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# Calcareous phytoplankton stratigraphy of Neogene marine sediments eastern of Heraklion, Crete, Greece

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**Abstract:** Biostratigraphic correlations of marine deposits are largely based on calcareous nannofossils. Reliability of bioevents or biohorizons is of high importance. In order to contribute to the late Miocene to Pliocene stratigraphy of central north Crete Island (Greece), two sections of the Neogene deposits of eastern Heraklion Basin are presently biostratigraphically investigated. Lithostratigraphically the "Cape Chersonissos" section belongs to Ambelouzos (lower part) and Aghia Varvara (middle & upper part) Formations, while the calcareous nannofossil assemblage if it is assigned to the CN9a (*Discoaster berggrenii*) & CN9bA (*Amaurolithus primus*) subzones of Upper Tortonian to Lower Messinian. The "Piskopiana" section belongs to the Finikia Formation, its nannofossil assemblage characterizes the CN11b (*Discoaster asymmetricus*) subzone of Lower Pliocene (Zanclean) and it shows for the first time strata of such age being recorded in the Limin Chersonissos-Piskopiana area. Additionally, many significant biohorizons of calcareous nannofossils and their degrees of reliability help to improve the stratigraphic evolution of the studied paleobasin according to the latest published astrobiochronological scheme of Raffi et al. (2006).

**Zusammenfassung:** Biostratigraphische Korrelationen mariner Sedimente basieren weitgehend auf kalkigen Nannofossilien. Die Verlässlichkeit von Bioevents oder Biohorizonten ist von großer Bedeutung. Um Beiträge zur Stratigraphie des Obermiozän und Pliozän von Nordzentralkreta (Griechenland) zu liefern, werden zur Zeit zwei Profile neogener Ablagerungen im östlichen Heraklion-Becken untersucht. Lithostratigraphisch gehört Cape Chersonnos zur Ambelouzos-Formation (unterer Teil) und zur Aghia Varvara-Formation (mittlerer und oberer Teil), während die kalkigen Nannofossil-Gemeinschaften die Lokalität in die CN9a (*Discoaster berggrenii*) & CN9bA (*Amaurolithus primus*)-Subzonen des oberen Torton bis unteres Miozän stellt. Das Piskopiana-Profil gehört in die Finikia-Formation, seine Nannfossilien sind typisch für die CN11b (*Discoaster asymmetricus*)-Subzone des unteren Pliozän (Zanclium). Hier kann zum ersten mal gezeigt werden, dass Schichten diesen Alters im Raum Limin Chersonissos-Piskopiana vorkommen. Außerdem unterstützen die Untersuchungen der stratigraphischen Entwicklung in den Paläobecken die kürzlich veröffentlichten astrobiologischen Modelle (Raffi et al. 2006).

**Keywords:** Calcareous nannofossils, biostratigraphy, Tortonian, Messinian, Zanclean, Miocene, Pliocene, Chersonissos, Heraklion, Crete, Greece

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## 1. Introduction

Aegean Sea is considered a physical laboratory. Among the first geophysical works are those of McKenzie (1970) and Makris (1978). A very serious contribution in the geology is by no doubt the work of Jacobshagen (1986, 1994). It is generally believed, that southward retreat of the trench in the Hellenic Arc System induced the arc migration, giving subsequently birth and shape to the modern Hellenic Arc System configuration (Wortel & Spakman 1992). The Aegean Sea extension (mainly at the southern part of it) and the southward movement of Crete Island were both caused by the rollback effect of the slab and broadly the subduction zone (Le Pichon 1982, Meulenkamp et al. 1994). This rollback process is believed to start about 12 my ago (Meulenkamp et al. 1994). In addition, the active tectonics deformation of the Aegean region is dominated not only by extensional but by combined strike-slip motions and compressional tectonics as well (Jackson 1994, Meulenkamp et al. 1994). The concentration of slab pull forces causes a pattern of subsidence with development of depocenters and uplift migrating along strike. Subsequently, it prevailed a maximum crustal thinning and subsidence in the region of Cretan Sea (mainly of Neogene age, but it continues nowadays as well), which produced the back-arc basin(s) at the north of Crete as it was firstly suggested by studies of Makris (1978), Angelier et al. (1982) and Wortel & Spakman (2000).

Presumably, the Neogene basins of Crete Island are generally considered the result of the prementioned subsidence and subsequent extension. Two marine sedimentation cycles (of Miocene and Pliocene age respectively) were originally distinguished on Crete (Christodoulou 1963, Frydas & Keupp 1996). It is now accepted that a third cycle exist, which although geographically limited, represents the Pleistocene transgression (Keupp & Bellas 2000). The Miocene-Pliocene deposits of Heraklion are considered among the most extended of Crete. The configuration of Heraklion Neogene Basin of central Crete is tectonically controlled by two wide fault zones or systems, developed relative perpendicular to each other. The first of them, adjacent to Heraklion city, is running in the N-S direction and represents a shoal, while the second segment situated to the south of Heraklion (Messara plain), produced the Messara fault-trough along the E-W direction (Delrieu et al. 1991, 1993) and it is bordered to the south by the Asteroussia Mountain range. Further tectonic data on central Heraklion for Late Pliocene to Recent are given in Papanikolaou & Nomikou (1998), Fassoulas (2001), Ten Veen & Kleinspehn (2003), Peterek & Schwarze (2004) and Hinsbergen & Meulenkamp (2006).

Since there is very extensive literature concerning the lithostratigraphy and micropaleontology of Crete, the authors refer to Keupp & Bellas (2000) and for central Crete to Frydas et al. (2008), which include most of relative references. Previous micropaleontological studies on this area like Sissingh (1972), Zachariasse (1975), Jonkers (1984), Theodoridis (1984) and Driever (1988) were focused on isolated outcrops distributed. The concentrated stratigraphical research of Late Miocene and Pliocene deposits in the central Crete (Heraklion Basin) using calcareous and siliceous fossils, has started with the earlier works of Frydas (1985, 1987, 1990, 1994, 1998, 1999, 2004) and Frydas et al. (1994). The prolongation of Heraklion Basin to the South and southwest of central Crete is called Messara Basin or Plain. Preliminary biostratigraphic data concerning the NE Mires area have been published by Bellas & Keupp (2004), while recently the largest part of the Messara marine stratigraphy was analytically investigated by Frydas et al. (2008). Among other authors, Drinia et al. (2005) and Koskeridou (2006) reported on central Crete benthic Foraminifera and Mollusc issues (Atsipades section, eastern Messara Basin), while Brachert et al. (2006), Reuther et al. (2006) and Mertz-Kraus et al. (2009) refer to Tortonian-Messinian age shallow-marine clastics and carbonates with exceptionally well reef-growth from Messara. Very recently, Bellas & Keupp (2009) studied the ancient Gortys area in Messara, using calcareous nannofossils biostratigraphy.

The present work contributes to the completion of previous stratigraphical investigations and analyses in central Crete and it is particularly focused in the north-eastern part deposits of Heraklion Basin (Chersonissos-Malia area), which are not well known and little attention has been given to now, out of certain macropaleontological studies (Anapliotis 1967, Symeonidis & Konstadinidis 1967, Böger & Willmann 1979). In order to improve our knowledge of the late Cenozoic geological history of this area, we study two Neogene outcrops at Cape Chersonissos and Piskopiana using calcareous nannofossils biostratigraphy, reporting on the relative age (biozones) of these marine deposits. Furthermore, the reliability of some known biohorizons of calcareous nannofossils has been evaluated along the studied sections and their applicability concerning the biochronological correlation in the eastern Mediterranean Sea is commented. For this purpose, we have used semiquantitative data of calcareous nannofossils.

## 1. Methodology

### 2.1 Studied Material

For the location of the studied sections it was used the topographic map of the Greek Geographical Army, sheet "Mochos" (of Crete Island) in a scale of 1:50,000 (Edition 1989). Two sections were litho- and biostratigraphically studied in detail. Both of them are situated between Heraklion and Aghios Nikolaos cities in the eastern part of Heraklion Province of central Crete. Cape Chersonissos section is located on the left hand (to the west), along the main street driving from Limin Chersonissos town to the homonymous Cape (Fig. 1), shortly after Sarantaris village at ca. 0.7 km distance from it. Piskopiana section is located on the new national road crossing at a east-west direction the Crete Island (ca. 1.7 km SSW of Limin Chersonissos), on the road connecting Aghios Nikolaos, Malia and Chersonissos driving further west to Heraklion, between Koutouloufarion and Piskopiana villages, directly on the right side of the street and at the eastern entrance of the former village (Fig. 1).

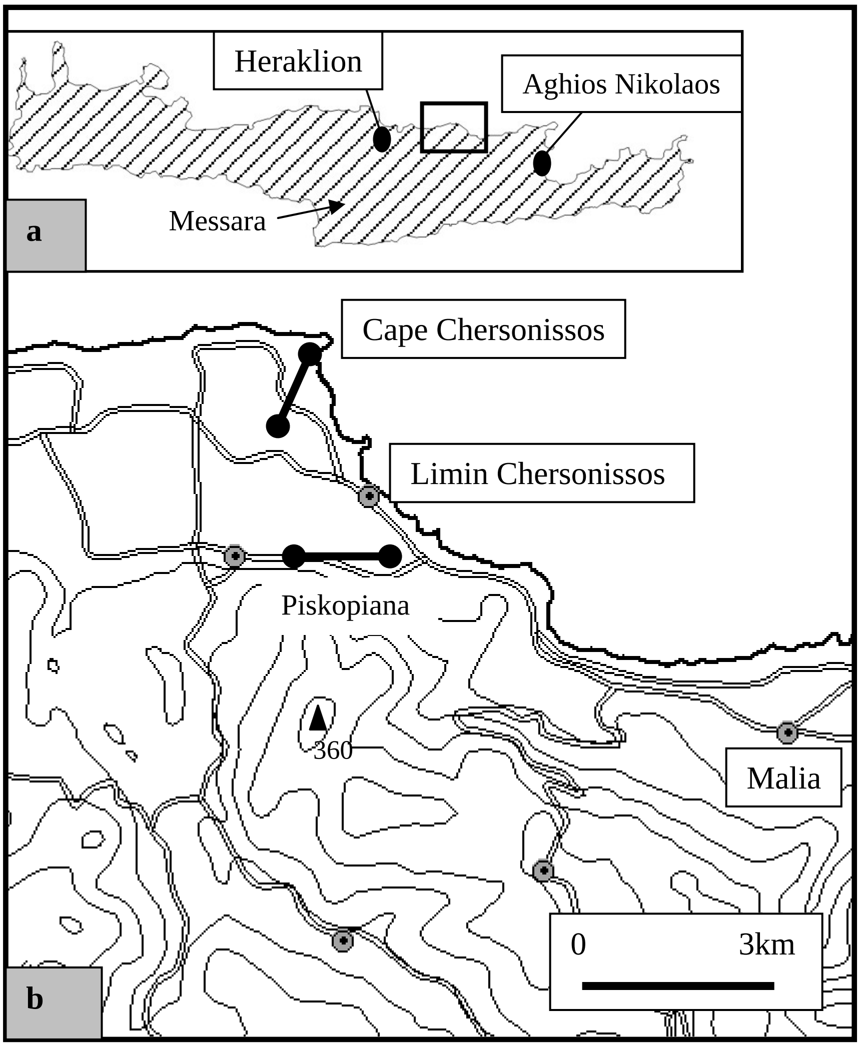


**Fig. 1: (a)** Inlet: Crete Island of Greece. **(b)** Location map of studied sections in the Heraklion Province. 1: Cape Chersonissos and 2: Piskopiana east of Heraklion city and west of Malia town, near Limin Chersonissos, Crete, Greece. Contour interval 60 m.

### 2.2 Methods

During the field work, 16 samples of marls and silty to sandy marls were taken from the two sections and proceed to the laboratory. Smear slides preparation of soft sediment samples followed standard techniques. Micropaleontology was based on the calcareous nannofossils identification under both the normal light microscope (LM at magnifications of ca. 1000x) and the scanning electron microscope (SEM) samples using gold coating.

A quantitative and subsequently semiquantitative study using the calcareous nannoplankton has been also performed. In our case decompaction of sediment was not taken into account. Quantification of species (counting 300 individuals per sample -see smear slide-) is presented in Tables 1 and 2 for each section, based on the following pattern: **A** (Abundant) = >20%, **C** (Common) = 10-20%, **F** (Few) = 4-10% and **R** (Rare) = 1-4%. Reworking is shown by r.

The biostratigraphic schemes used are the "standard" zones of Martini (1971) (NN) and Okada & Bukry (1980) (CN). Taxonomy, additional useful bioevents and their paleomagnetic position and biochronological calibration are based on Pierce & Hart (1979), Theodoridis (1984), Perch-Nielsen (1985), Martini & Müller (1986), Driever (1988), Winter & Siesser (1994), Young et al. (1994), Berggren et al. (1985, 1995), Raffi & Flores (1995), Sprovieri et al. (1996), Fornaciari (2000), Negri & Villa (2000), Van Couvering et al. (2000), Lourens et al. (2004), Raffi et al. (2003, 2006) and Morigi et al. (2007).

## 2. Results

### 3.1 Sedimentary Formations Lithostratigraphy

Lithostratigraphy and basic paleontology of the Formations consisting the wide eastern Heraklion area, follows that of the IGME Geological Sheet “Mochos” (1989), Frydas et al. (2008) and our own observations:

Both studied sections are located in the area extending north (Cape Chersonissos section) and south-south-western (Piskopiana section) of Limin Chersonissos village. These sections are appearances of Neogene strata of the eastern part of North Heraklion Basin, lithostratigraphically very difficult to assign to a particular Formation, since different Formations are developed along each section. According to the map of IGME, sheet “Mochos”, Cape Chersonissos area incorporate deposits of Middle to Late Miocene age, which are assigned a) to the Viannos Formation, b) to the Ambelouzos Formation and c) to the Aghia Varvara Formation. No reference is made for Pliocene age strata in this area.

(a) The Viannos F. includes well-bedded, greenish or dark-grey to dark-blue clays, silty clays and well-sorted brownish sands of fluvial to lacustrine origin (lignite-lenses are locally intercalated) and considered of middle Miocene age. It includes *Planorbis, Neritina* and *Brothia*.

(b) The Ambelouzos F. includes marine, brackish and fluviatiler conglomerates, brownish sands, siltstones and grayish, silty or sandy clays or marls of Tortonian age. Patch-Reefs of *Porites* are also present at certain stratigraphic levels, particularly in the south Heraklion Basin (Messara) (co. Brachert et al. 2006, Reuther et al. 2006, Mertz-Kraus et al. 2009). Macrofossils include *Planorbis*, *Neritina*, *Melanopsis*, *Unio*, *Hydrobia*, *Terebralia*, *Ostrea*, *Crassostrea*, *Cerithium*, *Turritella*, *Pecten*, *Natica*, *Conus*, *Murex*, *Arca* and *Clypeaster* (Anapliotis 1967). It is assigned to the *Neogloboquadrina acoastaensis* (Blow) planktonic Foraminifera Zone (Zachariasse 1975). This Formation calcareous nannofossils assemblages include the Subzones CN8a (*Discoaster bollii*), CN8b (*Discoaster loeblichii*) to CN9a (*Discoaster berggrenii*) of Tortonian and Messinian in Messara area (Frydas et al. 2008).

(c) The Aghia Varvara F. includes bioclastic, partly breccious and reefal limestones. To the south-south-western (Messara), thick evaporites with breccia intercalations or massive breccia of chaotic appearance with secondary gypsum characterize this formation. Locally, fine-laminated diatomite layers compound the upper part of the formation. Fossils include Bryozoa, various Corals, *Clypeaster*, *Pecten*, *Lithothamnium* and *Heterostegina*. Calcareous nannofossil assemblages recovered from this formation were assigned to the subzones CN9bA (*Amaurolithus primus*) to CN9bB (*Amaurolithus delicatus*) of the uppermost Tortonian to Messinian, while considering the siliceous microfossils, the assemblages characterize the Diatom biozone *Nitzschia miocenica* and the Silicoflagellate biozone *Distephanus speculum speculum* (Frydas et al. 2008).

Viannos and Aghia Varvara Formations are extensively distributed in the studied area. Ambelouzos F. appears near Cape Chersonissos only in a small proportion relative to the whole Neogene, while a few minor outcrops of Pliocene age occur to the west and this formation dominate in the wide Heraklion area.

### 3.2 Cape Chersonissos Section - Lithostratigraphy (Fig. 2)

The studied section is ca. 15 m thick and can be subdivided into three parts; the lower, the middle and the upper.

A finely bedded, marly limestone, ca. 3 m in thickness, comprises the lower part of the Cape Chersonissos section. A thick, ca. 9 m of light sandy to sandy marl follows upwards, making the middle part. All 6 samples were taken from this (soft) part of the section (Fig. 2). To the top, a hard, biogenic to reefal lime-stone cap closes the section (upper part). It covers the marly strata with an irregular, erosional contact and has a thickness of ca. 3 m.

In our opinion and according to the previous formations descriptions, our field observations and the IGME map, the lower marly limestone of the Cape Chersonissos section (basal part) most probably belongs to the Ambelouzos F.

According to an older assumption of Sissingh (1972), the marl deposits of this section (middle part) belong to the Tefeli Formation (sensu Meulenkamp et al. 1979), which is supposed to be composed by clays, lignites, sands, conglomerates and less marls. Since, strata of this formation are not included in the younger IGME map sheet “Mochos” published in 1989, although the Neogene deposits were proceeded by the same Utrecht group of scientists, like Meulenkamp and Jonkers (as also Sissingh did), it is unlikely that the middle part of the section belongs to the Tefeli F. It is more likely that the sandy marls of Cape Chersonissos belong to the Aghia Varvara Formation, as also do the upper part of the studied section.

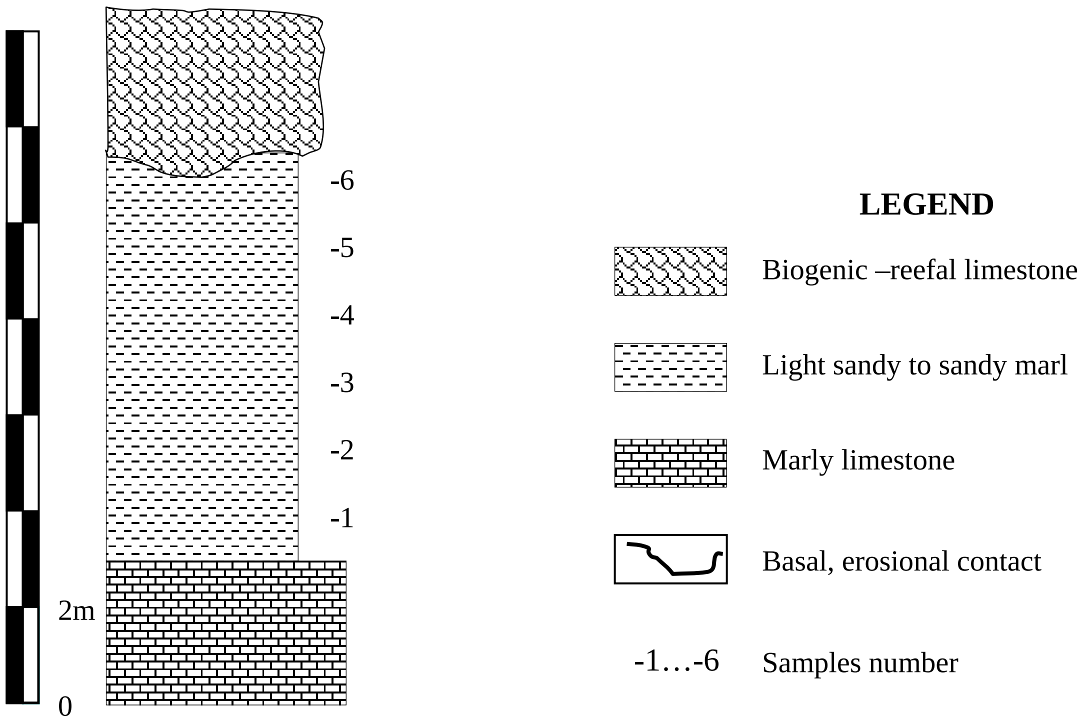


**Fig. 2:** Lithostratigraphy and studied samples position of Cape Chersonissos section, Heraklion Province, Crete.

Reefal and generally biogenic-remains limestones are very common constitutes of the latter formation (cf. also Frydas et al. 2008) and in accordance with the geological map of IGME, such deposits, together with those of Viannos F. are quite extensively distributed over the Limin Chersonissos wide area. Although extensively present in the area, strata of Viannos F. did not record along the studied section of Cape Chersonissos. They occur at both sides of the main street driving to Malia town to the east, bearing abundant fresh-water (limnic) Gastropods identified by Böger & Willmann (1979).

### 3.3 Section Piskopiana - Lithostratigraphy (Fig. 3)

The area of Piskopiana-Koutouloufarion can be placed in the Finikia Group. These strata represent deposition in the Lower to Middle Pliocene time-span. Finikia Group unconformably overlies the Vrysses Group of Late Miocene age (Meulenkamp et al. 1979). It incorporates most Late Neogene Formations, which consist of open marine, usually homogenous marls and clays, locally laminated. The latter intercalations may sometimes be diatomite beds, including Diatoms and Silicoflagellates. The strata of Piskopiana section are placed to the Stavromenos Formation or its lateral equivalent the Parathámna Formation (Zachariasse 1975).

This Formation is conformably overlying the Tefeli Formation deposits (Sissingh 1972). It generally consists of grayish marls, bearing intercalations of limestones, sands and conglomerates. Important microfossils like planktonic Foraminifera include according to Zachariasse (1975), the *Globorotalia margaritae* Bolli & Bermudez, *G. puncticulata* (Deshayes), *G. bononiensis* Dondi and *G. crassaformis* Galloway & Wissler. According to the Geological map of IGME, sheet “Mochos” (1989), the Pliocene strata exclusively occurring at the western part of the sheet, are assigned to the Finikia Formation, consisting of “white, homogenous marls or marly limestones and beige, often sandy marls with laminated intervals, passing upwards into brownish sands and/or calcareous sandstones”.

The studied Piskopiana section is ca. 12 m thick (Fig. 3) and can be subdivided into three parts; the lower, the middle and the upper. Main geologic characteristic of the section is the presence of a normal fault, which presents a high degree angle (ca. 70˚), cutting almost the whole section strata to the base of it (at the level of the local street).

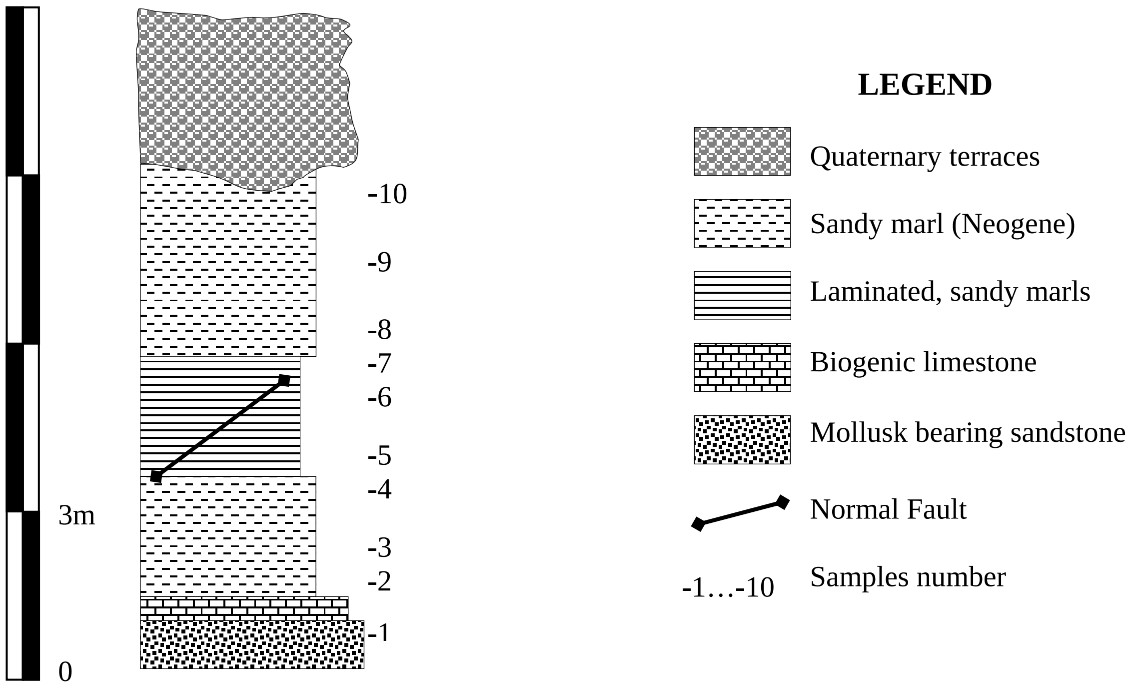


**Fig. 3:** Lithostratigraphy and studied samples position of Piskopiana section, Heraklion Province, Crete.

The lower part of the section includes a) at the base ca. 0.80 m in thickness of light grey, loose to moderately compact, silty sand to sandstone, locally oxidized, alternating with layers bearing large fossil marine Mollusks (Lamellibranches), followed upwards by b) ca. 0.50 m of beige, hard biogenic, marly limestone. The middle part starts c) with ca. 2.50 m in thickness of yellowish sandy marl, followed by d) ca. 2.20 m thick alternations of grayish to yellowish laminated sandy marls and e) again sandy marls of ca. 3 m in thickness. At the top, the upper part, f) a ca. 3 m compact conglomerate of Quaternary? age resembling a terrace, closes the section.

It seems that sedimentologically, marine deposition starts with shallow-water deposits (a and b), then follows a deepening, transgressive sequence (c, d and e) and the deposition closes with a new shallowing (regressive) event (f: conglomerate cap). The studied for biostratigraphic purposes samples (1-10) represent all but the last layer (f).

## 4. Calcareous nannofossils - biostratigraphy

### 4.1. Late Miocene

**Biozone CN9** – *Discoaster quinqueramus*

The few to common consistently occurrence of the *Discoaster berggrenni* / *D. quinqueramus* group in co-existence with few *D. mendomobensis* indicate the lower part of zone CN9 (according to Okada & Bukry, 1980) and specifically the upper part of the subzone CN9a – *D. berggrenii* (Upper Tortonian), which corresponds to the middle to upper part of the subzones NN11a of Martini (1971), CN9a of Raffi & Flores (1995) and MNN11a (Paracme Beginning -PB- of *Reticulofenestra pseudoumbilica* of Raffi et al. 2003). The stratigraphical interval of this subzone corresponds to the lower part (basal samples 1 and 2) of the Cape Chersonissos section. *D. pentaradiatus* (Lowest Occurrence -LO- at 9.1 Ma) is also presented in rare to few abundance, as well as rare sporadic *R. pseudoumbilica*, indicating that its PB which started at 8.761 Ma (according to Raffi et al. 2003) is continued section upwards.

**Tab. 1:** Semiquantitative distribution and biostratigraphy of calcareous nannofossils along the Cape Chersonissos Section.

| **U. Tortonian** | | **Lower Messinian** | | | | | **STAGES** |
|---|---|---|---|---|---|---|---|
| CN9a *D. berggrenii* | | CN9bA *Amaurolithus primus* | | | | | ← Subzones |
| **1** | **2** | **3** | **4** | **5** | **6** | | ← Samples – Species ↓ |
| | | R | | R | R | | *Amaurolithus primus* |
| | R | R | | R | | | *Calcidiscus leptoporus* |
| | | | R | R | R | | *C. macintyrei* |
| R | | F | | F | | | *Dictyococcites antarcticus* |
| R | R | | | | | | *Discoaster asymmetricus* |
| R | R | | | | | | *D. bellus* |
| R | F | F | F | C | C | | *D. berggrenii*/*D. quinqueramus* group |
| C | C | F | F | A | A | | *D. brouweri* |
| R | R | | | | | | *D. calcaris* |
| | | F | R | F | F | | *D. challengeri* |
| | R | R | | R | | | *D. decorus* |
| R | R | | | | | | *D. exilis* |
| | | R | F | F | F | | *D. intercalaris* |
| | | F | | R | F | | *D. loeblichii* |
| R | R | F | R | | F | | *D. mendomobensis* |
| | R | | r | | | | *D. neorectus* |
| F | | R | R | F | F | | *D. pentaradiatus* |
| | | F | F | R | | | *D. surculus* |
| | R | R | | | R | | *D. tristelifer* |
| F | | F | F | C | C | | *D. variabilis* |
| | | R | R | | | | *Geminilithella jafari* |
| | | | | R | R | | *G. rotula* |
| | | R | | R | | | *Hayella situliformis* |
| | F | | F | F | F | | *Helicosphaera carteri* |
| R | F | R | | C | C | | *H. sellii* |
| | | R | R | R | | | *Pontosphaera discopora* |
| | R | | | R | | | *P. multipora* |
| R | | R | R | | R | | *Reticulofenestra pseudoumbilica* |
| | F | F | | F | F | | *Rhabdosphaera clavigera* |
| | | | R | R | | | *Rh. perlonga* |
| | R | R | | R | | | *Scyphosphaera apsteinii* |
| F | C | C | C | F | C | | *Sphenolithus abies*/*S. moriformis* group |
| | R | | | R | R | | *Syracosphaera pulchra* |
| | | R | R | F | | | *Umbilicosphaera sibogae* |
| Semiquantitative distribution of calcareous nannofossil species per sample as follows: **A**= Abundant (>20%), **C**=Common (10-20%), **F**=Few (4-10%), **R**=Rare (1-4%), **r**= reworked | | | | | | | |

The subzone CN9a - *D. berggrenii* in this work can be correlated with the equivalent subzone NN11a – *D. quinqueramus* (sensu Martini 1971) for the Neogene sediments of the section Loussakies, the middle part of the Gribeliana, Platanos, Polyrrinia and Charchaliana sections in western Crete (Frydas 1993, Frydas & Keupp 1996, Bellas et al. 2007), the lower Panassos section (samples 1-4) and the middle Psalida section (samples 9-20) in central Crete (Frydas 2004, Frydas et al. 2008). Usually, the F.A.D of *A. primus* at 7.17 Ma indicates the base of subzone CN9bA- *A. primus* (Raffi & Flores 1995), which corresponds to the subzones NN11b (lower part) of Martini (1971), CN9b (Okada & Bukry 1980) and MNN11b-c (Raffi et al. 2003). Therefore, *A. primus* and/or *Amaurolithus* spp. are considered as the boundary species for the beginning of the Messinian Stage which age was laid down at 7.17 Ma by Berggren et al. (1995). These authors have estimated in an earlier work the beginning of the Messinian through the F.A.D of both *A. delicatus* and *A. primus* at 6.5 Ma (Berggren et al. 1985).

**Tab. 2:** Semiquantitative distribution and biostratigraphy of calcareous nannofossils along the Piskopiana Section.

| **Upper Zanclean** | | | | | | | | | | | **STAGE** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **CN11b** - *Discoaster asymmetricus* | | | | | | | | | | | ← Subzones |
| **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | | ← Samples – Species ↓ |
| | R | | | | | | R | | | | *Acanthoica acanthus* |
| | | | R | | | | R | | | | *A. acanthifera* |
| | | R | | | R | F | | F | R | | *Amaurolithus delicatus* |
| | | | | R | | | R | F | | | *Blackites spinosus* |
| | F | | R | | F | F | R | F | F | | *Calcidiscus leptoporus* |
| R | | F | | R | F | C | C | A | A | | *C. macintyrei* |
| | R | R | | | R | | | | | | *Coccolithus pelagicus* |
| F | | F | C | C | | R | C | C | C | | *Discoaster asymmetricus* |
| F | | C | C | | C | | F | A | A | | *D. brouweri* |
| | R | | | R | R | | | R | | | *D. challengeri* |
| | R | | F | F | | R | | F | | | *D. pansus* |
| F | | | C | F | | C | | F | | | *D. pentaradiatus* |
| | F | R | | | F | | | C | R | | *D. surculus* |
| F | | F | | R | R | | F | | | | *D. variabilis* |
| | R | | | R | | | R | | | | *Geminilithella jafari* |
| | | R | R | | | R | | | | | *G. rotula* |
| | F | F | | | F | | F | F | F | | *Helicosphaera carteri* |
| | | | R | | | R | | R | | | *H. sellii* |
| F | | F | | R | F | | | F | | | *Neosphaera coccolithomorpha* |
| | F | | F | | | F | R | | F | | *Pontosphaera discopora* |
| F | | F | | C | | C | C | F | C | | *Reticulofenestra minuta* |
| R | F | F | R | | F | F | F | R | F | | *R. minutula* |
| R | | R | C | F | F | C | F | C | F | | *R. pseudoumbilica* |
| | C | C | | F | | | F | F | F | | *Rhabdosphaera clavigera* |
| | R | | R | R | | | F | | | | *Rh. perlonga* |
| | | R | | | R | | | | R | | *Scyphosphaera amphora* |
| R | | | R | R | | | | | R | | *Sc. apsteinii* |
| F | F | C | C | | F | F | C | C | C | | *Sphenolithus abies/S. moriformis* group |
| | R | | R | | R | | R | R | | | *Syracosphaera pulchra* |
| R | R | | | | | R | R | | | | *S. ribosa* |
| | | R | | | R | | R | R | R | | *Umbelosphaera tenuis* |
| | F | F | | F | | C | C | C | F | | *Umbilicosphaera sibogae* |
| Semiquantitative distribution of calcareous nannofossil species (300 specimens per sample were counted) as follows: **A**= Abundant (>20%), **C**=Common (10-20%), **F**=Few (4-10%), **R**=Rare (1-4%) | | | | | | | | | | | |

Considering the biohorizon of LO *A. delicatus*, it is not reliable for open oceanic correlations and has been excluded from the important Late Miocene biohorizons (Raffi et al. 2006). Recently the LO datum of *A. primus* was further laid down to 7.424 Ma (Raffi et al. 2006, Tab. 3) and it was given an A (first) degree of reliability. Consequently, the Tortonian/Messinian boundary was also dated at 7.424 Ma for the Eastern Mediterranean, although generally it is dated at 7.246 Ma (Lourens et al., 2004). The stratigraphical interval of the CN9bA subzone starts at the boundary of Upper Tortonian/Lower Messinian with the first (lowest) occurrences, although very rare, of *A. primus* (sample 3) and corresponds to the upper stratigraphic part of the Cape Chersonissos section (samples 3 to 6), which is placed in the lower Messinian. Furthermore, the facts that *Nicklithus (A.) amplificus* was not recorded (LO at 6.684 Ma in Eastern Mediterranean; Tab. 3) and the paracme of *R. pseudoumbilica* is continued to the top of the studied samples (s. 6) (PE of *R. pseudoumbilica* is dated at 7.167 Ma in the Eastern Mediterranean), points to a lowest Messinian age for the uppermost strata of the Cape Chersonissos section.

**Tab. 3**: Astronomical age estimates (in My) of significant calcareous nannofossil biohorizons, ages of stage boundaries and their paleomagnetic position in the uppermost Miocene to Lower Pliocene stratigraphic interval (according to Lourens et al. 2004, Raffi & Flores 1995, Raffi et al. 2006).

| **Biohorizon** | **Zone/ subzone** | **ODP Leg 138** | **ODP Sites 925, 926** | **Eastern Mediter-ranean** | **(Sub) Chron** |
|---|---|---|---|---|---|
| **PLIOCENE Zanclean-Piacenzian** | **3,600 Ma** | | | | **C3r** |
| HO *Sphenolithus* sp. | CN12aA-CN12aB | 3.65 | 3.52-3.56 | 3.7 | C2Ar |
| HO *Reticulofenestra pseudoumbilica* | CN11b-CN12aA (NN14/15-NN16) | 3.79 | 3.81-3.82 | 3.839+ | C2Ar |
| LCO *Discoaster asymmetricus* | CN11a-CN11b (NN13-NN14/15) | 4.13 | | 4.120* | C2Ar |
| HO *Amaurolithus primus* | CN10c-CN11a | 4.50+ | | | C3n.1r |
| HO *Ceratolithus acutus* cross-over *C. acutus-C. rugosus* | | 5.04 | 5.046+ 5.054 | | C3n.4n |
| LO *Ceratolithus rugosus* | CN10b-CN10c (NN12-NN13) | | 5.054* | | C3n.4n |
| HO *Triquetrorhabdulus rugosus* | | | 5.279 | | C3r |
| | | | | | |
| **MIOCENE / PLIOCENE - Messinian / Zanclean** | **5.332 Ma** | | | | |
| LO *Ceratolithus acutus* | CN10a-CN10b | 5.32 | 5.345* | | C3r (top) |
| HO *Discoaster quinqueramus* | CN9bC-CN10a (NN11b-NN12a) | | | 5.54+ | C3r |
| HO *Nicklithus amplificus* | CN9bB-CN9bC | | 5.978 | 5.939+ | C3An/C3r |
| LO *Nicklithus amplificus* | CN9bA-CN9bB | | 6.909 | 6.684* | C3Ar (top) |
| PE *Reticulofenestra pseudoumbilica* | | | 7.077 | 7.167* | C3Ar |
| | | | | | |
| **MIOCENE Tortonian-Messinian** | **7.246 Ma** | | | | |
| LO *Amaurolithus primus* | CN9a-CN9bA (NN11a-NN11b) | | 7.362 | 7.424* | C3Br.2r |
| LCO *Discoaster surculus* | | 7.88 | | | C4n.2n |
| LO *Discoaster berggrenii* | CN8-CN9a (NN10-NN11a) | 8.52 | 8.294* | | C4r.2r |
| HCO *Minylitha convalis* | | 7.78-8.3 | | 8.685* | C4r.2r |
| PB *Reticulofenestra pseudoumbilica* | | | 8.785 | 8.761 | C4r.2r |
| LO *Discoaster pentaradiatus* | | 9.1 | | | C4r.1n |
| ****LO:** Lowest Occurrence, +**HO:** Highest Occurrence, **LCO:** Lowest Consistent Occurrence, **HCO:** Highest Consistent Occurrence, **AB:** Acme Beginning, **PB:** Paracme Beginning, **PE:** Paracme End | | | | | |

The subzone CN9bA in this work can be correlated to the lower half part of the subzone NN11b (Martini 1971), concerning the Neogene sediments of the upper part in the Platanos, Polyrrinia, Charchaliana and Cherethiana sections in western Crete (Frydas 1993, Frydas & Keupp 1996, Keupp et al. 2000) and the upper Panassos (samples 5-8) and Mires, Psalida composite sections (samples 15-17 and 21-26) in central Crete (Frydas 2004, Frydas et al. 2008).

## 4.2. Early Pliocene

**Subzone CN11b** (*D. asymmetricus)*

The calcareous nannofossil assemblage of the Piskopiana section (Tab. 2, samples 1 to 10) belongs to the subzone CN11b *Discoaster asymmetricus* (Upper Zanclean, lower Pliocene) of Okada & Bukry (1980) (Table 2), according to the co-occurrence of *D. asymmetricus* (Lowest Common Occurrence -LCO- at 4.13 Ma and at 4.120 Ma for the Eastern Mediterranean) and *Reticulofenestra pseudoumbilica* (Highest Occurrence -HO- at 3.839 Ma, Table 3). Biostratigraphically, it is very important that both species, *D. asymmetricus* and *R. pseudoumbilica* present a consistent occurrence in rare to common abundance along the studied section, and therefore the CN12aA subzone (uppermost CN11b) is not recorded (considers the small stratigraphic interval between the HO of *R. pseudoumbilica* and the HO of *Sphenolithus* spp.).

Also present are *Discoaster pentaradiatus* (L.A.D at 2.52 Ma), *D. surculus* (L.A.D at 2.63 Ma) and *Sphenolithus* spp. in few to common abundance (HO at 3.7 Ma in Eastern Mediterranean, Table 3), but *Discoaster tamalis* is absent (key nannofossil for the next upwards following biozone NN16, having its First Appearance at 3.7 Ma in Rio et al. 1984, Shackleton et al. 1995).

Other important biohorizons like a) the HO of *Amaurolithus delicatus*, b) the Lowest Occurrence (LO) of *Helicosphaera sellii* and c) the Paracme Interval of *Discoaster pentaradiatus* near the HO of *R. pseudoumbilica*, were excluded from the astrobiochronological scheme for global biostratigraphic correlation published by Raffi *et al*. (2006), considering them of limited value or not reliable. According to the previous data, it is obvious that the strata of the Piskopiana section straddle a stratigraphic interval of less than 281 kyrs (between the LCO of *D. asymmetricus* and the HO of *R. pseudoumbilica*; Tab. 3).

This subzone corresponds to the combined biozone NN14 + NN15 of Martini (1971, Martini & Müller, 1986) and the subzone CN11b of Raffi & Flores (1995) and corresponds to the siliceous microfossils (a) Diatom Biozone *Nitzschia jouseae* and (b) the silicoflagellate subzone *Distephanus boliviensis boliviensis* (Frydas 1985, 1987, 1990, 1994, 1998, 1999, 2004, 2006, Frydas & Keupp 1992, 1996, 2000, Frydas et al. 2008, Bellas & Keupp 2004).

In this work, the subzone CN11b can be correlated with the biozones NN14 + NN15 for the Neogene deposits of the upper part of the Tavronitis and Lardas sections in western Crete (Frydas 1993, Frydas & Keupp 1996, Keupp & Bellas 2000) and the lower part of Kourtiani Kefala composite section of central Crete (samples 1-4; Frydas et al. 2008).

## 5. Conclusions

Two sections of Neogene deposits from the eastern part of the great Heraklion Neogene Basin of central Crete Island are litho- and biostratigraphically investigated, in order a) to refine the existed stratigraphic framework and b) to submit new data based on calcareous nannofossils. Sixteen samples of marls and sandy marls were proceeding for the micropaleontological investigation of the present study using standard techniques.

Lithostratigraphically, the Cape Chersonissos section is subdivided into two parts. The lower part of it (base) can be placed in the Ambelouzos Formation, while the middle and upper parts of it are characteristic of the Aghia Varvara Formation. Both formations deposits are dated as Late Miocene (Tortonian to Messinian). Limnic strata of the Viannos Formation dated also as middle to Late Miocene with abundant Gastropods were observed, but are not recorded in the studied sections.

The Piskopiana section can be placed in the Finikia Formation (of Finikia Group according to Meulenkamp et al. 1979), which is dated as Pliocene in age. These early Pliocene strata terminated the Messinian Salinity Crisis of the Mediterranean (MSC). The present work shows that the deposits of Piskopiana section certainly characterize not the initial (basal) stage of Pliocene transgression, but the development of it into open marine conditions.

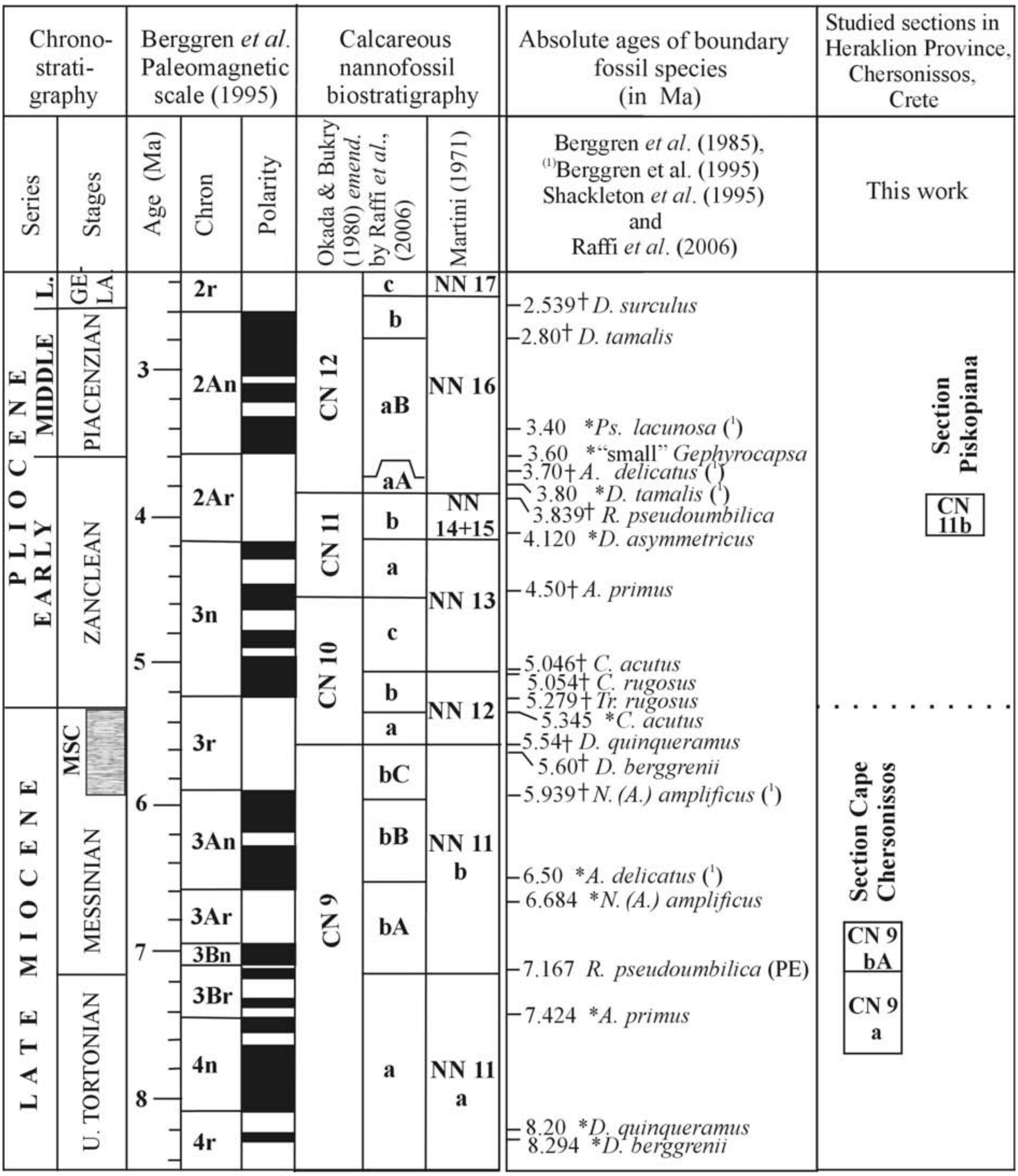


**Fig. 4:**. Chronostratigraphy, Paleomagnetics, calcareous nannofossil biostratigraphy and astrobiochronology of significant nannofossil biohorizons, used for placement of the two studied sections namely the Cape Chersonissos and Piskopiana (right column), both located near Chersonissos-Malia in the north central Crete Island. Abbreviations follow notes in Tab. 3.

Biostratigraphically, the Cape Chersonissos section, was considered before as Lower (Early) Tortonian in age (Zachariasse 1975). According to the present study age determinations, the calcareous nannofossil assemblages recovered from the middle part of the section and the bioevents markers are assigned to the CN9a: *Discoaster berggrenii* (samples 1-2) and CN9bA: *Amaurolithus primus* (samples 3-6) subzones [sensu Okada & Bukry (1980) emend. by Raffi & Flores 1995 in Raffi et al. (2006)] (Fig. 4), which chronostratigraphically point to Late Tortonian and Early Messinian respectively. The assemblage of Piskopiana section (samples 1-10) is assigned to the CN11b: *Discoaster asymmetricus* subzone *(sensu* Okada

& Bukry, 1980) or its equivalent combined NN14+15 Zones of Martini (1971), pointing to a Late Zanclean age (Lower Pliocene).

Considering the reliability of bioevents, certain species biohorizons data are applied following the Neogene astrobiochronological scheme of Raffi et al. (2006), which was largely based on the astronomical calibration of Lourens et al. (2004) (Tab. 3). Definition of the CN9a/CN9bA subzones boundary is based on the reliability of the Lowest Occurrence (LO) of *A. primus* biohorizon, which was recently given an A degree (best reliable in Raffi et al. 2006). Other biohorizons used are the PE of *Reticulofenestra pseudoumbilica* with degree of reliability D (Paracme End at 7.167 Ma in eastern Mediterranean), the absence of *Nicklithus amplificus* given a C degree of reliability (LO: Lowest Occurrence at 6.684 Ma in eastern Mediterranean) the LCO of *Discoaster asymmetricus* (Last Common Occurrence at 4.120 Ma in eastern Mediterranean) and the Highest Occurrence of *R. pseudoumbilica*, A degree of reliability (HO at 3.839 Ma in eastern Mediterranean).

It is obvious that our results show the existence of a new Zanclean (Pliocene) outcrop (Piskopiana section) in the vicinity of Limin Chersonissos, improving the resolution of the Geological map of Greece (1989) sheet "Mochos", since sediments of such age are not included according to the map.

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**Plate 1**

Calcareous nannofossils from the Cape Chersonissos (figs. 1-14, 17-20, 23, 25-28) and Piskopiana sections (figs. 15, 16, 21, 22, 24) of Crete Island. All figures are scanning electron micrographs (SEM) out of fig. 12 (optical microscope, normal light, **OM**). Scale bar equals 5.0 μm (figs. 1-11, 17, 18 and 28), and 2.0 μm (figs. 12-16 and 19-27). Small s is for sample number.

**Figs. 1, 6:** *Discoaster quinqueramus* Gartner (s. 4,6)

**Figs. 2, 9:** *Discoaster surculus* Martini & Bramlette (s. 4)

**Fig. 3:** *Discoaster mendomobensis* Wise (s. 6)

**Fig. 4:** *Discoaster exilis* Martini & Bramlette (s. 2)

**Fig. 5:** *Discoaster asymmetricus* Gartner (Tortonian species, s. 2)

**Fig. 7:** *Discoaster calcaris* Gartner (s. 2)

**Fig. 8:** *Discoaster brouweri* (Tan Sin Hok) (s. 6)

**Fig. 10:** *Discoaster neorectus* Bukry (s. 2)

**Fig. 11:** *Discoaster pentaradiatus* (Tan Sin Hok) (s. 6)

**Fig. 12:** *Amaurolithus primus* (Bukry & Percival) (**OM**, s. 2)

**Figs. 13, 23:** *Syracosphaera pulchra* Lohmann. 13: side view with distal spire to right (s. 2), 23: proximal view (s. 6)

**Fig. 14:** *Rhabdosphaera clavigera* Murray & Blackman (s. 6)

**Fig. 15:** *Blackites spinosus* (Deflandre & Fert) (Piskopiana section, s. 8)

**Fig. 16:** *Umbelosphaera tenuis* (Kamptner) (Piskopiana section, s. 8)

**Fig. 17:** *Helicosphaera carteri* (Wallich), proximal view (s. 5)

**Fig. 18:** *Helicosphaera sellii* Bukry & Bramlette, proximal view (s. 5)

**Fig. 19:** *Scyphosphaera apsteinii* Lohmann (s. 5)

**Fig. 20:** *Umbilicosphaera sibogae* (Weber-Van Bosse) (s. 5)

**Fig. 21:** *Syracosphaera ribosa* (Kamptner) Borsetti & Cati (Piskopiana section, s. 8)

**Fig. 22:** *Acanthoica acanthos* Winter & Siesser (Piskopiana section, s. 8)

**Fig. 24:** *Neosphaera coccolithomorpha* Lecal-Schlauder (Piskopiana section, s. 9)

**Figs. 25, 26:** *Calcidiscus leptoporus* (Murray & Blackman), 25: distal view (s. 6), 26: proximal view (s. 6)

**Fig. 27:** *Reticulofenestra pseudoumbilica* (Gartner), proximal view (s. 6)

**Fig. 28:** A coccosphere of *Reticulofenestra* coccoliths (s. 6)

# PLATE 1

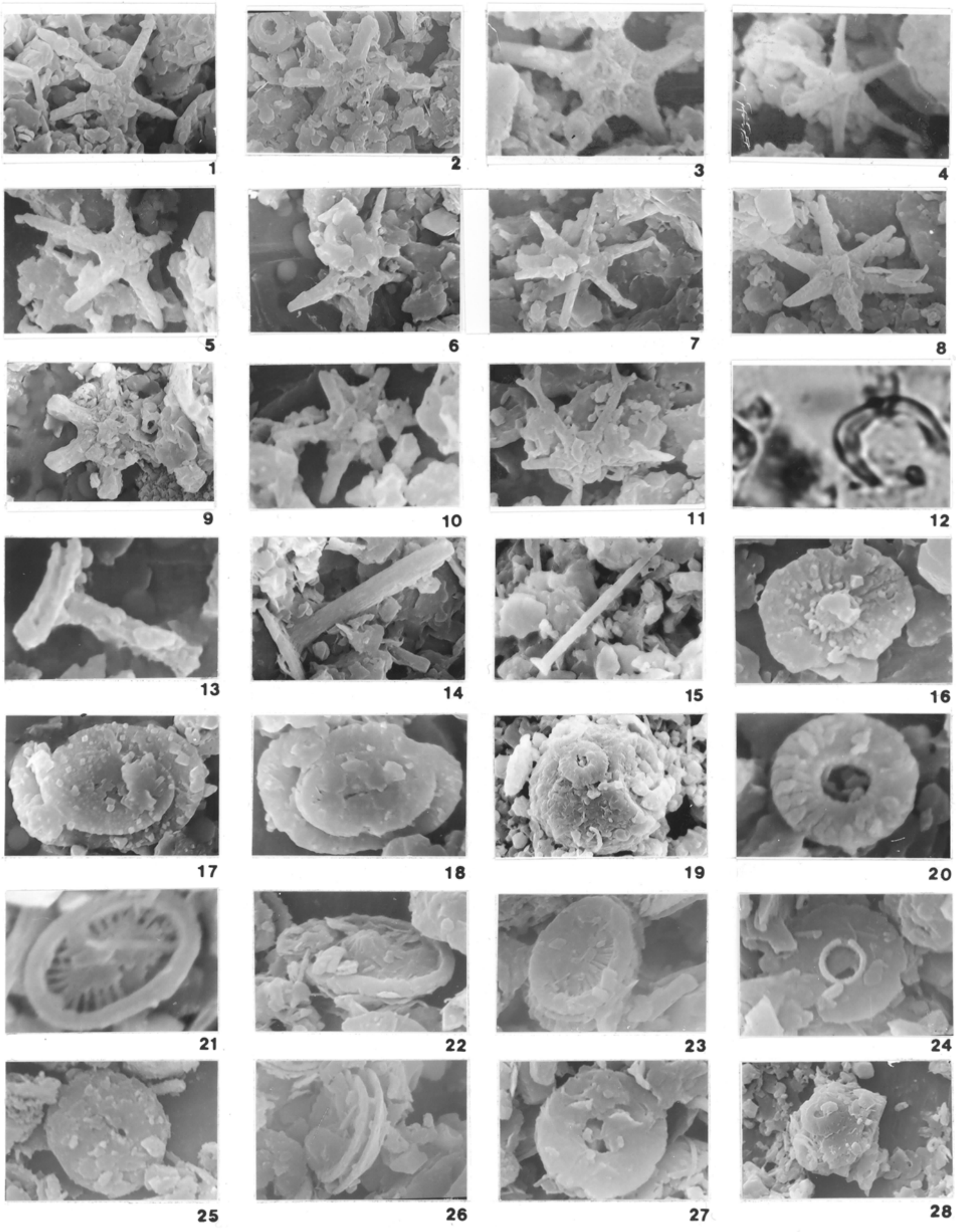

**Plate 2**

Calcareous nannofossils. Most species recovered from the Piskopiana section. Figures 10-12 and 15 are from Cape Chersonissos section of Crete Island. All figures are scanning electron micrographs (SEM), out of figs. 13-15 and 20 (optical microscope, normal light, **OM**). Scale bar equals 1.0 μm (figs. 1-9 and 16-22), 2.0 μm (figs. 10-15). Small s is for sample number.

| | |
|---|---|
| **Figs. 1, 2:** | *Reticulofenestra pseudoumbilica* (Gartner), 1: distal view, 2: proximal view (s. 9) |
| **Fig. 3:** | *Umbilicosphaera sibogae* (Weber-Van Bosse) (s. 7) |
| **Figs. 4, 7:** | *Helicosphaera sellii* Bukry & Bramlette, 4: distal view, 7: proximal view (s. 9) |
| **Figs. 5, 8:** | *Helicosphaera carteri* (Wallich), 5: distal view, 8: proximal view (s. 9) |
| **Figs. 6, 9:** | *Calcidiscus leptoporus* (Murray & Blackman), 6: distal view, 9: lateral view (s. 9) |
| **Figs. 10, 12, 14:** | *Discoaster intercalaris* Bukry, 10,12: Cape Chersonissos section (s. 6), 14: s. 3 (**O.M**) |
| **Fig. 11:** | *Discoaster decorus* Bukry, Cape Chersonissos section, s. 2 |
| **Fig. 13:** | *Discoaster brouweri* (Tan Sin Hok) (**OM**, s. 9) |
| **Fig. 15:** | *Discoaster neorectus* Bukry, Cape Chersonissos section, (**OM**, s. 2) |
| **Fig. 16:** | *Reticulofenestra minutula* (Gartner) (s. 3) |
| **Fig. 17:** | *Scyphosphaera apsteinii* Lohmann (s. 9) |
| **Figs. 18, 19:** | *Sphenolithus abies/moriformis* group (s. 9) |
| **Fig. 20:** | *Discoaster asymmetricus* Gartner (**OM**, s. 9) |
| **Fig. 21:** | *Discoaster surculus* Martini & Bramlette (s. 9) |
| **Fig. 22:** | *Rhabdosphaera clavigera* Murray & Blackman (s. 9) |

# PLATE 2