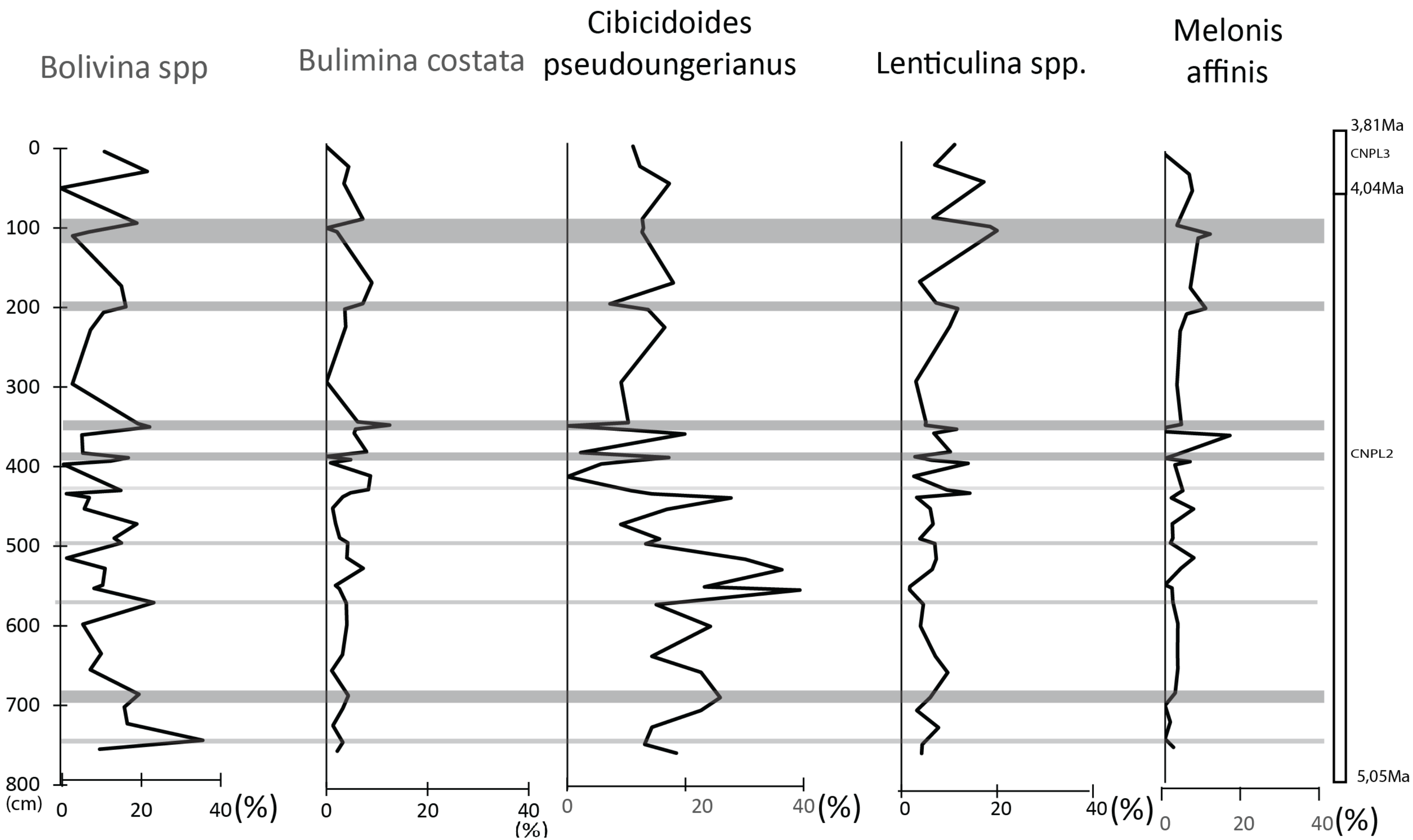

Fig. 14 Species relative abundances

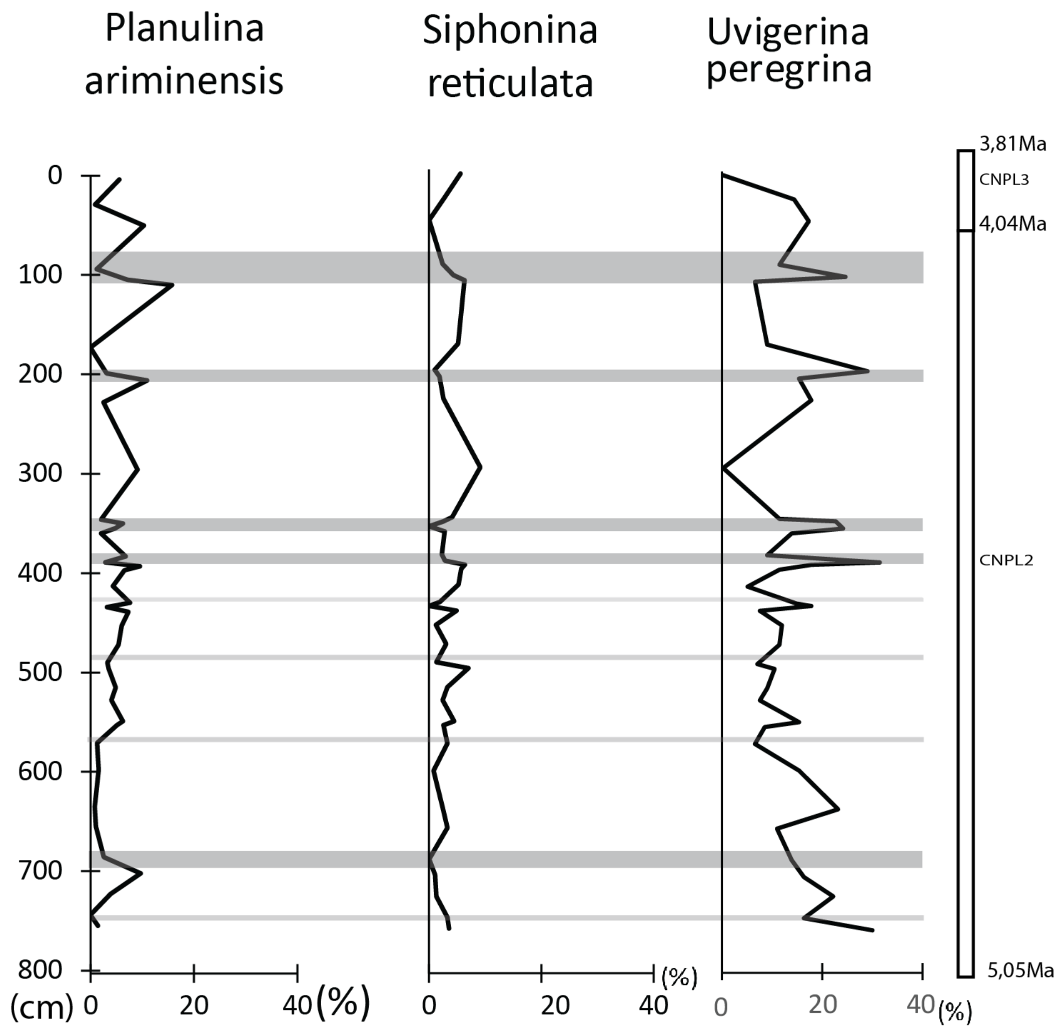

Fig. 15 Species Relative abundances (cont.)

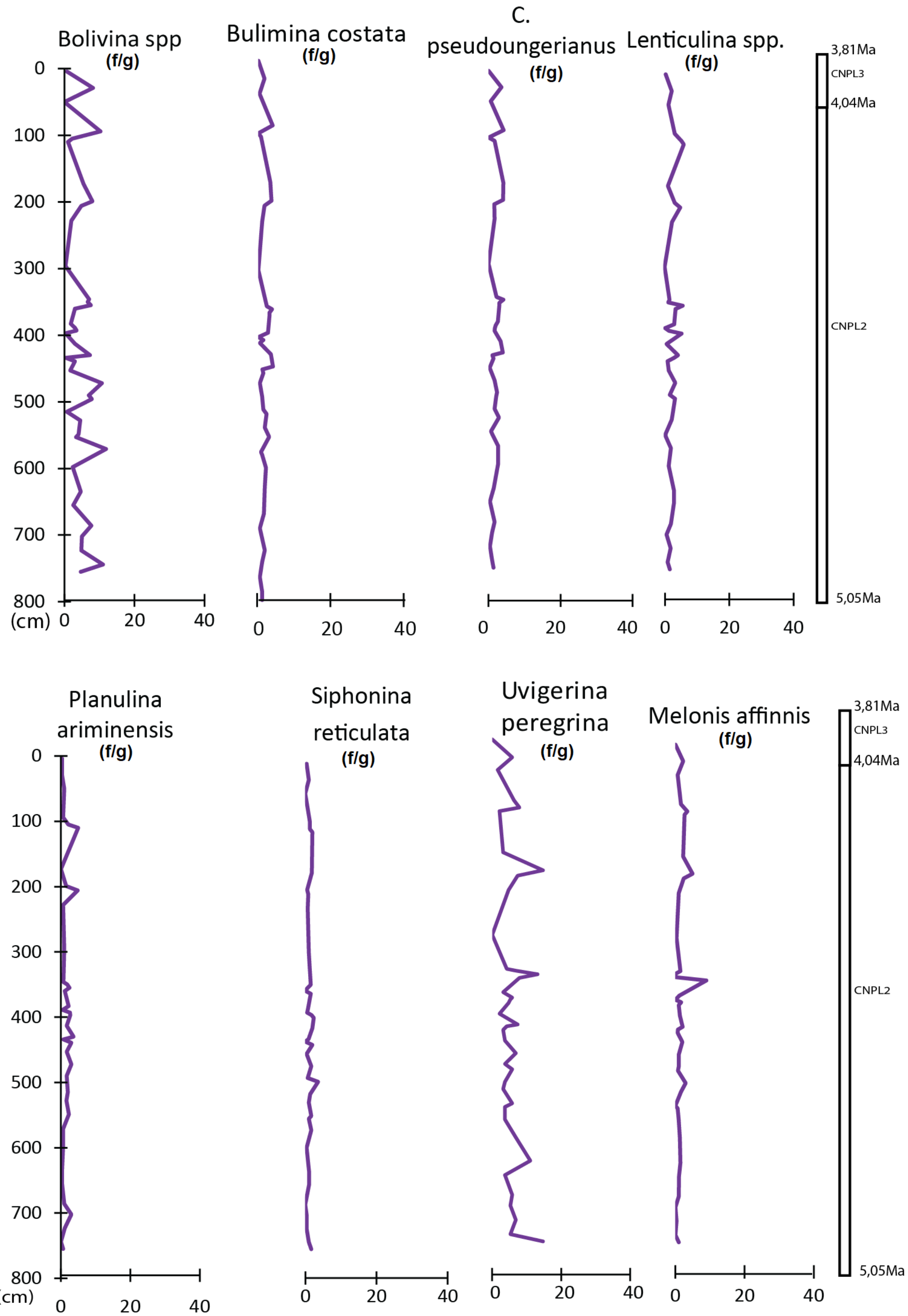

Fig. 16 Species Absolute abundances

Benthic Foraminiferal Oxygen Index

Kaiho's Benthic Foraminiferal Oxygen Index (BFOI) was calculated based on species abundances using the methods outlined by Kaiho (1994). BFOI values were calculated following the definition of indicators (oxic, suboxic, and dysoxic) and the equations of Kaiho (1994a) and plotted in fig.17.

BFOI values in core 3 fluctuate between 15,25% and 66,67%, indicating low oxic conditions across the core. However, in 350cm depth the BFOI takes a minimum value of -20,18%, where it indicates dysoxic conditions, as shown in fig.18. The BFOI values follow a steady trend of fluctuations with important percentages at 105cm (15,25%), 199cm (16,09%), 389cm (18,75%), 493cm (20%), 686cm (41,18%) and 744cm (23,75%), Additionally, at 430cm and 571cm depth, the BFOI shows values equal to 24,4% and 42,86% which indicates low oxic conditions.

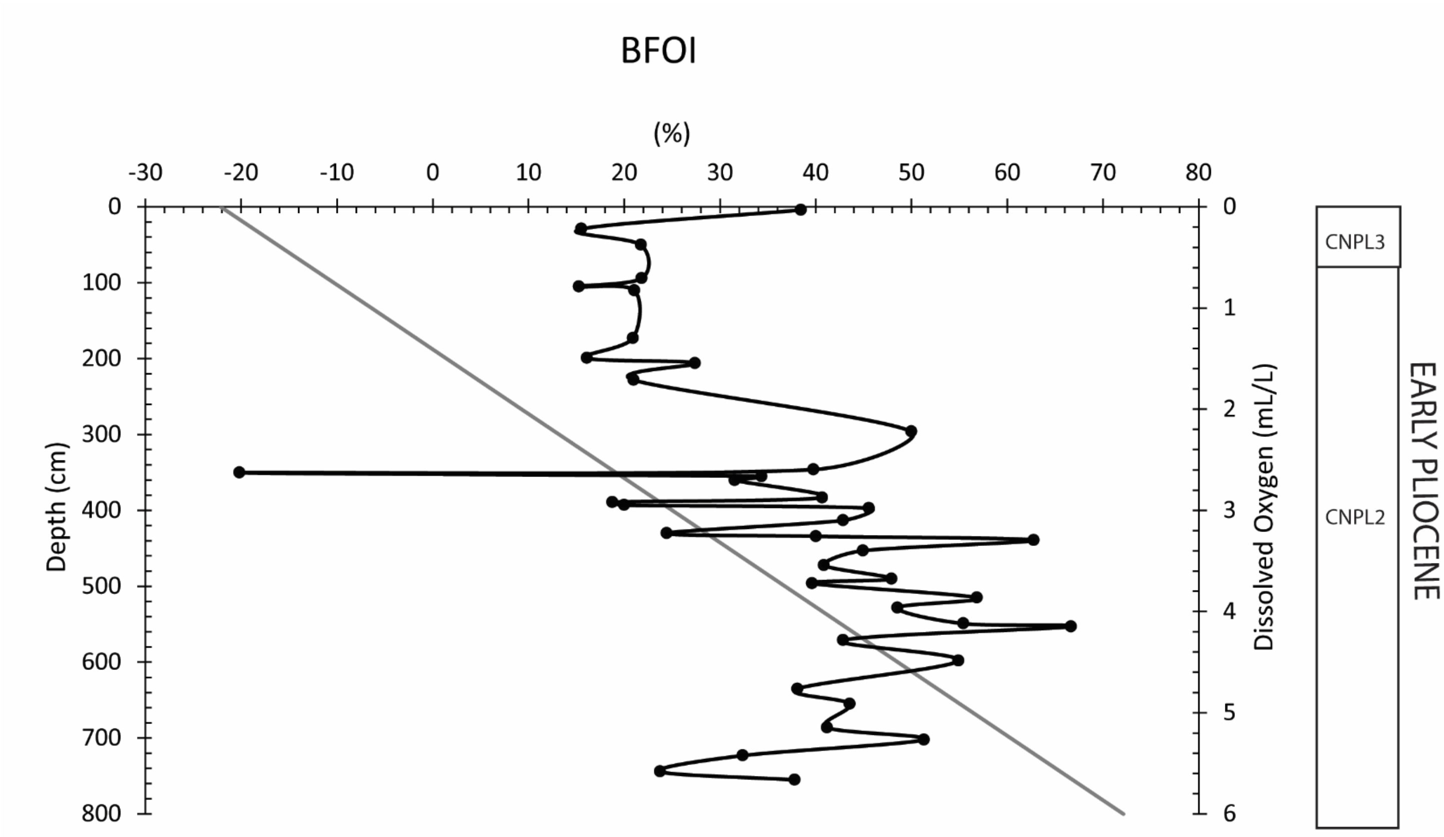

Fig. 17 Benthic Foraminifera Oxygen Index

Discussion

Early Pliocene Potential Sapropelic Layers and Low Oxygen Events

According to the observations of the previous chapter, the Early Pliocene sediments that consist core 3 are characterized by a diverse benthic foraminiferal fauna, typical to open marine environments in matters of species richness and dominance, with an increasing abundance of lower epibathyal fauna (>500-700 m) and periodic occurrences of some epiphytic taxa. This is depicted in the absolute abundance values with the maximum value reaching 55,3 forams per gram. The benthic foraminiferal fauna of Site 378 is characterized by high rates of mostly calcareous infaunal benthic foraminifera and periods of low oxic conditions with the fauna being characterized by dysoxic, suboxic and low ratios of oxic indicators. These observations suggest that the potential sapropelic layers that occurred in the basin represent deposition on a sea floor where sufficient oxygen existed to support a rather diverse benthic community with moderate abundances. After combining the data mentioned above, 5 potential sapropelic layers and 3 intervals where low oxic (LO) events occurred are observed. Those potential sapropelic layers and LO events are visible at the above plotted diagrams with gray lines.

Potential Sapropelic Layers

The interval **95-105cm** is identified as the first layer that presents potential sapropel-like sediment deposition. The benthic foraminiferal assemblage is also described by sharply decreased total absolute abundance, species richness, Shannon index and higher Dominance values. The fauna is characterized by infaunal, mostly calcareous species, with the Epifaunal to Infaunal percentage reaching 37,35% and a low RI (0,6%) indicating small transport of epiphytic taxa. BFOI values range from 21,83% to 15,25%, suggesting low oxic conditions which further confirms the possible sapropelic layer deposition on a sea floor where sufficient oxygen existed to support a diverse benthic community. Relative abundances of infaunal species are sharply increased *Bolivina spp* (19,28%), *Bulimina costata* (7,23%), and *Uvigerina peregrina* (24,29%) while epifaunal species Lenticulina spp. values sharply decrease at 6,63%.

In the second potential interval **188-204cm**, RI confirms a rather low value of 8,55% and Epifauna to Infauna is between 29,25-54,63% indicating abundant infaunal species. The BFOI value at 16,09% further confirms the potential sapropelic layer deposition by indicating a low oxic environment with dysoxic, suboxic and low ratios of oxic indicators characterizing the benthic calcareous foraminiferal fauna. Species relative abundances show increased values of infaunal species *Bolivina spp* (16,49%), *Bulimina costata* (7,22%) and *Uvigerina peregrina* (28,87%) (figs.15-17).

In interval **350-355cm** occurs the third potential sapropelic layer which showcases very interesting data (figs.15-17). The benthic foraminiferal assemblage is moderate with lower rates of species richness, Dominance and Shannon Index values. RI is also low at 2,28-2,73% and the Epifauna to Infauna percentage is equal to approximately 28,05%, indicating dominance of infaunal species. BFOI value is the minimum in this study, with BFOI= -20,18, revealing suboxic conditions (0,3 – 1,2 mL/L). These data indicate that during the deposition, dissolved oxygen was in low concentrations and as a result the benthic foraminiferal assemblage was only represented by low abundances of infaunal taxa. This is further proven by the high values of the relative abundances of infaunal species *Bolivina spp* (22,5%), *Bulimina costata* (12,5%) and *Uvigerina peregrina* (24,04%) and the complete disappearance of epifaunal species *Cibicidoides pseudoungerianus* and *Cibicidoides spp* that are in high abundances in other parts of the core and are considered oxic indicators (Kaiho, 1994).

The fourth potential sapropelic layer in interval **390-396cm** is supported by the benthic foraminiferal assemblage. Total absolute abundance, Species richness, and Shannon Index present low values, Dominance showcases a sharp increase and the RI index (10,13%) and the Epifauna to Infauna high value (46,48%) indicate the presence of mostly epifaunal to shallow infaunal species and significant transfer. Those are further approved by the relative abundances of infaunal species *Bolivina spp* (17,7%), *Bulimina costata* (4,76%), and *Uvigerina peregrina* (17,46%). BFOI gives a value at 20% indicating low oxic conditions (figs.15-17).

Interval **433 – 437cm** is identified as the fifth potential sapropelic layer (figs.15-17). the values of total absolute abundance (22,5), Species richness (19) and Shannon Index (0,08) are sharply increased while Dominance is abruptly decreased at 0,07. Furthermore, Epifauna to Infauna percentages decrease at 47,65% as well as the BFOI at 24,44% suggesting a low oxic environment with the calcareous benthic foraminiferal assemblage being characterized by dysoxic, suboxic and low ratios of oxic indicators. Agglutinated to calcareous benthic foraminifera values range from 5,88 to 4,72. Infaunal species relative abundances reach sharp peaks such as *Bolivina spp* (15,29%), *Bulimina costata* (8,28%) and *U. peregrina* (17,46%).

Low Oxic events

In interval **485 – 491cm**, values of total absolute abundance, Species richness, Dominance and Shannon Index are moderately increased and RI reaches 7,61%. However, BFOI values interval 24,4 – 40% indicate low oxic conditions and species relative abundances have increased values for *Bolivina spp* (15,29%) and *U. peregrina* (17,46%). Additionally, oxic indicator species C. pseudoungerianus and S. reticulata, show sharp increases at values 14,29 – 27,69% and 4,88% respectively, indicating an improvement on oxygen conditions. Despite the improvement, according to the BFOI, the oxygen levels are still low, which leads to the characterization of this interval as a Low Oxic event (LO).

Interval **686 – 700cm** is also characterized as a LO event. The benthic foraminiferal assemblage confirms this suggestion with the values of BFOI reaching 41,18%, which is described as low oxic conditions (Kaiho, 1994). The assemblage is characterized by dysoxic, suboxic and low ratios of oxic indicators for calcareous benthic foraminifera, with relative abundance values sharply increased for species *Bolivina spp* (19,83%) and *Bulimina costata* (4,31%) but also increased values of oxic indicator *Cibicidoides pseudoungerianus* (25,86%)

The last LO event occurs at interval **751 – 755cm**. The situation is similar to the first LO event with moderate Total absolute abundance, Dominance, Species Richness and Shannon index values, low R.I. values (3,31%) and low ratio of Agglutinated to calcareous benthic foraminifera (2,74%) and epifauna to Infauna ratio (49,2). BFOI values are also low at 23,75 - 37,8%, indicating low oxic conditions. Relative abundances are increased for *Bulimina costata* (3,26%) and *Uvigerina peregrina* (29,8%), as well as the oxic indicator species C. pseudoungrianus (18,44%).

The abundant species in these intervals have some important ecological characteristics that help define identify the above sapropel layers. *Bolivina spp* species can tolerate dysoxia (Murray, 2006). *B. dilatata* is distributed from shallow to very deep water in muddy sediment (Von Daniels, 1970), it is highly opportunistic and attracted to areas with high organic fluxes (Jorissen et.al., 1992). It is highly associated with both Pliocene and Quaternary sapropels (Cita and Podenzani, 1980). *Bulimina costata* is shallow-infaunal, associated with high contents of organic matter in the sediment (Schmiedl et al., 1997, Jorissen et al., 1998) and is found in low oxygen content areas with a steady flux of food (Licari et al., 2003, Rasmussen, 2005). *Siphonina reticulata* is also frequent in Plio-Pleistocene deposits and is characterized as an open marine species, not tolerant to salinity or oxygen fluctuations (Van der Zwaan, 1983; Jonkers, 1984). *Cibicidoides pseudoungerianus* and *Cibicides spp* are considered oxic indicators as they prefer better oxygen conditions (Kaiho, 1994). Furthermore, the disappearance of *B. spathulata* in depths associated with the beginning of the sapropels indicates the start of total O_2 deficiency, since this is the last species to disappear in such conditions (Rasmussen et.al., 2005). The species occurs in oxygen minimum zones in areas of high and steady supply of organic matter (Schmiedl et.al., 1997; Licari et.al., 2003; Gooday, 2003). *Uvigerina peregrina* is a shallow infaunal species, with highest abundances occurring where there is a rich supply of organic matter (Altenbach and Sarnthein, 1989; Altenbach et al., 1999; Fontanier et al., 2002). Species that further confirm the deposition of Early Pliocene sapropels in Core 3 in smaller abundances (<5%) are *Stilostomella spp*, which occurs in laminated sapropel beds in Crete's Pliocene deposits (Jonkers, 1984) and is unable to tolerate environmental stress induced by ocean ventilation and productivity changes (Hess and Kuhnt, 2005).

The foraminiferal assemblage that was studied can lead to the conclusion that the Early Pliocene North Cretan Basin was characterized by a diverse benthic foraminiferal fauna of an open marine environment, with an increasing abundance of lower epibathyal fauna.

Early Pliocene and Holocene sapropel S1

Changes in the oxygenation and food availability of the deep-sea ecosystems are closely linked to the hydrology borderlands of the East Mediterranean. These changes reflect orbital and suborbital climate variations of the high northern latitudes and the African monsoon system. In the case North East Mediterranean, the African monsoon system affects the nutrient input of the Nile river (Schmiedl et al., 2010). Enhanced organic matter flux from the variations of that system, leads to increased sedimentary organic carbon concentrations, that is a main characteristic of sapropelic layers (cf. Kidd et al., 1978; Sigl et al., 1978; Anastasakis and Stanley, 1984, Abu-Zied et al., 2008). Open-ocean benthic foraminiferal distribution patterns are mainly controlled by the organic carbon flux reaching the sea floor from surface-water productivity, and by the amount of dissolved oxygen in bottom/pore waters and during eutrophic conditions there is no food limitation but an increasing potential for oxygen limitation, and infaunal species tend to dominate the assemblage (Jorissen et al., 1995; Jorissen, 1999b). Moreover, abundance of food without considering lower porewater oxygen concentrations (Corliss and Chen, 1988) are conditions that promote the existence of infaunal taxa (Abu-Zied et al., 2008). Sapropel S1 (10.2–6.4 ka BP) is characterized by strongly dysoxic conditions punctuated by episodic reventilation events in the Aegean Sea. The benthic foraminiferal fauna during the S1 sapropel deposition was marked by drops in benthic foraminiferal number and diversity with more significant drops in the southern Aegean Sea than to the north (Kuhnt, 2007) due to the latter having a connection to the Black Sea and therefore changes in the inflow of nutrients.

In the case of North Aegean Sea, during the sapropel layer S1a (10.2–8.0 ka) deposition, the bottom water was characterized by dysoxic to oxic conditions and by a high abundance of species tolerating surface sediment and/or pore water oxygen depletion, and the presence of *Uvigerina mediterranea* that thrives in oxic mesotrophic-eutrophic environments (Triantaphyllou et al., 2016). In contrast, during sapropelic layer S1b (7.7–6.4 ka) deposition, bottom water is characterized by oxic conditions and low abundances of foraminiferal species tolerant to oxygen depletion in contrast to the rise of *Uvigerina mediterranea* values.

Similar conditions appear during the deposition of the Early Pliocene potential sapropelic layers in the Cretan Basin. During the possible sapropelic formation there are low oxic to suboxic conditions with infaunal species dominating the assemblage that tolerate those dissolved oxygen conditions. However, at some point the foraminiferal assemblages, showcase a recolonization of oxic indicator species and more well oxygenated deep waters (BFOI values) that still remain in the low oxic conditions nevertheless. Therefore, those intervals can be characterized as LO events that have increased abundances of species that prefer better oxygenation (*C. pseudoungerianus, S. reticulata*) and imply that the bottom water was better oxygenated than during the previous potential sapropelic layers deposition.

Conclusions

The benthic foraminiferal assemblage of the North Cretan Basin indicates that, in the Early Pliocene, the basin was an area characterized by periods of low oxygen or oxygen depletion and eutrophic conditions that became the key factors in the formation of the Early Pliocene potential sapropelic layers that exist on the area. The benthic foraminiferal fauna of the area is rich, diverse, and consists of normal-sized specimens with an increasing abundance of lower epibathyal fauna and periodic occurrences of some epiphytic taxa (i.e. *C. lobatulus, Neoconorbina sp., C. refulgens*) that are the product of in-basin transfer. Five potential sapropelic layers and three low oxic events were observed through the characteristics of the benthic foraminiferal assemblage.

The study of the benthic foraminiferal assemblages of the Early Pliocene Cretan Basin indicates that the area was characterized by "open marine" conditions with periods of high organic flux and low oxygen rates. The results that are acquired from this study can offer insight to the deposition trends of the Early Pliocene depositions that share similar characteristics with sapropelic layers and indicate that their formation conditions are similar to those of sapropel S1 during Holocene in the Aegean Sea, further confirming that sapropel formation is mainly controlled by precession and fluctuations in the organic flux and dissolved oxygen. The Early Pliocene benthic foraminiferal assemblages are heavily impacted by organic flux and dissolved oxygen fluctuations and as a result are dominated by infaunal taxa that can tolerate low oxygen levels in the potential sapropelic layers and with higher abundances of oxic indicator species in the Low Oxic events. Reconstructing past environmental profiles of n back arc basins through deep – sea benthic foraminiferal research is crucial in order to understand the paleoenvironmental evolution of our planet's deep oceans and further investigate the long-term effects of the event of the Messinian Salinity Crisis in the Eastern Mediterranean of the Early Pliocene epoch.

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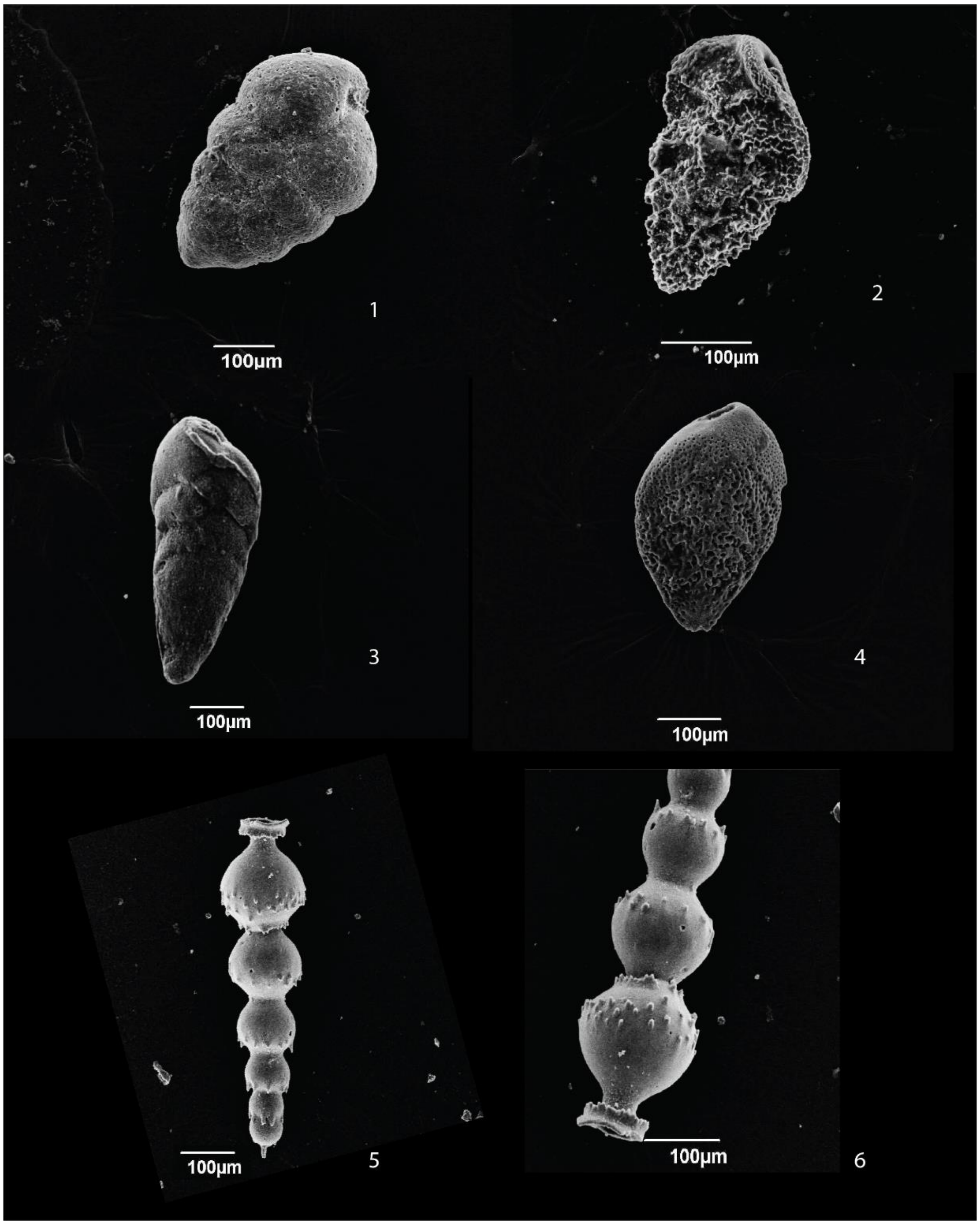
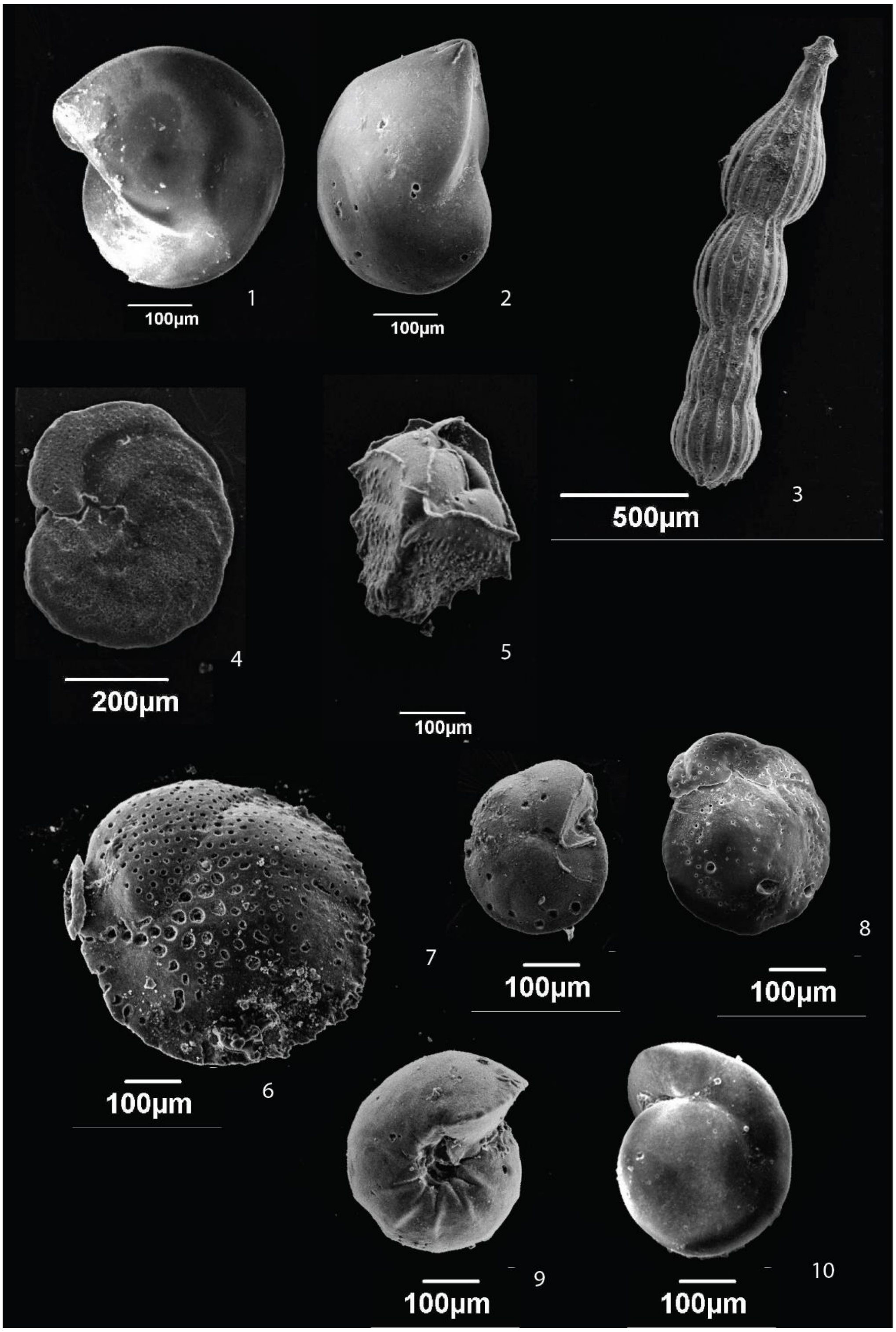
Appendix

PLATE 1



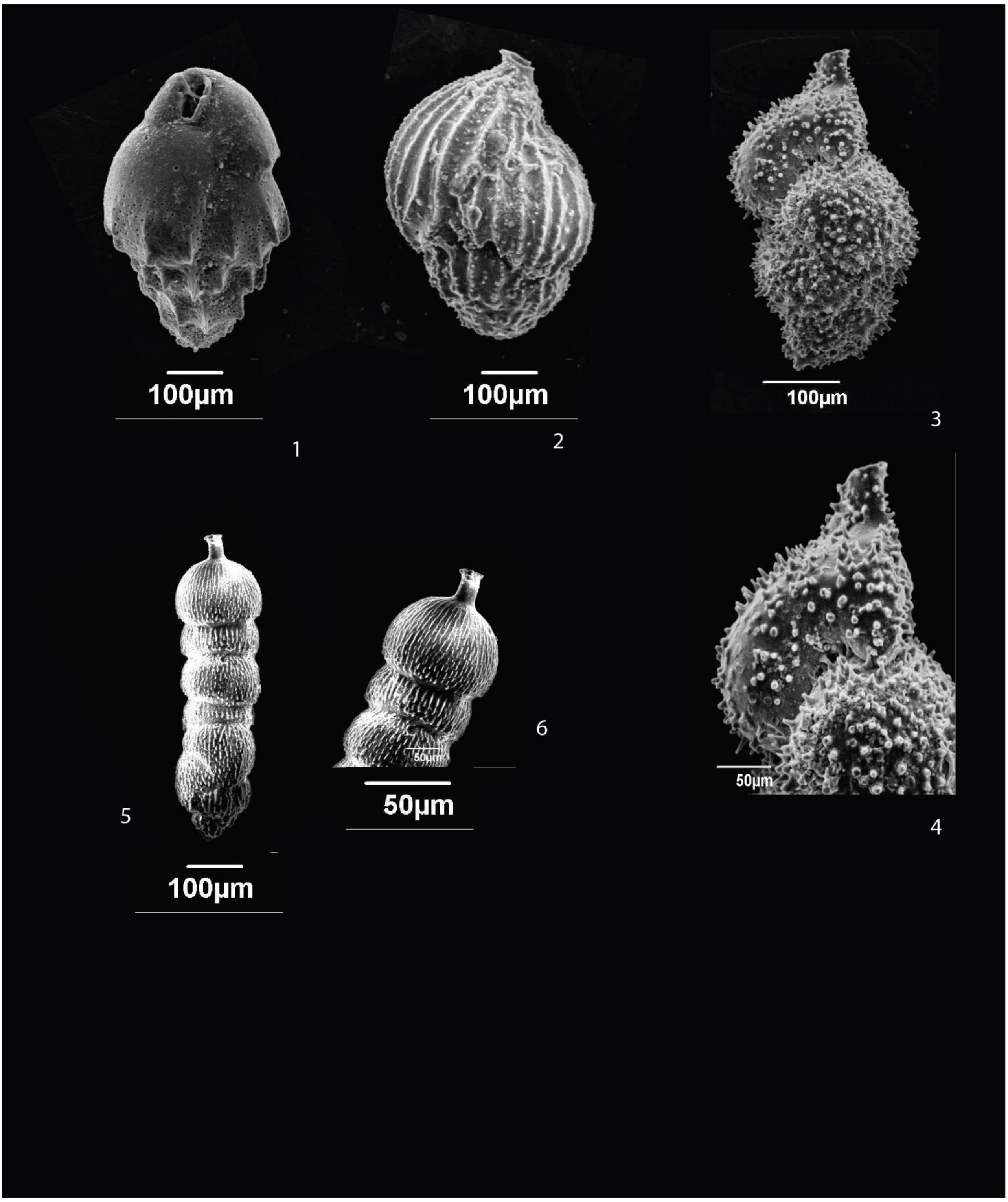
1. *Karreriella bradyi* (Cushman), 2. *Bolivina pseudoplicata (Heron-Allen and Earland),* 3. *Bolivina spathulata* (Williamson), 4. *Bolivina dilatata* (Reuss), 5,6. *Stilostomella adolphina* (d'Orbigny)

PLATE 2



1.*Lenticulina cultrata* (De Montfort), 2. *Lenticulina gibba* (d'Orbigny), 3. *Amphicoryna scalaris* (Batsch), 4. *Planulina ariminensis* (d'Orbigny), 5. *Reusella spinulosa* (Reuss), 6. *Siphonina reticulata* (Czjzek), 7,8. *Cibicidoides pseudoungerianus* (Cushman)

PLATE 3



1. *Bulimina costata* (d' Orbigny), 2. *Uvigerina peregrina* (Cushman), 3,4. *Uvigerina proboscidea* (d'Orbigny), 5,6. *Rectuvigerina cylindrica* (Schwager)

Additional Data

Species A-Z	
amphicoryna proxima	lagena striata
amphicoryna scalaris	lagena sulcata
anomalina sp	lenticulina cultrata
anomalinoides sp	lenticulina gibba
astacolus spp	lenticulina spp
bigenerina nodosaria	marginulina sp
bolivina pseudoplicata	melonis affinis
bolivina dilatata	mucronina sp
bolivina spathulata	nonionella turgida
bolivina striatula	nonionelina sp
bulimina aculeata	nuttalides truempyi
bulimina costata	planularia spp
bulimina inflata	planulina ariminensis
chilostomella oolina	pleurostomella sp
cibicides dutemplei	pseudonodosaria spp
cibicides wuellerstorfi	pseudopolymorphina sp
heterolepa bradyi	pullenia qinqueloba
cibicidoides mundulus	pullenia bulloides
cibicidoides pachyderma	rectuvigerina cylindrica
cibicidoides pseudoungerianus	rectuvigerina phlegeri
cibicidoides spp	reusella spinulosa
dentalina spp	siphonina reticulata
fissurina annectens	siphonina tubulosa
fissurina marginata	siphonodosaria sp
fissurina spp	stilostomella adolphina
fursenkoina complanata	stilostomella advena
fursenkoina sp	stilostomella sp
gyroidina soldanii	textularia agglutinans
gyroidina sp	textularia pseudorugosa
hanzawaia boueana	trifarina bradyi
hyalinea balthica	uvigerina proboscidea
karreriella bradyi	uvigerina peregrina
laevidentalina advena	uvigerina sp
lagena spp	

Table 1 Species A-Z

Samples of Core 3A		
Section	Top/Bottom interval (cm)	Core depth (cm)
0	4-6	4
0	29-30	29
1	11-12	50
1	55-56	94
1	66-67	105
1	71-72	110
1	134-135	173
2	11-12	199
2	18-19	206
2	40-41	228
2	108-109	296
3	9-10	346
3	13-14	350
3	18-19	355
3	22-23	360
3	46-47	383
3	52-53	389
3	56-57	393
3	60-61	397
3	76-77	413
3	93-94	430
3	97-98	434
3	102-103	439
3	116-117	453
4	5-6	472
4	23-24	490
4	29-30	496
4	48-49	515
4	61-62	528
4	82-83	549
4	86-87	553
4	104-105	571
4	131-132	598
5	18-19	635
5	38-39	655
5	69-70	686
5	85-86	702
5	106-107	723
5	127-128	744
5	138-139	755

Table 2 Samples of Core 3A

Infaunal Taxa	Epifaunal Taxa
amphicoryna proxima	cibicides dutemplei
amphicoryna scalaris	cibicides wuellerstorfi
anomalina sp.	heterolepa bradyi
anomalinoides sp	cibicidoides mundulus
astacolus sp	cibicidoides pachyderma
bigenerina nodosaria	cibicidoides pseudoungerianus
bolivina pseudoplicata	cibicidoides sp
bolivina dilatata	fissurina annectens
bolivina spathulata	fissurina marginata
bolivina striatula	fissurina sp
bulimina aculeata	gyroidina soldanii
bulimina costata	gyroidina sp.
bulimina inflata	hanzawaia boueana
chilostomella oolina	hyalinea balthica
dentalina spp	karreriella bradyi
fursenkoina sp	lenticulina spp.
laevidentalina advena	lenticulina cultrata
lagena sp	lenticulina gibba
lagena striata	nuttalides truempyi
lagena sulcata	planulina ariminensis
marginulina sp	planulina sp
melonis affinis	siphonina reticulata
mucronina sp	siphonina tubulosa
nonionelina sp.	textularia agglutinans
nonionella turgida	textularia pseudorugosa
planularia sp	
pleurostomella sp	
pseudonodosaria spp	
pseudopolymorphina sp	
pullenia qinqueloba	
pullenia bulloides	
rectuvigerina phlegeri	
rectuvigerina cylindrica	
reusella spinulosa	
siphonodosaria sp	
stilostomella sp	
stilostomella adolphina	
trifarina bradyi	
uvigerina peregrina	
uvigerina proboscidea	

Table 3 Infaunal and Epifaunal species based on Murray (2006), Kaiho (1994), Rasmussen (2005)

Dysoxic - Suboxic Indicators	Oxic indicators
bolivina dilatata	cibicides dutemplei
bolivina spathulata	cibicides wuellerstorfi
bolivina striatula	cibicidoides mundulus
bulimina aculeata	cibicidoides pachyderma
bulimina costata	cibicidoides pseudoungerianus
bulimina inflata	cibicidoides sp
dentalina sp	nuttalides truempyi
fissurina annectens	
fissurina marginata	
fissurina sp	
fursenkoina complanata	
fursenkoina sp	
gyroidina soldanii	
gyroidina sp.	
lagena spp	
lagena striata	
lagena sulcata	
lenticulina sp.	
lenticulina cultrata	
lenticulina gibba	
melonis affinis	
nonionelina sp.	
nonionella turgida	
pullenia qinqueloba	
pullenia bulloides	
pleurostomella sp	
stilostomella sp	
stilostomella adolphina	
trifarina bradyi	
uvigerina proboscidea	
uvigerina peregrina	
uvigerina sp	
valvulineria complanata	

Table 4 Dysoxic, Suboxic and Oxic indicator species based on Kaiho (1990, 1994)

Samples	Species Richness	Dominance	Shannon index
3/0 4-6	15	0,07	2,67
3/0 29-30	26	0,07	2,95
3/1 11-12	12	0,73	0,74
3/1 55-56	31	0,08	2,87
3/1 66-67	18	0,13	2,43
3/1 71-72	22	0,10	2,60
3/1 134-135	19	0,08	2,70
3/2 11-12	22	0,07	2,83
3/2 18-19	27	0,06	3,04
3/2 40-41	24	0,08	2,87
3/2 108-109	16	0,13	2,42
3/3 9-10	20	0,07	2,79
3/3 13-14	17	0,09	2,53
3/3 18-19	18	0,09	2,61
3/3 22-23	28	0,07	2,96
3/3 46-47	21	0,08	2,71
3/3 52-53	13	0,12	2,29
3/3 56-57	24	0,07	2,91
3/3 60-61	27	0,07	2,99
3/3 76-77	23	0,08	2,82
3/3 93-94	27	0,07	2,93
3/3 97-98	20	0,07	2,79
3/3 102-103	24	0,14	2,57
3/3 116-117	24	0,07	2,89
3/4 5-6	27	0,07	2,98
3/4 23-24	28	0,07	2,94
3/4 29-30	29	0,07	2,98
3/4 48-49	19	0,15	2,36
3/4 61-62	18	0,15	2,40
3/4 82-83	18	0,11	2,50
3/4 86-87	17	0,21	2,17
3/4 104-105	25	0,09	2,72
3/4 131-132	23	0,10	2,64

Table 5 Bioindices