

Biostratigraphy of calcareous nannofossils and palaeoenvironments in the Lower Miocene of the Albanian–Thessalian Basin (Albania)

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Abstract: The Albanian–Thessalian Basin, which is located in the vicinity of Mount Morava, includes Eocene to Middle Miocene sediments with a poorly-known, calcareous nannofossil content. This study is focused on the investigation of calcareous nannofossil assemblages from the Lower Miocene sediments outcropping in the area, resulting in the correlation to the global nannofossils zones/subzones NN2–NN3/CN1c–CN2, as well as to the zonation from the Mediterranean area, where the MNN2b and MNN3a biozones have been identified. An early-middle Burdigalian age for the studied outcrops is supported by primary and secondary index species (*Helicosphaera ampliapertura*, *Helicosphaera mediterranea*, *Sphenolithus belemnus*, *Sphenolithus disbelemnus*, *Sphenolithus pseudoheteromorphus*). Quantitative analyses were performed on calcareous nannofossils and statistics were applied to all of the counted samples. Based on the statistical analysis, short-time fluctuations in palaeoenvironmental parameters, such as temperature, salinity and eutrophic regime, are documented through the changes in the calcareous nannofossil assemblages and their abundance patterns. The depositional palaeoenvironment indicates changes in basin water depth, with influence of cold upwelling currents, terrigenous nutrient influx, and increased palaeoenvironmental perturbations over short time intervals.

Keywords: Burdigalian, Morava Mts. (Albania), biostratigraphy, palaeoenvironment, statistics, calcareous nannofossils

Introduction

Lower Miocene sediments are widespread in the southern part of the Albanian–Thessalian Basin (ATHB, Albania) and are part of the third sedimentary cycle of Burdigalian–Langhian age from the area of Mount Morava. The stratigraphic record of the intramontane ATHB (Bourcart 1922) transgressively overlies the Mirdita and Krasta–Cukali zones (Fig. 1A) and represents the continuation on the Albanian territory of the Mesohellenic Trough (Brunn 1956; MHB) from Greece. The ATHB–MHB is the largest molassic-type basin of the Hellenides, reaching a length of approximately 300 km and a width of 30–40 km, out of which 85 kilometres lie on the territory of Albania. Kiliyas et al. (2015) considered the MHB to be a NNW–SSE oriented strike-slip and piggy-back basin, which evolved from the middle Eocene to the Quaternary as a succession of overlapping basins (Ferrière et al. 1998). Similar findings regarding the ATHB infill mention various sedimentary cycles deposited in the interval between the middle Eocene and Quaternary. The biostratigraphy of the Albanian–Thessalian Basin was previously established based on the molluscs and foraminifera content (Adrianova et al. 1961; Pashko 1965, 2018; Pashko et al. 1973). The calcareous nannofossils from the area were studied by Kumati et al. (1997), who also reported data on palynomorphs and foraminifera.

The aims of this study are as follows: 1 – to obtain new data on the calcareous nannofossils content of the Lower Miocene succession of the area of Mount Morava (Albania);

2 – to compare and to correlate the identified assemblages with local, regional, and global zonations; 3 – to identify the calcareous nannofossil palaeoecological preferences; and 4 – to reconstruct the palaeoenvironmental evolution of the area during the Early Miocene interval.

Geological setting

The ATHB–MHB is a major sedimentary basin located on the tectonic boundary between the external and internal units of the Albanides (Hellenides), namely the Krasta–Pindos units to the west and the Korab–Pelagonian micro block to the east, following the same NW–SE direction of the Hellenides. On the territory of Albania, the basin is considered to be partially developed on the ophiolitic Mirdita unit after the Krasta orogenesis and its overthrusting on the Adria microplate; the latter being represented by Kruja carbonate platform and Ionian zones (Aliaj 2012). Data suggest that the molassic thick pile of sediments containing marine turbidites and siliciclastic shelf deposits (Bourcart 1925; Brunn 1956; Aubouin 1959; Pashko et al. 1973; Zelilidis et al. 1997, 2002; Aliaj 2012; Ferrière et al. 2013) reach a thickness of 4–4.5 km and that the basin was infilled between the upper Lutetian (ca. 45 Ma) and middle Miocene (ca. 15 Ma). The stratigraphical framework in the ATHB, in comparison to the MHB, demonstrates a higher order subdivision into formations based on the lithology and supported by changes in macrofaunal content (molluscs

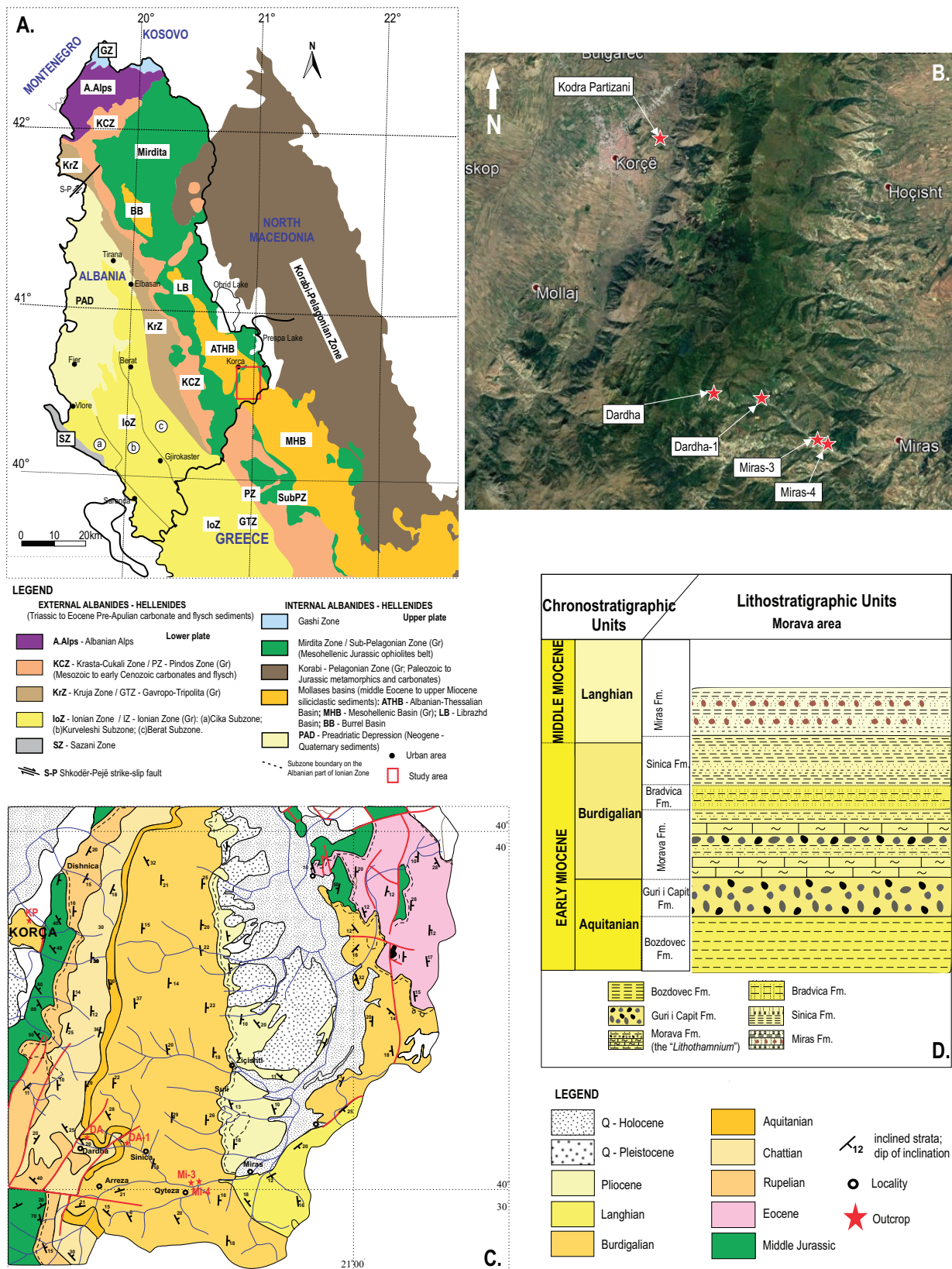


Fig. 1. Simplified map showing the location of the ATHB–MHB on the territories of Albania and Greece (A), and of the studied area within the ATHB (sketch modified after Robertson & Mountrakis 2006 and Aliaj 2012); satellite image (Google Earth) of the area of Mount Morava (B); location of the investigated transects on geological map (simplified after Xhomo et al. 2002; map 1:200 000) (C); lithostratigraphy of the lower–middle Miocene sequences (Morava area) of the Albanian–Thessalian Basin (after Pashko et al. 1973) (D).

mostly and foraminifera; Pashko et al. 1973; Pashko 2018). Currently, there is no correlation between the sedimentary sequences from Albania and Greece; the existing research being restricted to each country according to the specific requirements.

The investigated area is located in the southern part of the Albanian–Thessalian Basin, in the neighborhood of Mount Morava (ATHB, Albania; Fig. 1B,C). The Lower Miocene sediments are well-developed in this area (Fig. 1D). The basal Burdigalian is recognized by the presence of limestones with *Lithothamnium* of the Morava Fm. (Bourcart 1922; Pashko et al. 1973; Xhomo et al. 2002; Fig. 1D), which gradually overlies the Aquitanian Guri i Capit Formation, while to the south (in Dardha section), it covers the Dardha “Schlier”. The limestone is associated with medium-grained sandstones, conglomerates lenses and grey-bluish marlstones with molluscs, echinoids, fossil plants, and large foraminifera (*Lepidocyclina elephantina*) (Pashko 2018).

The overlying sediments belong to the Bradvica Formation (Fig. 1D) and consist of massive fine- to medium-grained sandstones, fossiliferous grainstones, siltstones, and marlstones (Pashko et al. 1973; Pashko 2018). In the upper part, the conglomerates are more frequent, while the topmost is mainly silty and fine-grained sandstone, with plant remains, rare and poorly-preserved molluscs, as well as abundant foraminifera.

The Bradvica Formation is gradually overlain by the sediments of the Sinica Formation (Fig. 1D), which was initially considered Burdigalian in age (Pashko et al. 1973). It represents a thick sedimentary sequence composed of grey-bluish marlstones, siltstones and fine-grained sandstones with fossils (*Flabellipecten* cf. *burdigaliensis*), followed by medium-grained massive sandstones, sandy limestones with pectinids, and *Lithothamnium*. The Burdigalian age of the above-mentioned formations (Morava and Bradvica) was assigned based on the foraminifera and molluscs. The Burdigalian planktonic foraminifera *Globigerinoides trilobus* Zone was recognized by Pashko et al. (1973), while Kumati et al. (1997) included the formations into the *Globigerinoides trilobus*–*Catapsydrax dissimilis* Zone, *Globorotalia scitula*–*Globorotalia acrostoma* Zone, and the *Globigerinoides bisphaericus* Zone. The benthonic foraminifera assemblages can be included into the *Miogypsina globulina* Zone (Pashko et al. 1973). Based on calcareous nannofossils, Kumati et al. (1997) assigned parts of

the sediments to the *Helicosphaera scissura* and *Helicosphaera ampliapertura* Biozones (Vathi 1993). The abundant planktonic foraminifera from the base of the Sinica Formation were attributed to the *Globigerinoides trilobus* Zone (late Burdigalian; Pashko et al. 1973), while the presence of *Globorotalia praemenardi*, *G. mayeri*, and *Globoquadrina dehiscentes* in association with *Praeorbulina glomerosa* and *Praeorbulina glomerosa curva* suggest the *Praeorbulina* s.l. Subzone (early Langhian) for the upper part of the succession. The benthonic foraminifera association was considered Burdigalian in age (Pashko et al. 1973). The mollusc assemblages from ATHB as indicated by Pashko et al. (1973) display high similarity to those of the Pre-Adriatic Basin, with some species indicating the Burdigalian and other suggesting a Langhian age (Pashko 1965, 2018).

Material and methods

Lithostratigraphy of the investigated transects

Five transects (Table 1) were sampled and a total of 207 samples were investigated for the study of the calcareous nannofossil content, out of which 15 were barren.

Dardha-1 Transect (Da-1)

Samples from Dardha-1 section (Fig. 2A) were collected from small outcrops at different locations on the left side of the road, which connects the villages of Dardha and Sinica. A total of 26 samples were collected from marlstone and siltstone deposits of this section.

Dardha Transect (Da)

The Dardha transect (Fig. 2B) represents a sedimentary succession of more than 110 m, composed mainly of blue-greyish marlstones to dark grey siltstones, with beige fine-grained thin to medium-bedded sandstone layers of 3–25 cm in thickness. A total of 97 samples were collected at intervals of approximately 1 m. In the upper part of the succession, the sandstone layers become more frequent. This succession was included in the Dardha “Schlier” of upper Aquitanian age according to Bourcart (1922) and Pashko et al. (1973).

Table 1: Summary of the transects with their GPS position and the number of samples collected. The age is based on the results of this study.

| Transects | Details | Latitude | Longitude | Age | Samples |
|----------------------|----------|--------------|-------------------------------------|--------------------|---------|
| Dardha (Da) | | 40°31'14.04" | 20°49'54.16" | early Burdigalian | 97 |
| Dardha 1 (Da-1) | | 40°31'11" | 20°51'23" 20°51'24" 20°51'26" | early Burdigalian | 26 |
| Kodra Partizani (KP) | | 40°37'05.21" | 20°47'54.36" | early Burdigalian | 18 |
| Miras-3 (Mi-3) | Detail A | 40°30'10.3" | 20°53'31.7" | middle Burdigalian | 36 |
| | Detail B | 40°30'10.1" | 20°53'30.2" | middle Burdigalian | 6 |
| Miras-4 (Mi-4) | | 40°30'8.1" | 20°53'37.1" | middle Burdigalian | 24 |

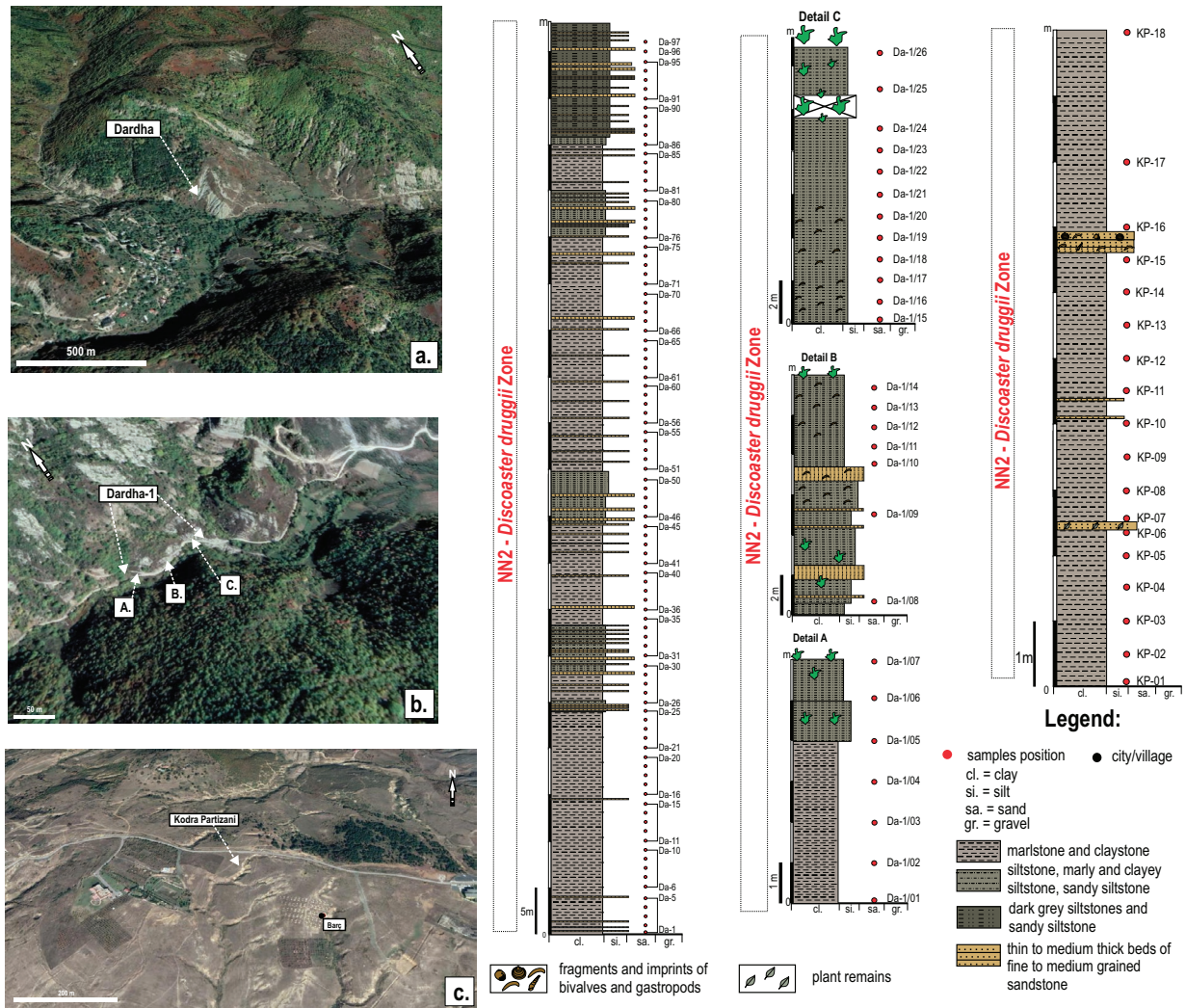


Fig. 2. Transects belonging to Zone NN2; location on satellite map and lithology of Dardha transect (a), Dardha-1 transect (b), and the Kodra Partizani transect (c).

Kodra Partizani Transect (KP)

Kodra Partizani (Fig. 2C) is a small transect comprising of a succession of grey-beige, finely-laminated marlstones with fine-grained sandstones intercalations with plant remains. In the upper part of the succession, a 0.40–0.60 m thick layer of calcareous sandstones with mollusca fauna occurs. A total of 18 samples were collected at intervals ranging from 0.30 m to 1m.

Miras-3 Transect (Mi-3)

Miras-3 transect (Fig. 3A, B) is located on the right side of the road connecting the villages of Miras and Sinica and is composed of light grey-blueish marlstones belonging to the Sinica Formation (Pashko et al. 1973). A total of 42 samples were investigated from this transect. Bivalve fragments and imprints are visible all along the sedimentary succession.

Miras-4 Transect (Mi-4)

Miras-4 transect (Fig. 3A, C) is located on the same road, at about 100 m above Miras-3, right in front of the bridge leading to the village of Qyteza. A total of 24 samples were collected and investigated from this transect. The succession is composed of light grey-blueish marlstones and siltstones with bivalve fragments and imprints from place to place. The blocks around this transect yield visible, badly-preserved bivalves, and thus no collection was possible.

Investigation techniques

The smear slides were prepared according to the standard techniques described by Bown & Young (1998) and were examined under polarized light in crossed-polars (XPL) and bright field (BF) with an Optika light microscope (LM) at 1000× magnification.

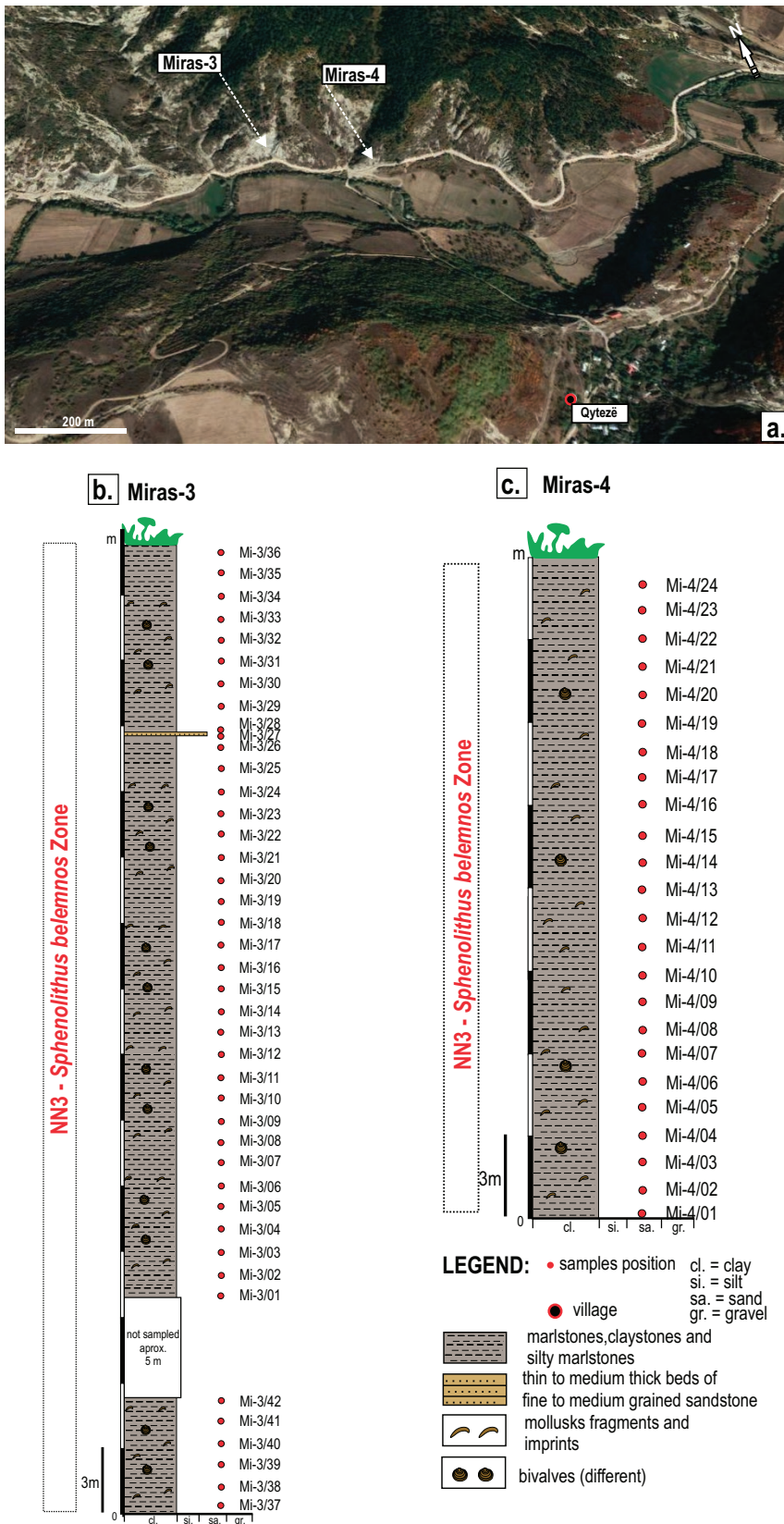


Fig. 3. Transects belonging to Zone NN3; location on satellite map (a); lithology of Miras-3 transect (b) and lithology of Miras-4 transect (c).

Quantitative data were collected under microscope by counting at least 300 specimens per sample (Bown & Young 1998), while at least 100 specimens were counted from the less-abundant samples. For samples with very poor content, only qualitative observations were carried out (presence/absence data). Extended counting was tentatively applied for selected marker species vs. a prefixed number of taxonomically related forms (species of helicoliths relative to 30 helicoliths, and sphenoliths relative to 30 to 100 sphenoliths; adapted after Backman & Shackleton 1983; Rio et al. 1990; Fornaciari & Rio 1996). Additionally, 300–500 FOV (Field of View) were investigated for rarer taxa and added to the species table. The calcareous nannofossil preservation was assessed as moderate to good (Roth & Thierstein 1972) as follows: G=good (all specimens can be identified at species level, but <5 % of the specimens are affected by dissolution, fragmentation and overgrowth) and M=moderate (when 25 % of the specimens cannot be identified at species level due to dissolution and overgrowth).

Due to the fact that the *Reticulofenestra* genus is the most abundant in the investigated sections, a special discussion on the size-based identification applied within this study is described as follows: *Reticulofenestra minuta* (very small placoliths <3 μm; two morphotypes are acknowledged herein, one with an opened central area and one which is nearly closed); *R. haqii* (small placoliths with size 3–5 μm and a central opening); *R. gelida* (medium to large specimens, >5–10 μm; with a nearly closed central area by a pore/long pore/slit); *R. daviesii* (medium sized placoliths, size 5–8 μm and central-area with a plug surrounded by a ring of pores); *R. pseudoumbilicus* (medium to large sized placoliths, >5–10 μm; elliptical with central opening; two sizes were separated 5–7 μm and >7 μm). All the specimens with a closed central area and a size of 3–5 μm were included in *Reticulofenestra* gr. 3–5 μm. They were assigned to two species, namely *R. antarctica* sensu Wade & Bown (2006)

(small placoliths with a small pore visible in the centre of the coccolith) and *R. producta* (small placoliths with closed/nearly closed central area).

The biostratigraphy follows the concepts of Martini (1971), Okada & Bukry (1980) and the zonations from the Mediterranean area (Vathi 1989, 1993; Fornaciari & Rio 1996; Di Stefano et al. 2008), with additional correlation to the open-ocean scheme of Backman et al. (2012).

The palaeoecological interpretation is based on the abundance of dominant species and their preferences in regards to various palaeoenvironmental parameters, such as: temperature, salinity, upwelling, wind-driven mixing and eutrophy. The species counts and percentages were treated using the Microsoft Excel application. The PAST program (Hammer et al. 2001) was used for statistics. The Clustered Bar was used to plot the fluctuations of the average amount of the most abundant species, along with the time interval. The average amount was calculated only from positive samples, while the barren samples and those not counted were excluded. Histograms on the number of species in each sample together with their frequency were plotted in the Past program. Multivariate Hierarchical Clustering using Ward's method and Principal Component Analysis were applied for statistical interpretation for each identified nannofossil zone.

Results

Calcareous nannofossil assemblage composition

A total of 44 in situ species were identified within the investigated sediments. This study records typical Early to Middle Miocene calcareous nannofossils species (Fig. 4; [Electronic supplement – Appendix 1](#)), the most common being the reticulofenestrids (*Cyclicargolithus floridanus*, *Reticulofenestra antarctica*, *R. gelida*, *R. haqii*, *R. minuta*, *R. producta*, *R. pseudoumbilicus*), *Coccolithus pelagicus*, *Sphenolithus moriformis*, *S. disbelemnus*, *S. pseudoheteromorphus*, *S. belemnus*, *Helicosphaera ampliapertura*, *H. carteri*, *H. mediterranea* and *H. walbersdorfensis*). The reworked assemblage exhibits a very low number of species with extremely low abundance.

The transects assigned to the middle–upper NN2 – *Discoaster druggii* Zone of early Burdigalian age exhibit moderately to slightly higher diverse assemblages (Fig. 5A). The lowest number (22 species) was found in Dardha-1, followed by 24 species in Kodra Partizani and the Dardha outcrop with 31 autochthonous taxa. The highest number of reworked taxa, both Paleogene and Mesozoic, was counted in the Dardha transect (25 Paleogene and 10 Mesozoic taxa). The reworked material is rather rare in the other two outcrops.

The sections assigned to NN3 – *Sphenolithus belemnus* Zone contain a higher proportion of in-situ association (Fig. 5A), with a total of 34 species in Miras-3 and 31 species in the Miras-4 transect. The Paleogene reworked material

doesn't exceed 10 species in Miras-3, or 9 in Miras-4, while the Mesozoic taxa are very rare.

In general, the number of species in individual samples can be described as moderate (Fig. 5B).

Calcareous nannofossil abundance and statistics

The most abundant species, based on which palaeoecological interpretation and statistical analysis were performed, are: *Reticulofenestra minuta*, *Cyclicargolithus floridanus*, *Coccolithus pelagicus*, *Reticulofenestra* gr. 3–5 μm (*R. antarctica* and *R. producta*), *Reticulofenestra haqii*, *Reticulofenestra pseudoumbilicus*, *Reticulofenestra gelida*, *Sphenolithus* spp. and *Helicosphaera* spp. (Fig. 6, [Electronic supplement – Appendix 2](#)). *Cyclicargolithus floridanus* is continuously distributed along the sampled outcrops, reaching the highest percentages in the Dardha transect (NN2 Zone), while starting from the Kodra Partizani transect upward into the NN3 Zone a drastic decrease in its abundance has been noticed. *Reticulofenestra minuta* is the most abundant within the investigated material, having a continuous distribution in all transects and reaching the highest percentage in Miras-3. Another long-ranging taxon is *Coccolithus pelagicus*, which reaches distinct peaks in Kodra Partizani and the Miras-4 outcrops.

The small reticulofenestrids with a closed central area assigned to *Reticulofenestra* gr. 3–5 μm display higher proportions in NN2 biozone (Dardha and Dardha-1), whereas a drastic decrease was noticed in the rest of the transects. The small reticulofenestrids with sizes ranging from 3 to 5 μm and with an open central assigned to *Reticulofenestra haqii* exhibit relatively low average amounts, except for the Kodra Partizani transect.

The medium to large sized reticulofenestrids (>5 μm) with an open central area were assigned to *Reticulofenestra pseudoumbilicus* and display a low abundance in Dardha and Dardha-1, with slightly increased percentages in the rest of the outcrops.

The species *Reticulofenestra gelida* (closed central area and size >5 μm) displays very low quantities. *Sphenolithus* spp. are present in all transects, however, its composition changes according to the specific time interval. The most abundant species is the long-range *Sphenolithus moriformis* (Seladian – Zanclean). In general, species belonging to this genus do not exceed 1–2 %. The helicoliths show low amounts in the NN2 Zone, with higher amounts being recorded within the NN3 Zone. The *Discoaster* genus is discontinuous and extremely rare, whereas *Umbilicosphaera jafari* exhibits very low percentages in all the transects.

The Hierarchical Clustering according to Ward's method for Zone NN2 indicated four clusters and seven sub-clusters, and the analysis for Zone NN3 separated five clusters and three sub-clusters ([Electronic supplement – Appendix 3](#); Fig. 7). The results have been interpreted according to specific palaeoenvironmental conditions, and are reflected by species abundance, fluctuations, and palaeoecology.

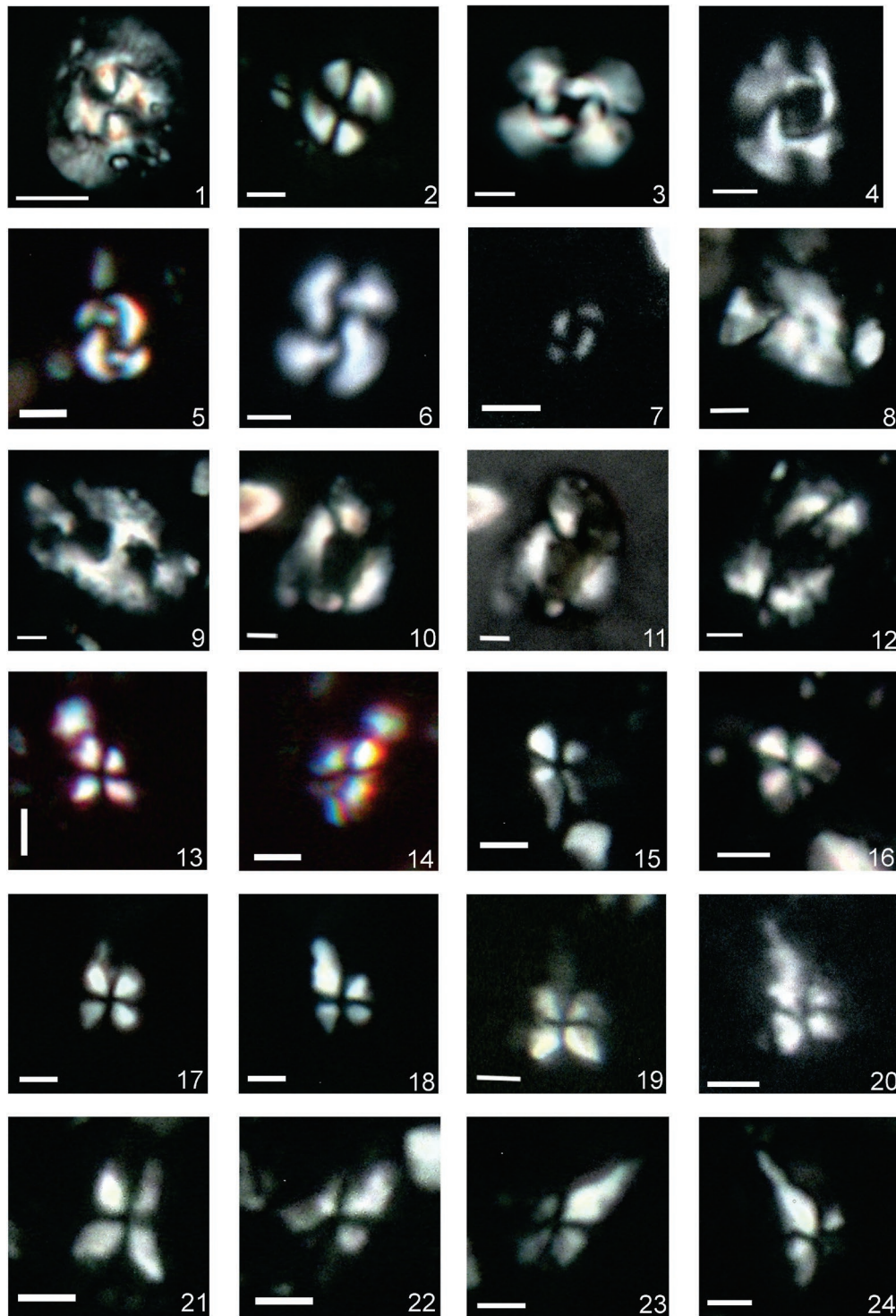


Fig. 4. Calcareous nannofossils (fig. 1 has a scale of 5 μm ; the rest have a scale of 2 μm): **1.** *Coccolithus miopelagicus* Bukry, 1971 (sample Da-13); **2.** *Coccolithus pelagicus* (Wallich, 1877) Schiller, 1930 (sample Da-48); **3.** *Cyclicargolithus floridanus* (Roth and Hay, in Hay *et al.*, 1967) Bukry, 1971 (sample Da-48); **4.** *Reticulofenestra pseudoumbilicus* (Gartner, 1967) Gartner, 1969 (sample Da-39); **5.** *Reticulofenestra haqii* Backman, 1978 (sample KP-09); **6.** *Reticulofenestra gelida* (Geitzenauer, 1972) Backman, 1978 (sample Mi-4/14); **7.** *Reticulofenestra minuta* Roth, 1970 (sample Mi-4/01); **8.** *Helicosphaera carteri* (Wallich, 1877) Kamptner, 1954 (sample Da-1/13); **9.** *Helicosphaera mediterranea* Muller, 1981 (sample Mi-4/12); **10, 11.** *Helicosphaera ampliapertura* Bramlette and Wilcoxon, 1967 (sample Mi-3/09); **12.** *Helicosphaera ampliapertura* Bramlette and Wilcoxon, 1967 (sample Mi-3/09); **13, 14.** *Sphenolithus disbelemnus* Fornaciari and Rio, 1996 (sample KP-18); **15.** *Sphenolithus disbelemnus* Fornaciari and Rio, 1996 (sample Mi-3/35); **16.** *Sphenolithus disbelemnus* Fornaciari and Rio, 1996 (sample Mi-3/04); **17, 18.** *Sphenolithus pseudoheteromorphus* Fornaciari and Agnini, 2009 (sample Da-79); **19, 20.** *Sphenolithus pseudoheteromorphus* Fornaciari and Agnini, 2009 (sample Mi-4/10); **21, 22.** *Sphenolithus belemnus* Bramlette and Wilcoxon, 1967 (sample Mi-3/16); **23.** *Sphenolithus belemnus* Bramlette and Wilcoxon, 1967 (sample Mi-4/16); **24.** *Sphenolithus belemnus* Bramlette and Wilcoxon, 1967 (sample Mi-4/20).

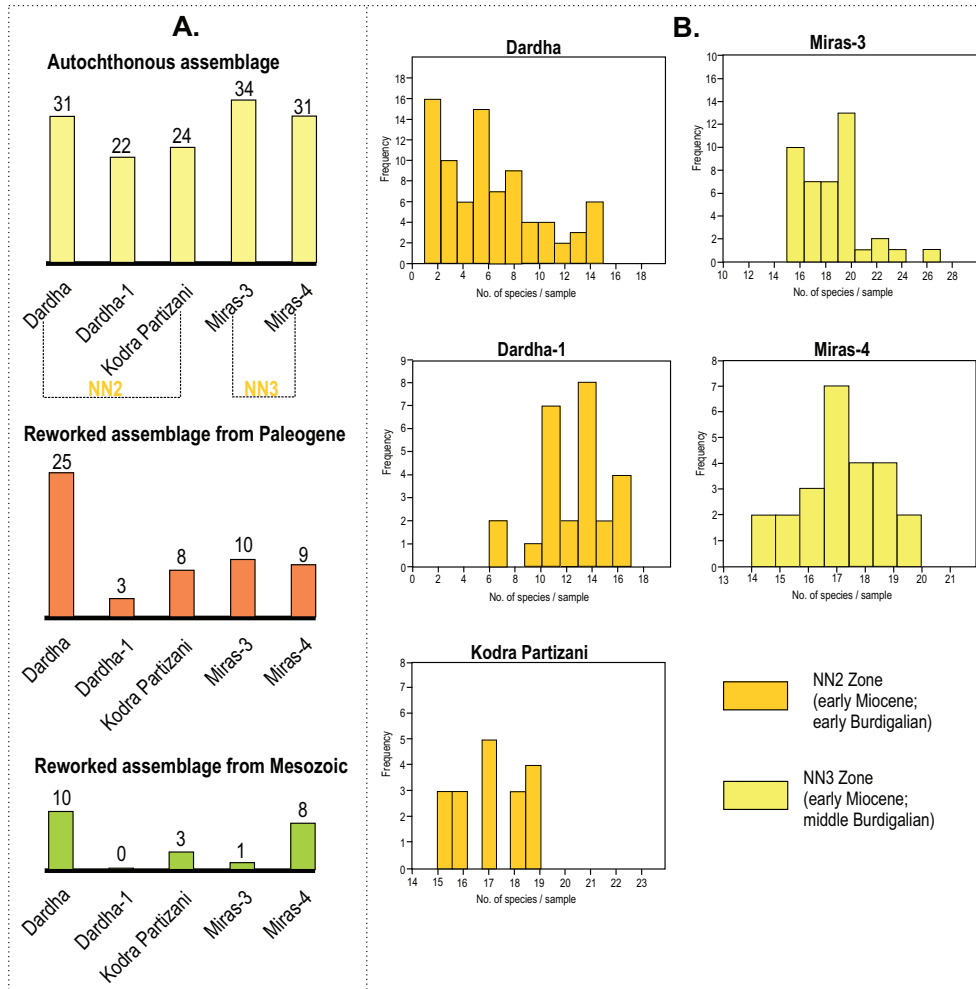


Fig. 5. Diversity plots of autochthonous and reworked calcareous nannofossil assemblages from each investigated transect (A); histograms plotting the number of species in each sample together with their frequency (B).

Discussions and interpretation

Early Miocene calcareous nannofossil biostratigraphy

The Early Miocene biostratigraphy is mainly based on the occurrence of species belonging to the *Sphenolithus* and *Helicosphaera* genus species (Fig. 8).

Several short-ranging marker species were identified; among them, the presence of *Helicosphaera ampliaperta* allowed for the attribution of the three oldest investigated transects to the middle-upper part of NN2 Zone/CN1c Subzone, above the FO of this species. This taxon was documented in rare percentages in the Dardha, Dardha-1, and the Kodra Partizani transects. Some older studies (Müller 1978; Theodoridis 1984; Fornaciari & Rio 1996) consider the FO of *Helicosphaera ampliaperta* to be one of the most reliable bioevents in the Mediterranean area dividing the long ranging NN2 biozone and approximating the Aquitanian/Burdigalian boundary (20.43 Ma; Gradstein et al. 2012). New data from the Contessa section (Italy; Fabbrini et al. 2019a) report for the first time the basal part of the *H. ampliaperta* biohorizon in

the Mediterranean area, using the constraints reported in Kasbohm et al. (2021), which place this bioevent at 20.35 Ma.

In the Mediterranean area, its FO is placed at the transition of MNN2a – *Helicosphaera carteri* PRZ/MNN2b – *Helicosphaera ampliaperta* PRZ (Fornaciari & Rio 1996). Various studies indicated that the *H. ampliaperta* FO is not a reliable bioevent in oceanic areas (Martini 1971; Backman et al. 2012; Fabbrini et al. 2019b). Vathi (1993) uses the FO of *H. ampliaperta* to define the base of his *Helicosphaera scissura* Zone of Burdigalian age, in the Ionian Zone (Albania). This species is more abundant and continuously present in the sediments assigned to the biozones NN3/CN2 (Miras-3 and Miras-4).

Another short ranging taxon, *Sphenolithus disbelemnus*, is not abundant, but is present in all transects assigned to NN2/CN1c and in Miras-3 (NN3/CN2). The FO of this species defines the base of CNM2 (Backman et al. 2012) and is calibrated at 22.48 Ma. Recent data indicate a slightly older age for this bioevent, namely at 22.56 Ma at Hole 1406A (NW Atlantic Ocean; Fabbrini et al. 2019b).

In the upper part of the NN2/CN1c biozones, another useful species for biostratigraphy is *Sphenolithus pseudohetero-*

morphus (Fornaciari & Agnini 2009). This is a rare species and is found in some samples from two transects (Dardha and Kodra Partizani), which were assigned to the upper NN2/CN1c biozones and also in the transects assigned to zones NN3/CN2. This taxon was mentioned and described in several sites from the western equatorial Indian Ocean (ODP Leg 115; Fornaciari et al. 1990; Rio et al. 1990), western equatorial Pacific Ocean (ODP Leg 130; Fornaciari et al. 1993) and western equatorial Atlantic Ocean (ODP Leg 154). The range of this taxon is said to overlap with that of *S. belemnus* (Fornaciari & Agnini 2009), being recorded also within NN3/CN2 Zones. At Hole U1406A (Fabbrini et al. 2019b), this species is present in a short interval within the range of biozone CNM4 (Backman et al. 2012).

At the base of Zone CN2, within the lower part of Zone NN3, another important marker is *Sphenolithus belemnus*, its FO being calibrated at 19.01 Ma in oceanic areas (Backman et al. 2012) and at 19.12 Ma in the Mediterranean (Foresi et al. 2014). These biozones correspond more or less to the Mediterranean biozones MNN3a – *Sphenolithus belemnus* TRZ, MNN3b – *Sphenolithus belemnus/Sphenolithus heteromorphus* IZ (Fornaciari & Rio 1996; Di Stefano et al. 2008) and *Sphenolithus belemnus* BZ (CNM5; Backman et al. 2012). The FO of *Sphenolithus belemnus* marks the base of the CN2/MNN3a/CNM5 biozones (19.01 Ma; Backman et al. 2012) and its LO is used to define the top of zones NN3/CN2 (Martini 1971; Bukry 1973a; Okada & Bukry 1980; Maiorano & Monechi 1997). The LCO of *S. belemnus* at 18.43 Ma is used to define the MNN3a/MNN3b boundary (Fornaciari & Rio 1996). New calibrated data for this bioevent indicate its LCO at 17.96 Ma in oceanic sediments (Backman et al. 2012; Fabbrini et al. 2019b) and at 18.01 Ma in the Mediterranean area (Foresi et al. 2014). This bioevent was identified by Fornaciari et al. (1990, 1993) in low-latitude sections and by Olafsson (1991) in mid-latitude areas, using quantitative investigations. Fornaciari & Rio (1996) suggest that in the Mediterranean, the FO and total distribution of *S. belemnus* are well-documented in foredeep settings, whereas its absence is more obvious in marginal settings. The FO and FCO of *S. belemnus* represent reliable bioevents in the Mediterranean area (Foresi et al. 2014). The species *Sphenolithus belemnus* is more or less continuously distributed along

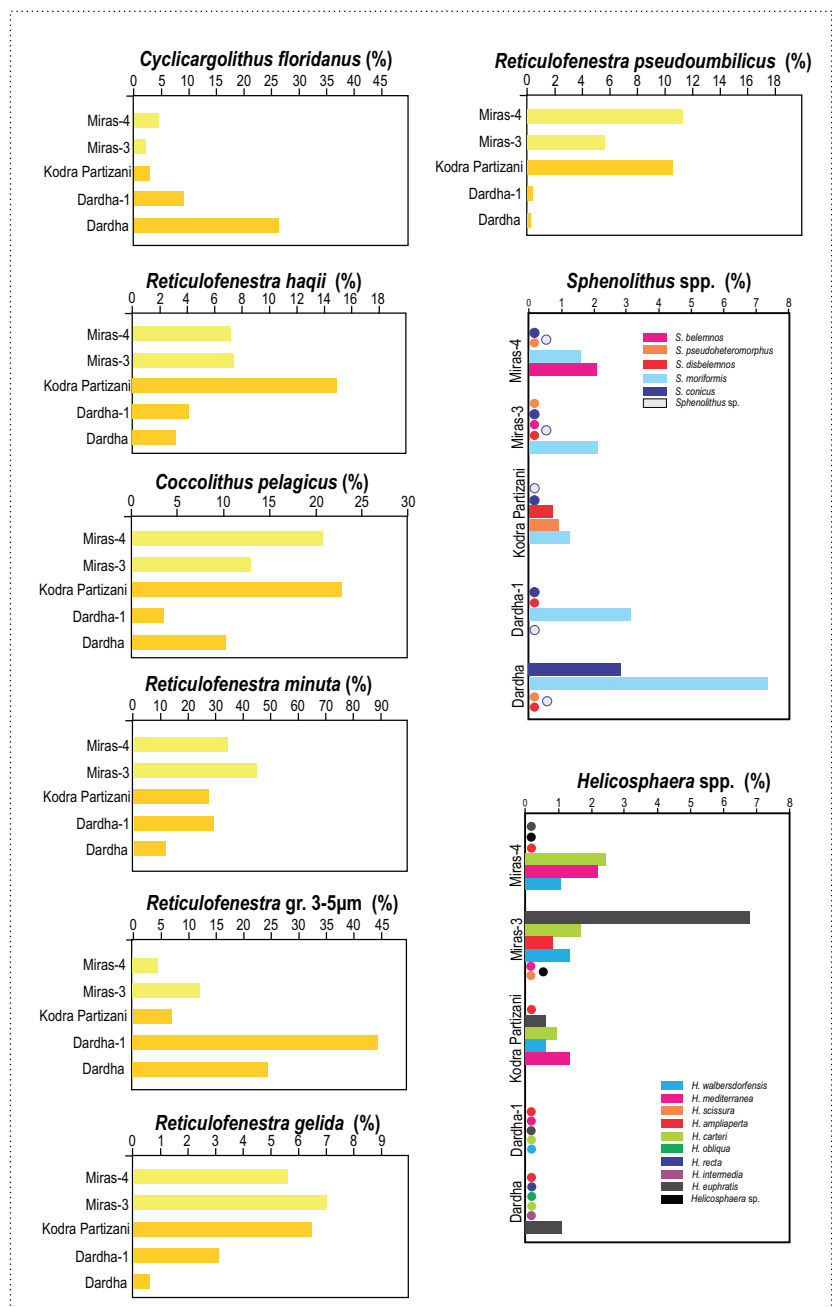


Fig. 6. Abundance plots per outcrop (average amounts) of selected species for palaeoecological interpretation.

Miras-3 and Miras-4 transects, with increased abundances in the latter, which is assumed to be younger in age.

Another useful helicolith taxon for the lower Miocene biostratigraphy is *Helicosphaera mediterranea*, whose FO is within zones NN2/CN1c (Müller 1981), above the FO of *H. ampliapertura*. It was first recorded from sediments of DSDP Leg 42A (Hole 372) in the Mediterranean area. It occurs in very low amounts in the middle – upper parts of zones NN2/CN1c (Dardha and Dardha-1) as well as in the Miras-3 transect (zones NN3/CN2), being more abundant in the Kodra

Partizani and Miras-4 transects. A well-known early–middle Miocene helicolith is *Helicosphaera walbersdorfensis*, ranging from the base of Zone NN4 (Burdigalian) to Zone NN8 (Tortonian stage; Boesiger et al. 2017). The taxon *H. walbersdorfensis* along with the variants placed under this description (*H. californiana*, *H. muelleriae*, *H. minuta*) are recorded from deep marine sections from California Continental Border (Bukry 1981), from the Papua New Guinea regions of Solomon Island (Varol 1989) and Cebu Philippine (Müller 1981). Within the investigated transects, the smaller atypical morphotypes with a shorter wing of *Helicosphaera walbersdorfensis*, similar to its variant *Helicosphaera californiana*, are present from the sediments assigned to the middle–upper zones NN2/CN1c Zones (Dardha-1 and Kodra

Partizani) and zones NN3/CN2 (Miras-3 and Miras-4), which are slightly older than the above reported FO. This older age record questions the previously established FO and the distribution of this taxon. The possibility of an erroneous interpretation and misidentification of *H. walbersdorfensis* with *Helicosphaera vedderi* (NN2–NN6; Bukry 1981; Young 1998; Boesiger et al. 2017) is excluded within this study due to the clear morphology and distinction between the aspect of the two species.

Based on the above-mentioned marker species, the transects Dardha, Dardha-1, and Kodra Partizani were assigned to the middle–upper part of the long-ranging *Discoaster druggii* Zone (NN2; Martini 1971) of early Miocene age (early Burdigalian) and to the *Discoaster druggii* Subzone of Okada

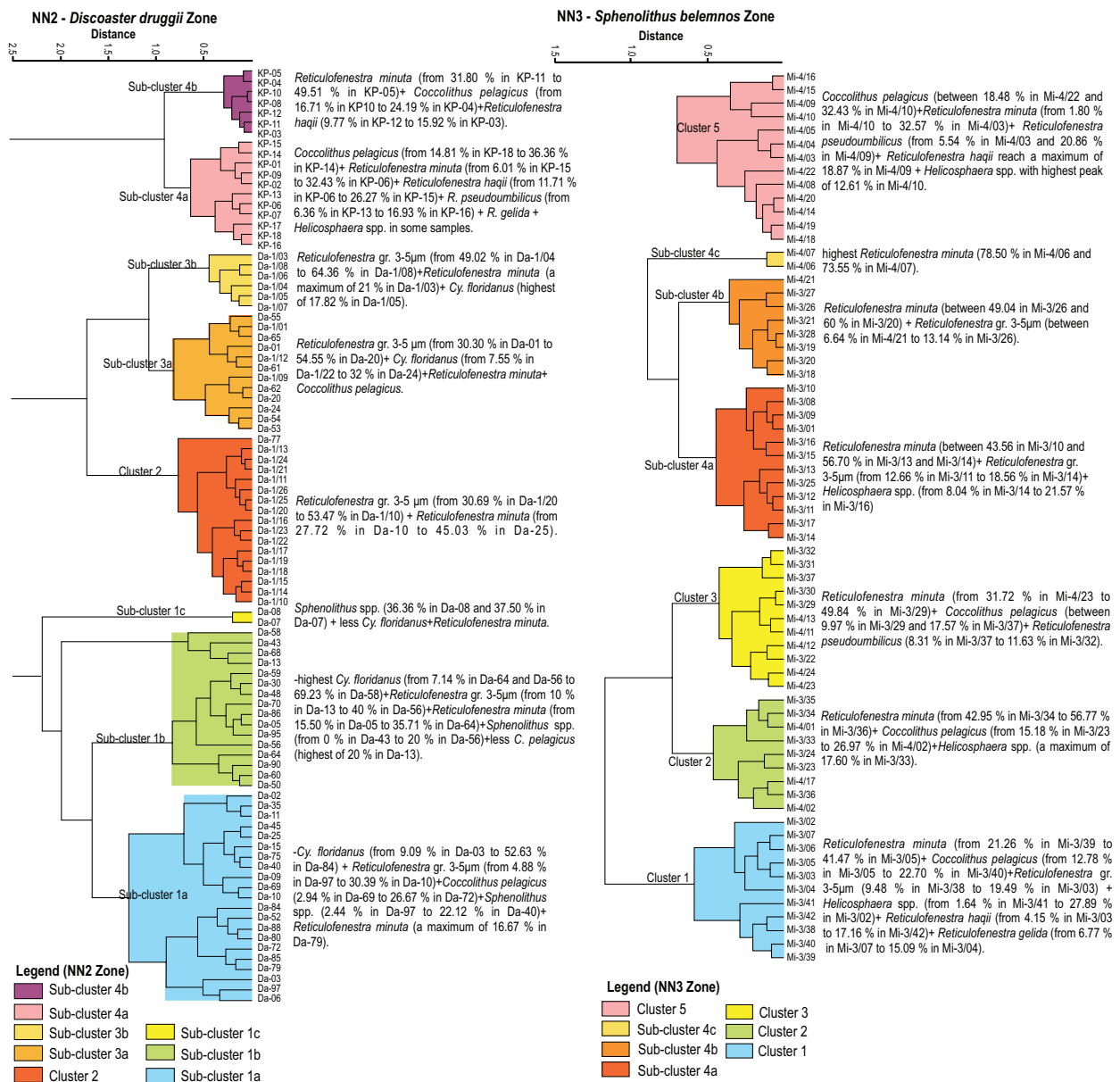


Fig. 7. Hierarchical Clustering according to Ward’s method for the investigated transects.

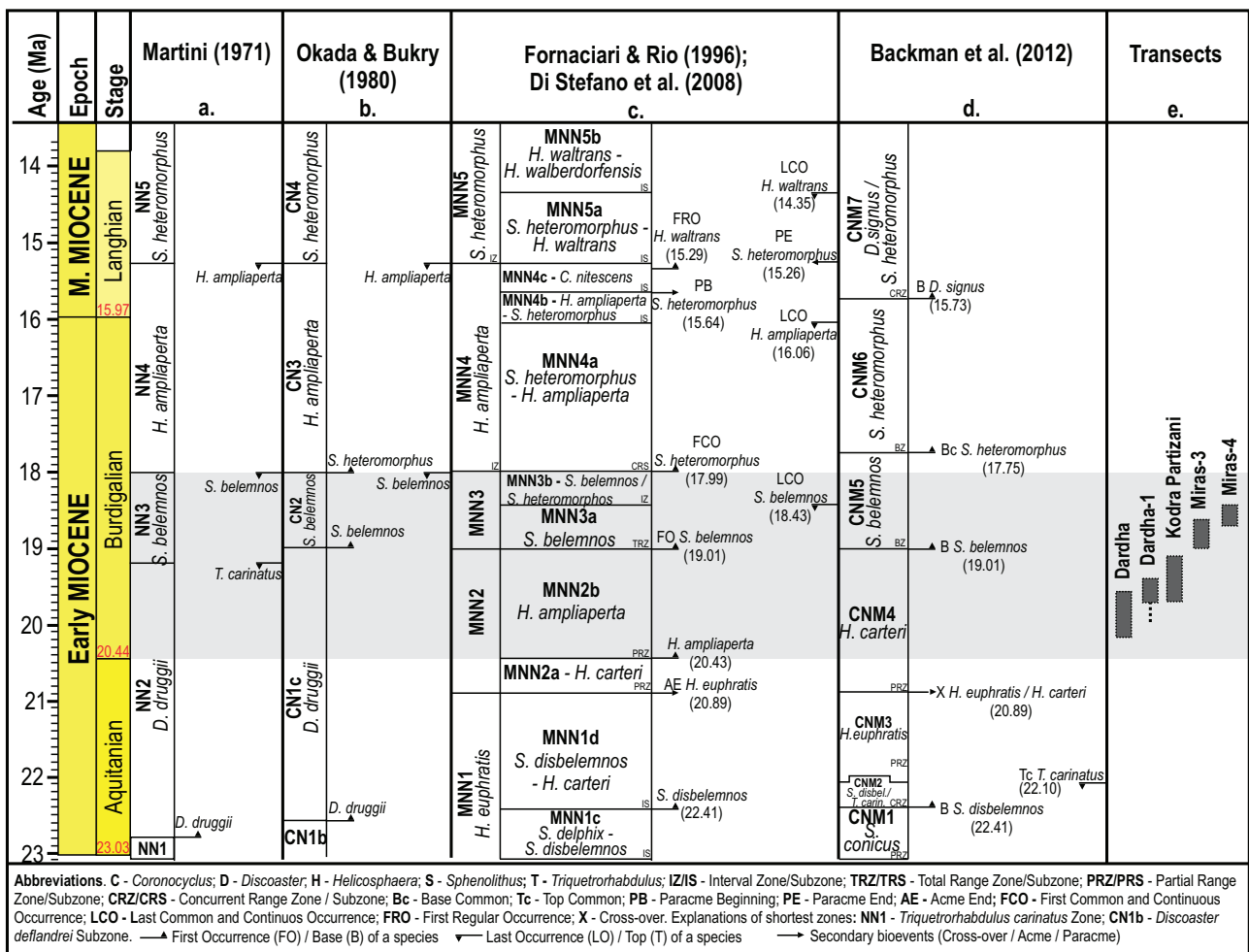


Fig. 8. Early Miocene standard biostratigraphy plotted along GTS2012 (Gradstein et al. 2012); various zonations schemes (a to d); supposed transects location along the investigated interval (e).

& Bukry (Subzone CN1c; 1980). A further subdivision and refinement of the Zone NN2/CN1c is supported by well-dated successive bioevents, which allowed for a clearer age assignment to the *Helicosphaera ampliaperta* PRZ (MNN2b; Fornaciari & Rio 1996) in the Mediterranean, and to the *Helicosphaera carteri* PRZ biozone of Backman et al. (CNM4; 2012). Additionally, these transects fall within the *Helicosphaera scissura* Zone of Vathi (1993) defined by the FO of *H. ampliaperta* to FO of *S. heteromorphus*. According to Vathi (1993), the *Helicosphaera scissura* zone correlates partially to the *Discoaster druggii* and *Sphenolithus belemnus* zones determined by Martini (1971), and with a part of CN1c (*Discoaster druggii* subzone) and CN2 (*Sphenolithus belemnus* zone) from Bukry (1973b, 1975).

Transects Miras-3 and Miras-4 were assigned to the *Sphenolithus belemnus* Zone (NN3; Martini, 1971), which corresponds to the homonymous CN2 Zone of Okada & Bukry (1980) of middle Burdigalian age. According to the Mediterranean zonation of Fornaciari & Rio (1996) and to the scheme for low-middle latitudes of Backman et al. (2012),

the intervals are attributed to the MNN3a and to CNM5 Biozones. The age attribution of the investigated transects was based on the presence of *Helicosphaera ampliaperta* (first occurrence/FO at the Aquitanian/Burdigalian boundary, in the middle part of the NN2/CN1c zones, Martini 1971 and Okada & Bukry 1980; base of MNN2b biozone, Fornaciari & Rio 1996), *Sphenolithus pseudoheteromorphus* (FO in the upper part of NN2/CN1c/MNN2b/CNM4 zones) and *Sphenolithus belemnus* (FO at the base of CN2/MNN3a/CNM5 zones).

Calcareous nannofossil palaeoecology and palaeoenvironment

The late Oligocene to Aquitanian transition (NN1 to lower NN2) corresponds to the opening of a new seaway connection from the Indian Ocean to the Mediterranean and further to the Paratethys (Rögl 1998). Warm water ingress and microfaunal exchange was possible during this time and were associated with the widespread deposition of larger foraminifera all around the Mediterranean and Paratethys. During the early –middle Burdigalian interval (upper NN2 to lower NN3),

a general warm climate and marine conditions prevailed in the Mediterranean area (Rögl 1998; Popov et al. 2004). These conditions are suggested in the ATHB by the characteristics of the calcareous nannofossils assemblages for this time interval.

Palaeoenvironmental reconstruction during Zone NN2

The Dardha transect is characterised by calcareous nannofossil assemblages grouped under cluster 1 and its sub-clusters (Figs. 7 & 9), with short intervals at different levels occupied by cluster 2 and sub-cluster 3a. The clusters are intergrading, have a heterogeneous distribution, and are characterised by more or less similar assemblages with elevated quantity of *Cy. floridanus*, small reticulofenestrads with a closed central area, *C. pelagicus*, and sphenoliths (cluster 1). Cluster 2 shows abundant small reticulofenestrads with a closed central area and *R. minuta*, whereas in sub-cluster 3a, the *Reticulofenestra* gr. 3-5 μm is associated with *Cy. floridanus* and in some samples with *R. minuta* and *C. pelagicus*.

The calcareous nannofossil assemblages belonging to cluster 1 indicate more open-marine conditions and a eutrophic palaeoenvironment, with minor nutrient fluctuations, except for the intervals with higher contents of *C. pelagicus*, which suggest that the short intervals of enrichment are due to moderate, cool-nutrient upwelling (McIntyre & Bé 1967; Okada & McIntyre 1979; Roth 1994; Cachão & Moita 2000; Ćorić &

Rögl 2004) and wind-driven mixing in the upper column (Auer et al. 2014, 2015). Low amounts of *R. minuta* indicate a decrease of fresh water influx, as well as reduced continental influence. The intervals with increased amounts of *Reticulofenestra* gr. 3–5 μm and *R. minuta* (cluster 2 and sub-cluster 3a) indicate a dynamic regime (Gartner et al. 1983) with higher continental material influx and possibly slight fluctuations of the water depth, which had shifted to shallower conditions. Small reticulofenestrads are known to flourish in eutrophic and upwelling conditions (Flores et al. 1997; Wells & Okada 1997; Bollmann et al. 1998; Kameo 2002).

In general, fluctuations from temperate to warmer SSTs are suggested by the alternating intervals with increased amount of sphenoliths (warmer) and with slightly higher *C. pelagicus*, which is a result of increased turbulence and cool-nutrient upwelling. In the Dardha transect, intervals with a very low content of calcareous nannofossil are recorded, which possibly indicate unfavourable palaeoenvironmental conditions.

The sedimentary succession of Dardha-1 transect is characterised by calcareous nannofossil association of cluster 2 and sub-clusters 3a and 3b (Figs. 7, 9). There is a distinct separation of sub-clusters 3a and 3b, which are located in the lower part of the succession (details A and B), as well as cluster 2 (details B and C) which occupies the middle and upper parts of it. The dominating species dictating the assemblages palaeoecology are the small reticulofenestrads with a closed central area (*R. producta* + *R. antarctica*) and *R. minuta*, which are all

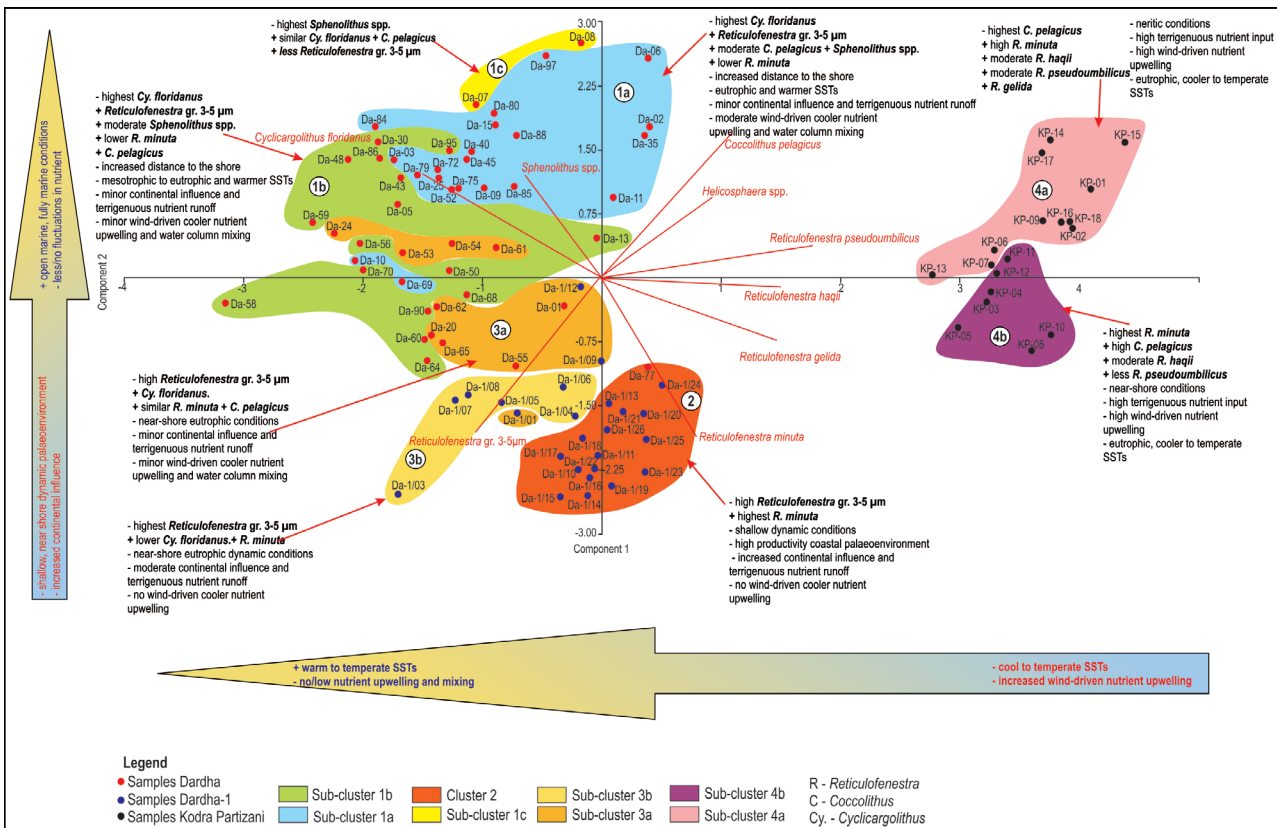


Fig. 9. Palaeoenvironmental conditions during the NN2 – *Discoaster druggii* Zone (early Burdigalian).

known to thrive in eutrophic, normal to brackish waters (Krhovský et al. 1992), indicating once again their preference for high fertility areas under the constant influence from the continent. The base of the profile belongs to sub-clusters 3a (samples Da-1/01) and 3b (samples Da-1/03 to Da-1/07) and contains the highest content of small reticulofenestrads, moderate quantities of *R. minuta*, and *Cy. floridanus* (sub-cluster 3b), and less *R. haqii*. These species indicate a eutrophic near-shore regime, with moderate continental nutrient runoff and fresh water input. The middle and upper parts of the succession (cluster 2) are characterised by a decrease of *Cy. floridanus*, which is replaced by the opportunistic *R. minuta*, thereby indicating an increased continental runoff (Haq 1980; Wade & Bown 2006; Auer et al. 2014; Kallanxhi et al. 2018), increased environmental stress and instability (Wade & Bown 2006; Auer et al. 2014; Holcová 2017; Kallanxhi et al. 2018), and shallow waters. Wet and humid climatic conditions have presumably triggered the increased continental runoff and the highly fertile palaeoenvironment.

The location on the PCA graph of the Kodra Partizani transect (Figs. 7 & 9) is clearly distinguishable from other two sedimentary successions and is associated exclusively to assemblages belonging to cluster 4 (sub-clusters 4a and 4b). The separation of two sub-clusters is based on calcareous nanofossil abundance fluctuations and shifts between *C. pelagicus* (sub-cluster 4a) and *R. minuta* (sub-cluster 4b), with additional *R. haqii*, *R. pseudoumbilicus*, and *R. gelida*.

The lowermost part of the transect (samples KP-01 and KP-02), the middle (samples KP-06, KP-07 and KP-09), and upper intervals (from KP-13 to KP-18) are characterised by assemblages with elevated amounts of *C. pelagicus*, which is described as a cold-water species (Okada & McIntyre 1979) known to thrive under high fertility palaeoenvironment, indicating increased eutrophication (Rahman & Roth 1990; Geisen et al. 2002). The elevated abundance of *C. pelagicus* is connected to cool-nutrient upwelling and wind-driven mixing of the upper water column (Rahman & Roth 1990; Giraudeau et al. 1993; Auer et al. 2014, 2015). Except for *C. pelagicus*, this association also contains moderate amounts of *R. minuta*, *R. haqii*, *R. pseudoumbilicus*, and lower amounts of the cool-water morphotype *R. gelida* (Geitzenauer 1972; Backman 1978), thereby suggesting a near-shore neritic palaeoenvironment, cool to temperate SSTs, with domination of cool rich-nutrient upwelling and wind-driven turbulence, prevailing over the continental influence.

The lower – middle part is occupied by the sub-cluster 4b (samples KP-03 to KP-05, KP-08, KP 10 to KP12) which represents a shift towards a more continental influence as supported by an increased quantity of *R. minuta* as the primary dominating species (Haq 1980; Wade & Bown 2006; Auer et al. 2014; Kallanxhi et al. 2018), followed by *C. pelagicus* and moderate quantities of *R. haqii* and *R. pseudoumbilicus*. In general, they all suggest a eutrophic, near-shore palaeoenvironment with richer continental nutrients availability, moderate mixing, and bottom cool nutrient upwelling. Temperate to cool SSTs are suggested for the Kodra Partizani transect.

Palaeoenvironmental reconstruction during Zone NN3

The base of Miras-3 (interval from Mi-3/38 to Mi-3/42 and from Mi-3/02 to Mi-3/07) is dominated by calcareous nanofossils belonging to cluster 1 (Figs. 7 & 10), and consist of a more diverse assemblage with elevated amounts of *R. minuta*, followed by moderate amounts of *C. pelagicus*, *Reticulofenestra* gr. 3–5 µm, *Helicosphaera* spp., *R. haqii*, and *R. gelida*.

The taxon *R. minuta* is known to prefer shallow, near-shore high productivity palaeoenvironments (Bukry et al. 1971; Haq 1980; Krhovský et al. 1992; Wade & Bown 2006; Auer et al. 2014) and withstand high-fluctuating conditions and environmental stress (Wade & Bown 2006; Auer et al. 2014; Holcová 2017; Kallanxhi et al. 2018), thriving under increased continental material and fresh water runoff. The species *C. pelagicus* is characteristic for middle to high latitudes (Wei & Wise 1990; Cachão & Moita 2000) and is a good tracer for wind-driven coastal upwelling (Rahman & Roth 1990; Giraudeau et al. 1993; Auer et al. 2014, 2015). It is associated with high fertility settings and increased preference for cool nutrients (Okada & McIntyre 1979), and indicates a eutrophic palaeoenvironment (Rahman & Roth 1990; Geisen et al. 2002) with temperate to cool SSTs (Persico & Villa 2004; Villa & Persico 2006; Villa et al. 2008; Ozdínová & Soták 2014).

The presence of elevated amounts of *Helicosphaera* spp., which is known to thrive under shallow hemipelagic conditions (Bukry et al. 1971; Haq & Lipps 1971; Perch-Nielsen 1985; Firth 1989; Krhovský et al. 1992; Nagymarosy 2000; Ziveri et al. 2004) and prefers high-eutrophic, fertile water masses (Flores et al. 2005; Melinte 2005; Narciso et al. 2010) with elevated terrigenous material input (Bukry et al. 1971; Narciso et al. 2010) and cool-nutrient upwelling (Ziveri et al. 1995; Ziveri et al. 2004), demonstrates an unstable, upper-water column regime (Švábenická 2002).

The increased *R. minuta*, *C. pelagicus*, and helicoliths are indicative of a eutrophic, near-shore palaeoenvironment, with moderate continental runoff balanced by wind-driven upwelling and possible changes in SSSs from normal to slightly-lowered, due to increased freshwater input. The presence within assemblages of moderate quantities of small reticulofenestrads with a closed central area (*R. producta* + *R. antarctica*), which are known to flourish under shallow mesotrophic marine conditions with normal salinity (Wade & Bown 2006), is more an expression of nutrient availability, since these species are able to withstand high-eutrophic, normal to brackish water masses (Krhovský et al. 1992). The species *R. haqii* is considered a warm oligotrophic taxon (Holcová et al. 2015), but when associated with *R. minuta* indicates opportunistic behaviour and a preference for high eutrophic conditions. The taxon *R. gelida* is a cold-water morphotype of *R. pseudoumbilicus* typical for sub-Antarctic areas (Geitzenauer 1972; Backman 1978) and its presence in moderate amounts might suggest a favourable, cooler environment with temperate to slightly cooler SSTs.

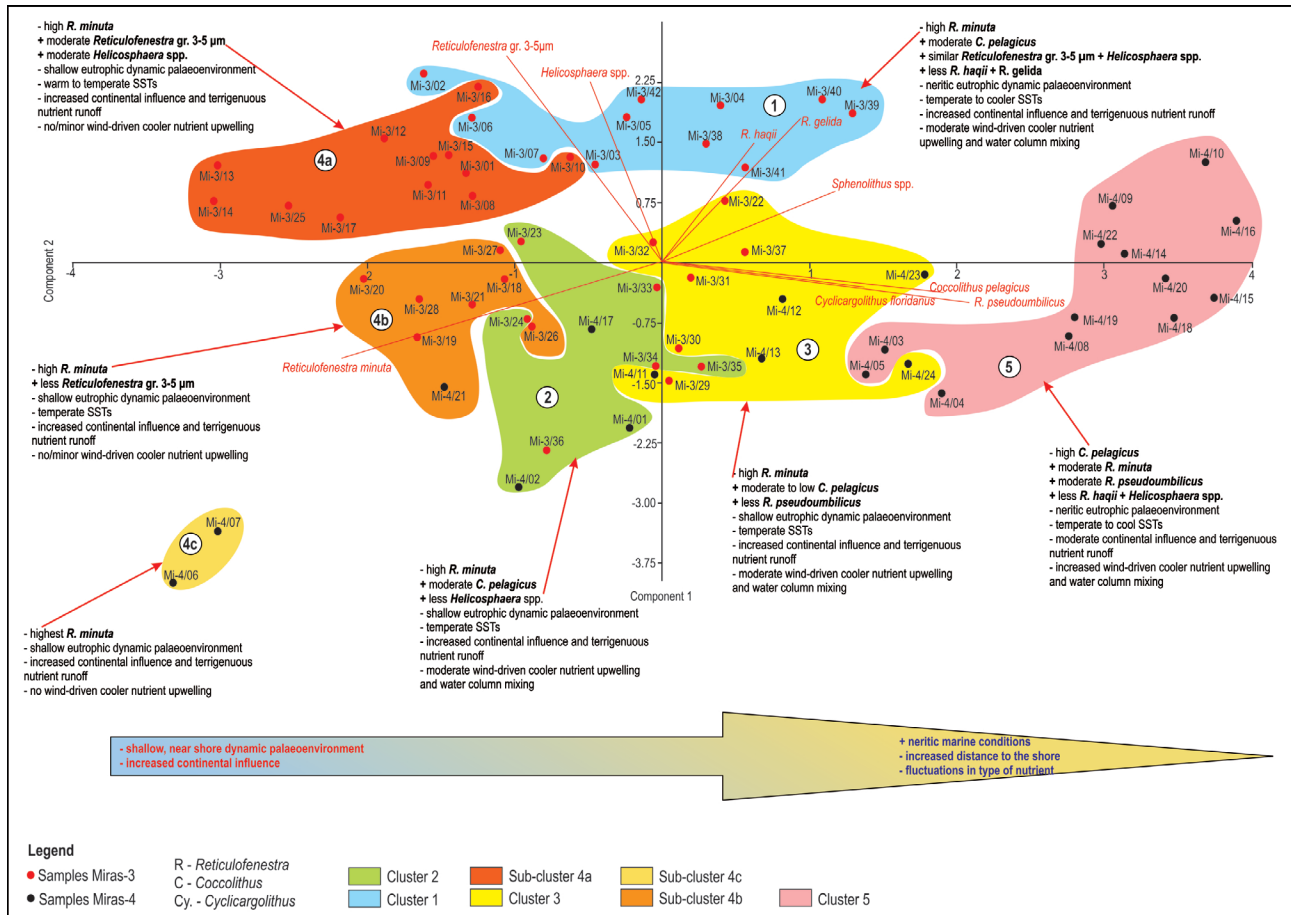


Fig. 10. Palaeoenvironmental conditions during the NN3 – *Sphenolithus belemnos* Zone (middle Burdigalian).

The next part of Miras-3 is characterised by a stable interval occupied by sub-cluster 4a (samples Mi-3/08 to Mi-3/17 and Mi-3/25) in the middle part of the transect, followed in the middle-upper part by sub-cluster 4b (interval from Mi-3/18 to Mi-3/21 and from Mi-3/26 to Mi-3/28), the latter separated by a very short interval belonging to clusters 2 and 3. The assemblages which characterise the sub-cluster 4a contain elevated amounts of *R. minuta* in combination with moderately small reticulofenestrads with a closed central area (*R. producta* + *R. antarctica*) and *Helicosphaera* spp.

This calcareous nannofossil assemblage indicates a shallow, near-shore eutrophic environment with elevated amounts of *R. minuta*, thereby denoting a strong continental influence and freshwater input. The presence of helicoliths, although known to prefer upwelling areas when found together with *C. pelagicus*, might be connected in this case to an increased proximity to the shore and slightly lowered salinities due to freshwater input. The decrease of *C. pelagicus* within cluster 4, combined with elevated amounts of *R. minuta* and small reticulofenestrads with a closed central area, might indicate a reduction of water turbulence and of cool-nutrient upwelling, less wind influence, or a shift in current direction (Auer et al. 2014). Sub-cluster 4b contains very high quantities of *R. minuta* with low to moderate amounts of small

reticulofenestrads with a closed central area, indicating a shallow near-shore highly eutrophic palaeoenvironment, with increased terrigenous influx and freshwater runoff, probably due to prolonged seasonality. The presence of *Reticulofenestra* gr. 3–5 μm in association with *R. minuta*, suggests a great adaptability of these species to an unstable palaeoenvironment and a preference for near-shore eutrophic conditions.

The upper part of the Miras-3 transect is characterised by calcareous nannofossil assemblages belonging to cluster 3 (sample Mi-3/22 and interval from Mi-3/29 to Mi-3/32), which is dominated by increased amounts of *R. minuta*, moderate amounts of *C. pelagicus*, and *R. pseudumbilicus*. The topmost part belongs solely to cluster 2 (from Mi-3/33 to Mi-3/36) and is characterised by high quantities of *R. minuta*, followed by increased amounts of *C. pelagicus* and moderate quantities of helicoliths species. Both clusters indicate near-shore, high-productivity palaeoenvironments, with increased continental runoff as indicated by the dominating *R. minuta*, with moderate to increased wind-driven upwelling and mixing as suggested by elevated quantities of *C. pelagicus*. Increased helicoliths in cluster 2 denote an unstable shallower regime, possible temperate SSTs, and slightly-decreased salinities. The presence of moderate amounts of *R. pseudumbilicus* in cluster 3 together with *R. gelida* might denote tolerance to

an increased nutrient supply and fluctuations from temperate to cooler SSTs.

The Miras-4 transect is dominated by cluster 5 (samples Mi-4/03 to Mi-4/05, Mi-4/08 to Mi-4/10, Mi-4/14 to Mi-4/16, Mi-4/18 to Mi-4/20 and Mi-4/22) with short intervals belonging to cluster 2 (samples Mi-4/01 and Mi-4/02), cluster 3 (Mi-4/11 to Mi-4/13 and Mi-4/23 to Mi-4/24), sub-cluster 4b (Mi-4/21) and 4c (Mi-4/06 and Mi-4/07), showing sudden changes within assemblages in regards to the quantity (increase/decrease) of the main autochthonous species, such as: *R. minuta*, *C. pelagicus*, *R. pseudoubilicus*, *R. haqii*, and *Helicosphaera* spp. The sudden fluctuations in the abundance of *R. minuta* are due to the quality and quantity of the terrigenous nutrient input, whereas the slight decrease in favour of *C. pelagicus* and replacement with *R. pseudoubilicus* and *R. haqii* indicates a shift towards a more marine influence in regards to the type of nutrient, mixing, and coastal wind activity.

In the lower part of Miras-4, a very short interval belonging to sub-cluster 4c, which contains the highest amounts of *R. minuta*, indicates an increased continental material influx and possible, slightly-lowered SSSs due to fresh water input. Cluster 5 has the most diverse assemblage and contains the lowest amounts of *R. minuta* out of all clusters. Slightly elevated quantities of *R. pseudoubilicus*, which is known to prefer temperate to tropical environmental conditions (Young et al. 2022; Nannotax3) and is associated with *C. pelagicus*, helicoliths species, and the cold-water morphotype *R. gelida* (Wei & Thierstein 1991), indicate an increased adaptability to upwelling and tolerance to nutrient availability (Auer et al. 2014), as well as to temperate to cool SSTs. The co-occurrence of *R. pseudoubilicus* and *R. gelida* in the assemblages denotes a seasonal climate character.

The Early Miocene calcareous nannofossil assemblages identified within the present study indicate a neritic eutrophic palaeoenvironment, humid and warm climate, fluctuations in terrigenous material supply, and increased coastal current activity, which is quite likely due to local palaeogeographical conditions. The regime, under which the transects assigned to the NN2/CN1c biozones were deposited during the early Burdigalian (Fig. 9), is regarded as open marine for the sedimentary succession of the Dardha, with less fluctuations in nutrient availability, and shallower, near-shore setting for Dardha-1 and Kodra Partizani, with variations in nutrient type and availability. Warm to cooler assemblages were recorded during this interval, their composition being influenced by the ratio between continental terrigenous input, wind-driven upwelling, and water column mixing. These data are also confirmed by the calcareous nannofossil assemblages described in this study and by their palaeoecological affinities. The palaeoenvironmental conditions, under which the transects assigned to NN3/CN2 biozones (Miras-3 and Miras-4) were deposited during the middle Burdigalian (Fig. 10), can be considered marine near-shore basinal, being characterised by calcareous nannofossil assemblages that indicate temperate to slightly cooler SSTs and elevated terrigenous nutrient influx,

which are occasionally combined with seasonal, wind-driven upwelling. In the ATHB, the characteristics of the calcareous nannofossil assemblages for this time interval (zones NN2–NN3) suggest the existence of a neritic eutrophic palaeoenvironment, humid and warm climate, fluctuations in terrigenous material supply, and increased coastal current activity, which is quite likely due to the palaeogeographical conditions.

Conclusions

- The calcareous nannofossils from the lower Miocene formations of the Albanian–Thessalian Basin (Albania) were studied quantitatively for the first time in order to reveal their biostratigraphic and palaeoecologic potential.
- Various Early Miocene primary and secondary index taxa were recorded within this work. For the first time, the species *Sphenolithus pseudoheteromorphus* is documented within the area of Mount Morava.
- The investigated lower Miocene deposits were assigned to the *Discoaster druggii* Zone (NN2)/*Discoaster druggii* Subzone (CN1c) and to the *Sphenolithus belemnos* Zone (NN3)/*Sphenolithus belemnos* Zone (CN2), corresponding within the Mediterranean zonation with *Helicosphaera ampliaptera* PRZ (MNN2b; early Burdigalian) and *Sphenolithus belemnos* TRZ (MNN3a; middle Burdigalian).
- As per this study, a new age is assigned to the Dardha transect (previously considered late Aquitanian), namely early Burdigalian.
- New data and clarifications regarding the age of some parts from the Sinica Formation (Miras-3 and Miras-4 transects) assigned these sediments to the middle Burdigalian (Zone NN3).
- Palaeoenvironmental reconstruction was carried out for each documented biozone.
- During the early Burdigalian (Dardha, Dardha-1 and Kodra Partizani), warm to cooler assemblages were recorded, as well as variations in the continental terrigenous input, wind-driven upwelling, and water column mixing.
- The marine conditions during the middle Burdigalian (Miras-3 and Miras-4) are considered as neritic with temperate SSTs, with short fluctuations in basinal conditions, high nutrient supply, seasonally-combined with wind-driven upwelling and mixing. Intervals with sea-level changes are associated with species diversification.
- This study contributes to a better understanding of the palaeoecology of various calcareous nannofossil species and associations in marginal settings and semi-enclosed basins, and highlights the palaeoenvironmental conditions of the area during the Early Miocene.

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Electronic supplementary material (Appendix 1–3) is available online at http://geologicacarpatica.com/data/files/supplements/GC-74-1-Kallanxhi_Suppl.docx