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FORAMINIFERAL BIOSTRATIGRAPHY AND PALAEOENVIRONMENTAL ANALYSIS OF THE BASAL PART OF KALAMAVKA FORMATION (LATE MIOCENE, IERAPETRA BASIN, EASTERN CRETE)

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Abstract

This work involves a preliminary quantitative analysis of benthic foraminifera for the purpose of the determination of palaeoenvironmental parameters (oxygenation, palaeobathymetry) of the depositional environment of the lower part of the typical section of Kalamavka Formation, in Ierapetra Basin, eastern Crete. The sediments of the studied section contain a rich foraminiferal fauna, mainly dominated by planktonic species. High resolution planktonic foraminiferal record reveals the presence of N. atlantica praeatlantica, N. acostaensis, P. siakensis suggesting an early Tortonian chronostratigraphic age. The quantitative assessment of palaeodepth, suggests deposition at middle shelf to bathyal water depths with moderate organic matter fluxes and elevated oxygen contents of the bottom water, typical for this water depth interval.

Key words: *Early Tortonian, microfauna, palaeobathymetry, Eastern Mediterranean.*

Περίληψη

Η εργασία αυτή αφορά στην πρόδρομη ποσοτική ανάλυση των βενθονικών τρηματοφόρων για το σκοπό του καθορισμού των παλαιοπεριβαλλοντικών παραμέτρων (οξυγόνωση, παλαιοβάθος) του περιβάλλοντος απόθεσης του κατώτερου τμήματος της τυπικής τομής του σχηματισμού Καλαμαύκα, στην λεκάνη της Ιεράπετρας, ανατολική Κρήτη. Τα ιζήματα του μελετώμενου τμήματος περιέχουν μια πλούσια πανίδα τρηματοφόρων, όπου επικρατούν τα πλαγκτονικά είδη. Το υψηλής ευκρίνειας αρχείο των πλαγκτονικών τρηματοφόρων αποκαλύπτει την παρουσία των ειδών N. atlantica praeatlantica, N. acostaensis, P. siakensis υποδεικνύοντας χρονοστρωματογραφική ηλικία Κατώτερο Τορτόνιο. Η ποσοτική εκτίμηση του παλαιοβάθους, έδειξε εναπόθεση στη μέση κρηπίδα έως την ανώτερη βαθύαλη ζώνη με μέτρια εισροή οργανικού υλικού και σχετικά αυξημένη περιεκτικότητα σε οξυγόνο, χαρακτηριστικό για αυτό το περιβάλλον.

Λέξεις κλειδιά: *Κατώτερο Τορτόνιο, Μικροπανίδα, Παλαιοβαθυμετρία, Ανατολική Μεσόγειος.*

1. Introduction

The Eastern Mediterranean region, which defines the region lying between the Caspian Sea and the Adriatic Sea through Caucasus, Anatolia, Aegean Sea and Greece, is one of the most tectonically active regions and one of the key regions for the understanding of fundamental tectonic processes, including continental rifting, passive margins, ophiolites, subduction, accretion, collision and post-collisional exhumation.

The island of Crete is located in the south eastern Mediterranean region. Its Late Tertiary–Quaternary tectonic evolution has been investigated since several decades by many researchers (e.g. Aubouin et al., 1976; Angelier, 1979; Le Pichon & Angelier, 1979; Hall et al., 1984; van Hinsbergen et al., 2005; among others) because of its significance in the geodynamic evolution of the eastern Mediterranean.

The present study concerns an integrated study of an early late Miocene (early Tortonian) succession located in the Ierapetra Basin, eastern Crete (Kalamavka Formation of Fortuin, 1977, 1978). The Kalamavka section provides an ideal archive spanning the early Tortonian, a time period characterized by intense tectonic activity in this region. The time of deposition of the Kalamavka Formation (Late Serravallian - Early Tortonian) coincides with the beginning of the fragmentation stage of the Aegean microplate (break - up stage), during extensional movements and thus the beginning of the "modern history" of the Aegean region. During this period, many lithostratigraphic and palaeogeographic changes took place. The Kalamavka Formation is considered to represent one lithologic unit that reflects the prevailing sedimentary regime at the time.

In order to establish the magnitude of palaeoenvironmental an palaeobathymetric changes, during the deposition of Kalamavka Formation, a highly successful and diverse group of amoeboid protists which belong within the newly-established supergroup Rhizaria (Nikolaev et al., 2004), were used as a tool of analysis.

2. Geology and Sedimentology

The study area is located in the Ierapetra Basin, in the eastern part of Crete (Fig. 1). Crete is part of the Hellenides mountain range created by the same tectonic activity that was responsible for the orogenesis of the Alps and the formation of the Mediterranean Sea.

The Neogene in eastern Crete was studied by a number of researchers (Dermitzakis, 1969; Gradstein, 1973; Zachariasse, 1975; Fortuin, 1977, 1978; Meulenkamp et al., 1979a, b; Meulenkamp & Hilgen, 1986; Drinia, 1989; Postma & Drinia, 1993; Pipponzi et al., 2004; Drinia et al., 2008) in various details. According to them, in the Ierapetra Basin, sedimentation started with the deposition of Middle Miocene terrigenous clastics followed by the Upper Miocene fluviolacustrine and open marine shelf, slope and basin-floor sediments. The lowermost Pliocene sediments are generally found as slump components and debris flow deposits (“marl breccias” sensu Fortuin, 1977). These deposits overlie the lower Messinian carbonates (Meulenkamp, 1985). According to Peters (1985), the marl breccias resulted from the spasmodic subsidence along the pre-existing but still active E–W and N–S trending fault systems. Deep marine marls and clays continued in the sedimentary succession. Finally, Quaternary deposits consisting of bioclastic limestones and Tyrrhenian marine terraces are found mainly on the south coast of the Ierapetra Basin (Angelier, 1979; Pirazzoli et al., 1982).

The studied section is exposed in the road section just north of the village of Kalamavka and it comprises bluish, fossiliferous, calcareous mudstones with occasional lenses or layers of fine to very fine grained sandstone. The mudstone is generally massive but in places thin laminations are visible. The sandstone beds are very thin and increase in abundance and thickness in higher stratigraphic levels (Fig. 2). The marls are generally massive due to bioturbation. At nonbioturbated intervals structures produced by traction and suspension fall-out are preserved (Drinia, 1989).

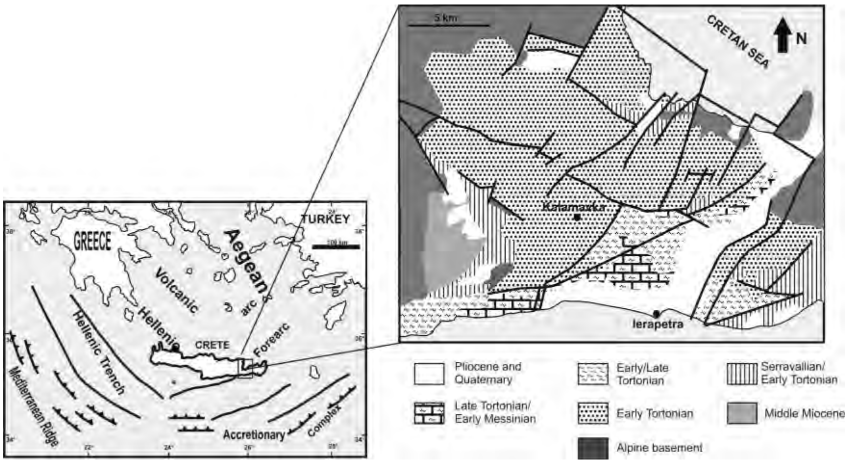

Figure 1 - Geological Sketch map of the Ierapetra Basin (modified from Fortuin 1977, 1978).

Figure 2 - General view of the studied section depicting intercalations of carbonate-rich marls with occasionally pure limestone layers.

3. Materials and Methods

A total of 20 samples were examined for the micropalaeontological analysis using standard laboratory procedures. Benthic foraminifera were picked from the 125-595 μm fractions after washing in water and wet-sieving, and splitting to the right size allowing picking the statistically significant number of 200-300 specimens of benthic foraminifera. The foraminifera were identified, sorted taxonomically, counted and the data compiled on to an Excel spreadsheet.

The number of planktonic foraminiferal tests was also recorded during picking.

The percentage of planktonic species in the total foraminiferal association (%P) was calculated as 100*P/ (P+B), in order to reconstruct palaeodepth and track sea-level changes. Interpretation of the obtained data was done according to Murray (1991), with divisions into inner shelf (<20% planktonic tests), middle shelf (20–50%), outer shelf (50–70%) and upper bathyal zones (>70% planktonic tests).

To estimate the depositional depth of the sediments, the general relationship between depth and the fraction of planktonic foraminifera with respect to the total foraminiferal population (%P) (Van der Zwaan et al., 1990) was used, following the equation: Depth (m) = $e^{3.58718 + (0.03534 * \% P)}$, where %P is the percentage of the total planktonic foraminifera of the association, calculated according to 100*P/(P+B), where P is the number of planktonic foraminifera specimens and B the benthic specimens. The reliability of the calculated palaeodepth can be biased by observation that the plankton/benthos ratio (P/B – ratio) is not only influenced by depth, but also by changes in oxygenation of bottom waters (Sen-Gupta & Machain-Castillo, 1993; Jorissen et al., 1995). Moreover, discrepancy between calculated palaeodepth and sedimentology has been pointed out by Hohenegger (2005). For this reason, Van Hinsbergen et al. (2005) excluded from the calculations of %B the deep infaunal (%S), which is not directly related to the depth.

4. Results and Analysis

4.1. Biostratigraphy

The biostratigraphic analysis was based on the qualitative analysis of planktonic foraminifera species performed on the total of samples. The specific identifications were conducted according to reference publications (Dermitzakis, 1978; Iaccarino, 1985; Hilgen et al., 2000; Foresi et al., 2002). For the biostratigraphic range of the studied section we only considered the appearance/disappearance of marker species.

The planktonic foraminifera assemblages consist of 16 categories: *Globigerina bulloides* gr., *Turborotalita quinqueloba, Globigerinita glutinata, Globoturborotalita druryi/nepenthes* gr., *Globoturborotalita decoraperta, Globigerinoides obliquus, Globigerinoides quadrilobatus* gr., *Catapsydrax parvulus, Globorotalia scitula, Globorotalia praemenardii/menardii* gr., *Globorotalia miozea, Paragloborotalia siakensis, Paragloborotalia partimlabiata, Orbulina* spp., *Neogloboquadrina atlantica-praeatlantica* and *Neogloboquadrina acostaensis*.

Among the taxa more or less continuously present, *G. bulloides*, *G. quadrilobatus*, *Orbulina* spp. are the most abundant species, whereas *G. glutinata*, *G. scitula*, and *Turborotalita quinqueloba* are rare. Specimens of *G. druryi/nepenthes* occur mainly in the lower part. *G. praemenardi/menardii* shows two main intervals of significant occurrence: in the lower and upper part of the section. *C. parvulus* and *P.* cf. *partimlabiata* are also present. In our record, *P. siakensis* occurs almost in all samples being more abundant in the middle –upper part. *N. acostaensis* is discontinuously present and *N. atlantica praeatlantica* occurs from the base of the section.

Within the studied interval we recorded the absence of *G. subquadratus* while *G. obliquus* exists in all the samples. The last common occurrence of *G. subquadratus* has been dated at 11.54 Ma (Hilgen et al., 2003; Lirer et al., 2002) while the first regular occurrence of *G. obliquus* is recorded at the same time. In the Mediterranean, this event coincides with the end of the first influx of the neogloboquadriniids. A paracme interval in its distributional range in the Mediterranean recorded at 11.54 to 11.2 Ma. The biostratigraphic boundaries of this paracme interval are determined by the last occurrence of *G. subquadratus* and the last occurrence of *P. siakensis* at 11.2 Ma (Hilgen et al., 2000; Caruso et al., 2002; Di Stefano et al., 2002; Foresi et al., 2002; Lirer et al., 2004; Iaccarino et al., 2004).

According to the distributional pattern of the neogloboquadriniids, the occurrence of *P. siakensis*, the absence of *G. subquadratus* and the presence of *G. obliquus* in all the samples, the section spans the time interval between 11.54 -11.2 Ma, suggesting an early Tortonian chronostratigraphic age.

4.2. Characteristics of the Benthic Foraminiferal Assemblages

The section is characterized by (i) ecological groups of benthic foraminifera faunas dominating in circalittoral environments (*Cibicides dutemplei* and *C. kullenbergi*) and bathyal (*Bulimina costata, Pullenia bulloides* and *Uvigerina* spp.); (ii) high diversity; and (iii) abundant planktonic foraminifera. The common occurrence of planktonic foraminifera, throughout the succession, suggests open marine connections to the oceanic realm. Textularids as well as miliolids are rare.

Upper-neritic taxa occur at variable relative abundances, including epiphytic species that live on aquatic vegetation in the photic zone such as *Cibicides lobatulus* and *C. refulgens*.

The result of planktonic percentage analyses performed in this study is shown graphically in Fig. 3. Planktonic/benthic ratios vary between 25 and 75% of the benthic assemblage. Application of van der Zwaan et al. (1990) regression indicates that deposition (Fig. 3), began at ~450 m (deep upper bathyal) and remained relatively stable (upper bathyal) for the first 80 cm of the record. An ensuing rapid regression resulted the sea level to fall 350m, attaining a palaeodepth ~100 m (middle shelf).

Based on the constructed palaeobathymetric curve, the sea then gradually transgresses (upper bathyal) and remained relatively constant with short-term fluctuations.

5. Discussion

5.1. Estimating Palaeobathymetry Using Benthic Foraminiferal Census Data

It has long been known that the percentage of planktonic foraminifera in modern sediments increases with water depth e.g. (Van der Zwaan et al., 1990, 1999; Van Hinsbergen et al., 2005; Boltovskoy & Wright, 1976; Gibson, 1989). The percentage (%) of planktonic foraminifera (P/P+B*100) is one of the most consistent proxies to assess palaeo-water depths. According to Murray (1976), the inner shelf is characterized by up to 20% of planktonic specimens, the middle shelf between 10 and 60%, the outer shelf between 40 and 70%, and the upper bathyal zone > 70%. The highest values, roughly 90%, are observed in the lower bathyal zone (Valchev, 2003). Finally, based on data from the Gulf of Mexico, Pflum & Frerichs (1976) consider that a %P of < 50% corresponds to the neritic zone, from 50% to 90% to the upper bathyal zone (200-1000 m) and > 90% to the middle and lower bathyal zone (1000-4000 m). Vella (1962) determined two deep water biofacies, based on high populations of planktonic foraminifera: (1) the semi-pelagic biofacies (600-1200 m), with percentage of planktonic foraminifera from 40%-60% and (2) the eupelagic biofacies (1200-4000 m), with percentage of planktonic foraminifera from 70% - 100%. The same author, however, points out that high percentage of planktonic foraminifera values can also sometimes be present in shallow environments owing to the predominance of inshore winds.

In our record, the percentage of planktonic foraminifera (P/B ratio, Fig. 3) varies between 38% and 75%, indicating an outer shelf to upper bathyal, semi-pelagic to temporaly eupelagic biofacies. The abrupt decline to 26% in sample KLM 6, at 100 cm (Fig. 3) implies sedimentation in the middle shelf (75-100 m). Based on Speijer & Schmitz (1998), this drop likely resulted from the dissolution of calcareous planktonic foraminiferal shells during the formation of the fossilized assemblages. In exceptional cases this change may also represent a real palaeoenvironmental change. If so, it is necessary to analyze the composition of planktonic foraminiferal assemblages.

5.2. Environmental Setting Derived from Benthic Foraminiferal Ecological Groups

It is well documented that the main factors controlling the distribution of foraminifera are two inversely related parameters, the flux of organic matter to the sea floor and the oxygen concentration of the bottom–water and sediment pore-water (Lutze & Coulbourn, 1984; Van der Zwaan et al. 1999; Linke & Lutze, 1993; Jorissen et al., 1992, 1995; Jorissen, 1999). In particular, changes in oxygen concentrations at the sediment-water interface play a major role in controlling benthic foraminiferal assemblages with some species exhibiting a tolerance to hypoxia and opportunistic life histories, and developing high population densities in some low oxygen environments, particularly in areas associated with high organic enrichment (Phleger & Soutar, 1973; Bernhard, 1986). Generally, in low-oxygen environments, benthic foraminifera are of ecological significance as they dominate the eukaryotic biomass in the benthic ecosystem (Moodley et al. 1997; Gooday et al. 2000a).

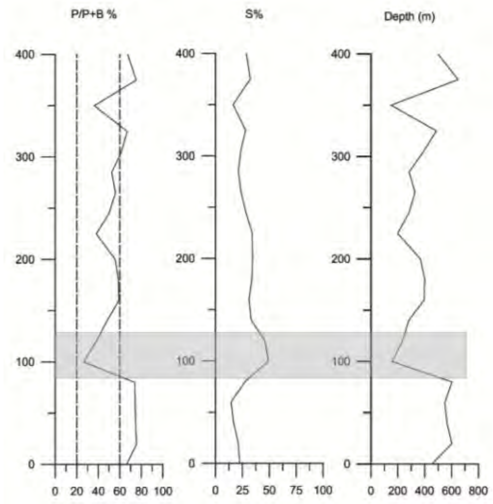

Figure 3 - Planktonic/Benthic ratio together with well-established redox front dwelling taxa and palaeobathymetric curve.

Many authors have noted the dominance in modern and anoxic low-oxygen environments of particular "opportunistic", r-selected species, (Bernhard, 1986; Mackensen & Douglas, 1989; Koutsoukos et al., 1990; Alve & Bernhard, 1995; Bernhard et al., 1997; Jorissen et al., 1998; Bernhard & Bowser, 1999; Fontanier et al., 2002). These taxa also occur in deep-infaunal microhabitats in well-oxygenated settings.

In general, there is a direct relationship between the level of oxygenation of the water and the mode of life of the benthic foraminifera, so that, in low oxygen conditions, deep infauna taxa, also known as environmental stress markers, predominate (van Hinsbergen et al., 2005). This group of taxa constitutes the "*well-established redox front dwelling taxa*" of Rogerson et al. (2006) and consists of *Bolivina* spp. except *B. plicatella* and *B. pseudoplicata*, *Bulimina* spp. (excluding the costate species); *Uvigerina* spp. (*U. semiornata* excluded); *Rectuvigerina* spp., *Valvulineria* spp., *Cancris* spp., *Fursenkoina* spp., *Stainforthia* spp., *Globobulimina* spp. and *Chilostomella* spp.

In this study, the percentage value of the "*well-established redox front dwelling taxa*" (Fig. 3) is used as an approximate measure of the degree of oligotrophy/eutrophy and related oxygen level in the studied record, based on data derived from modern oceans (Corliss & Chen, 1988; Rusoff & Corliss, 1992; Kaiho, 1994) and similarly used for interpreting trophic and oxygen conditions in ancient seas (Thomas, 1990; Widmark, 1995).

In the studied record, moderate values of stress markers (16 to 50%) with the co-occurrence of oxiphylic species suggest more or less oligotrophic, well oxygenated bottom waters, where a significant amount of food is consumed at the sediment surface and only a smaller portion enters the sediment, restricting deep infaunal life. The palaeoenvironment, with mixed sub-/dysoxic and oxiphylic species, was characterized by well-aerated bottom water with a redox boundary a few centimetres from the seafloor which was colonized by sub- and dysoxic foraminifers.

Based on our data and using the model proposed by Jorissen et al. (1995) to explain the microhabitats in terms of trophic conditions and oxygen concentrations, extreme oligotrophic and extreme eutrophic environments may be excluded. In the former, all metabolizable food would be consumed at the sediment surface and the underlying sediment would contain only small quantities of (refractory) organic material that would cause the absence of infaunal foraminifera. In the latter, epifaunal foraminifera are absent due to decreased oxygen content caused by the decomposition of organic matter. At the same time, opportunistic infaunal foraminifera shift to or near the sediment surface following the shift of the redox front towards the sediment surface.

6. Conclusions

The present study was undertaken to provide an indication of the palaeobathymetric range of deposition of the basal part of the Kalamavka Formation, located in the Ierapetra basin in eastern Crete. The biostratigraphic analysis based on planktonic foraminifera indicated a Lower Tortonian age (between 11.54 and 11.21 Ma). This time interval is considered very crucial for the studied area as it coincides with the beginning of the fragmentation stage of the Aegean microplate (break - up stage), during extensional movements and thus the beginning of the "modern history" of the Aegean region.

Based on the bathymetric/palaeobathymetric calculations, the Kalamavka section has been deposited at an estimated palaeodepth corresponding to the outer shelf to the middle bathyal zone (150- 600 m). Partly, a middle shelf depth of deposition was attained.

The fluctuations of the frequency values of stress-marker species indicated oligotrophic to mesotrophic conditions and well-oxygenated bottom waters..

7. Acknowledgments

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