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The Rupelian–Chattian transition in the north-western Transylvanian Basin (Romania) revealed by calcareous nannofossils: implications for biostratigraphy and palaeoenvironmental reconstruction

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Abstract: Sediments belonging to the Oligocene Vima Formation (located in the north-western part of the Transylvanian Basin, Romania) have been investigated for calcareous nannofossils content. Biostratigraphically, the sedimentary succession is late Rupelian–Chattian in age, belonging to the NP24 — *Sphenolithus distentus* and NP25 — *Sphenolithus ciperoensis* biozones, to CP19a — *Cyclicargolithus floridanus* and CP19b — *Reticulofenestra bisecta* Subzones and to the interval from CNO4 — *Sphenolithus distentus/Sphenolithus predistentus* CRZ to CNO5 — *Sphenolithus ciperoensis* TZ. The palaeoenvironment of the Fântânele section was reconstructed by means of calcareous nannofossils and statistics. Multivariate statistics were applied to the composition of autochthonous assemblages and the obtained clusters were used to assess the palaeoecological preferences of the nannofossils. We document changes from more stable open-marine regime, with temperate sea-surface temperatures interfering locally with influx of cooler water and enriched cool-nutrient supply for the late Rupelian–earliest Chattian (NP24), to shallower and possibly warmer near-shore marine eutrophic environment, with salinity fluctuations, increased terrigenous material run-off and freshwater influx for the remaining early Chattian (NP25).

Keywords: Rupelian–Chattian transition, Central Paratethys, Transylvanian Basin, calcareous nannofossils, biostratigraphy, palaeoenvironment, statistics.

Introduction

The Oligocene–Early Miocene interval is characterized by important palaeogeographical changes, due to intense tectonic activity, uplifting of the alpine mountain chains, all these bringing the reconfiguration of the area into two marine domains: the intracontinental Paratethys to the north and the Mediterranean to the south (Laskarev 1924; Báldi 1969, 1980; Rusu 1988; Săndulescu & Micu 1989; Rögl 1998, 1999). Distinct marine conditions associated with the above mentioned changes are reflected in the composition of macro- and micro-palaeontological assemblages, by the appearance of Paratethyan endemic assemblages, immediately after the first isolation of the Paratethys in the Early Oligocene (early Rupelian or early Kiscellian in the terms of Paratethyan stages). Within the NP23 biozone, blooms of endemic species *Pontosphaera fibula* and of other taxa such as *Reticulofenestra ornata* and *Braarudosphaera bigelowii*, are recorded all over the area (Gheţa et al. 1976; Krhovský et al. 1992; Haczewski 1989; Nagymarosy & Voronina 1992; Rusu et al. 1996; Nagymarosy 2000; Schultz et al. 2004; Melinte 2005; Melinte-Dobrinescu & Brustur 2008; Soták 2010; Oszczypko-Clowes & Żydek 2012), reflecting restricted basin palaeoenvironment characterized by anoxic conditions, reduced salinities and colder surface sea waters. All these environmental features can be attributed to the reduced seaway connection to the Mediterranean region (Rögl 1998, 1999).

The Early to Late Oligocene interval (late Rupelian to Chattian, or late Kiscellian to Egerian, in terms of Paratethyan stages), corresponding to the upper NP23 to NP25 biozones, is characterized by the re-establishment of normal marine conditions due to the opening of the sea-way connection with the Mediterranean Sea via the Slovenian corridor (Báldi 1986; Nagymarosy 1990; Rögl 1998, 1999; Popov et al. 2004). In the northern part of the basin a connection with the North Sea probably existed through the Rhine Graben (Berger 1996; Sissingh 1997; Rögl 1998, 1999; Popov et al. 2004), while to the south a well developed marine gateway through the eastern Mediterranean provided access from the Indo–Pacific realm (Rögl & Steininger 1983). These palaeogeographical and palaeoclimatic changes during the Oligocene (Kiscellian–early Egerian), are also reflected in the composition of calcareous nannofossil assemblages, and well documented by many authors, from several areas of the Paratethyan domain.

The aims of this study are: 1) to bring new contributions to the regional Oligocene biostratigraphy; 2) to investigate and record the calcareous nannofossil assemblages and bioevents, their diversity and abundance patterns; 3) to investigate the palaeoecology of the calcareous nannofossils, to reconstruct the palaeoenvironment based on the most abundant taxa and to compare the studied deposits to other localities on the regional and global scales.

Geological setting

The Transylvanian Basin is a major sedimentary basin surrounded by the Eastern and Southern Carpathians to the south and east, the Apuseni Mountains to the west and the Preluca–Țicău metamorphic massifs to the north. From a stratigraphic point of view, the Transylvanian Basin comprises sedimentary sequences extending from the Late Cretaceous to the Late Miocene (Krézsek & Bally 2006). The Oligocene sediments from the north-western part of the Transylvanian Basin were deposited into three distinct sedimentation areas (Rusu 1970), all named after the neighbouring crystalline massifs, which from the north-east to south-west are: the Preluca, the Meseş and the Gilău areas. The lateral extension of the formations from the Preluca area is lithologically uniform, in the Meseş and Gilău areas the lateral variations are characteristic (Rusu 1977).

The investigated sediments (Fântânele section) are part of the terrigenous Vima Formation (Lăzărescu 1957, emend. Rusu 1969), located south of the Preluca Massif, in the NW Transylvanian Basin (Fig. 1) and represent a continuous marine sedimentary succession spanning the Oligocene to Early Miocene (Popescu 1975; Mészáros 1991; Krézsek & Bally 2006; Filipescu 2011). Hofmann (1887) described the sediments from the north-western part of the Transylvanian Basin as “a deep water clay facies of Aquitanian age” with molluscs. Majzon (1950) mentioned foraminifera assemblages from deposits “similar to Kiscell clays”. Lăzărescu (1957) suggested a Late Oligocene age for these sediments and similarities to the boreal fauna. Mészáros & Marosi (1957) described molluscs from the “grey claystones and marlstones horizon”. Rusu (1969) included under the description of “Vima strata” all the sedimentary succession between the Ileanda Formation (of Rupelian age) and Hida Formation (of Early Miocene age). Rusu (1977) assigned the Vima Formation to the Egerian (late Rupelian–Chattian) in the Vima Syncline and to the Egerian–Eggenburgian (late Rupelian to Aquitanian) in the Glod Anticline. Additional data were published on foraminifera (Popescu 1971, 1972, 1975; Popescu & Iva 1971; Popescu & Brotea 1989), molluscs (Rusu 1977), ostracods (Olteanu 1980, 2002), and palinomorphs (Ionescu & Popescu 1995). Recent studies on the Vima Formation (Fântânele section) were focussed on planktonic and benthic foraminiferal biostratigraphy and palaeoecology (Székely & Filipescu 2015, 2016).

Mészáros (1991) traced the Oligocene/Miocene boundary within the Fântânele section, and considered the age of the Vima Formation as Oligocene to Early Miocene. Previous studies on Oligocene calcareous nannofossils from the NW Transylvanian Basin were done by: Popescu & Gheţa (1972), Mészáros et al. (1973, 1979), Martini & Moisescu (1974), Mészáros & Ghergari (1979), Mészáros (1984, 1991), Mészáros & Ianoliu (1989). Melinte-Dobrinescu & Brustur (2008) traced the Oligocene/Miocene boundary in the Vima Formation based on the first occurrence (FO) of *Sphenolithus capricornutus*.

Material and methods

Studied sections

The sampled outcrops consist of claystones, marlstones, siltstones, and thin sandstone intercalations. In all, 75 samples were collected from three outcrops (47.41477º N, 23.82699º E; 47.41356º N, 23.82637º E and 47.41195º N, 23.82692º E) of the Fântânele section (Fig. 1; Székely & Filipescu 2016), in order to analyse the calcareous nannofossil assemblages. The studied outcrops are labelled A, B and C, where the Transect A represents the oldest one and Transect C the youngest. Transect A represents a thick sequence (16 m thickness) of finely laminated silty claystones and marlstones, siltstones with thin intercalations of clayey fine grained sandstones. In the uppermost part compact coarse grained sandstone is present. The sampling resolution for Transect A is at intervals of 0.50 m. Transect B has an approximate thickness of 3 m and is mainly composed by fine laminated marly siltstones. Four samples were collected at a resolution of 0.50 m. Transect C has an approximate thickness of 7.5 m, and is lithologically composed of silty claystones and marlstones, intercalated with clayey siltstones and sandstones. High resolution sampling at intervals of 10–30 cm was applied.

Investigation methods

Smear slides, for all samples, were prepared using the standard smear slide technique (Bown & Young 1998) and were examined under the light microscope at 1000× magnification, in polarized light. Quantitative data were obtained from 34 samples by counting at least 300 specimens per sample (Bown & Young 1998), while for less abundant samples (20 samples) at least 100 specimens were counted. Due to the low calcareous nannofossil abundance, only qualitative investigations were done on 8 samples (FA1, FA4, FA9, FA29, FA36, FB10, FB25 and FB55) which have a very low amount of calcareous nannofossils, while 12 samples are barren in calcareous nannofossils (FB1, FB4, FB28, FB31, FB34, FB37, FB40, FB58, FB61, FB64, FB66 and FB70). The overall abundance of calcareous nannofossils per field of view (FOV) in each sample was assessed as follows: A — abundant

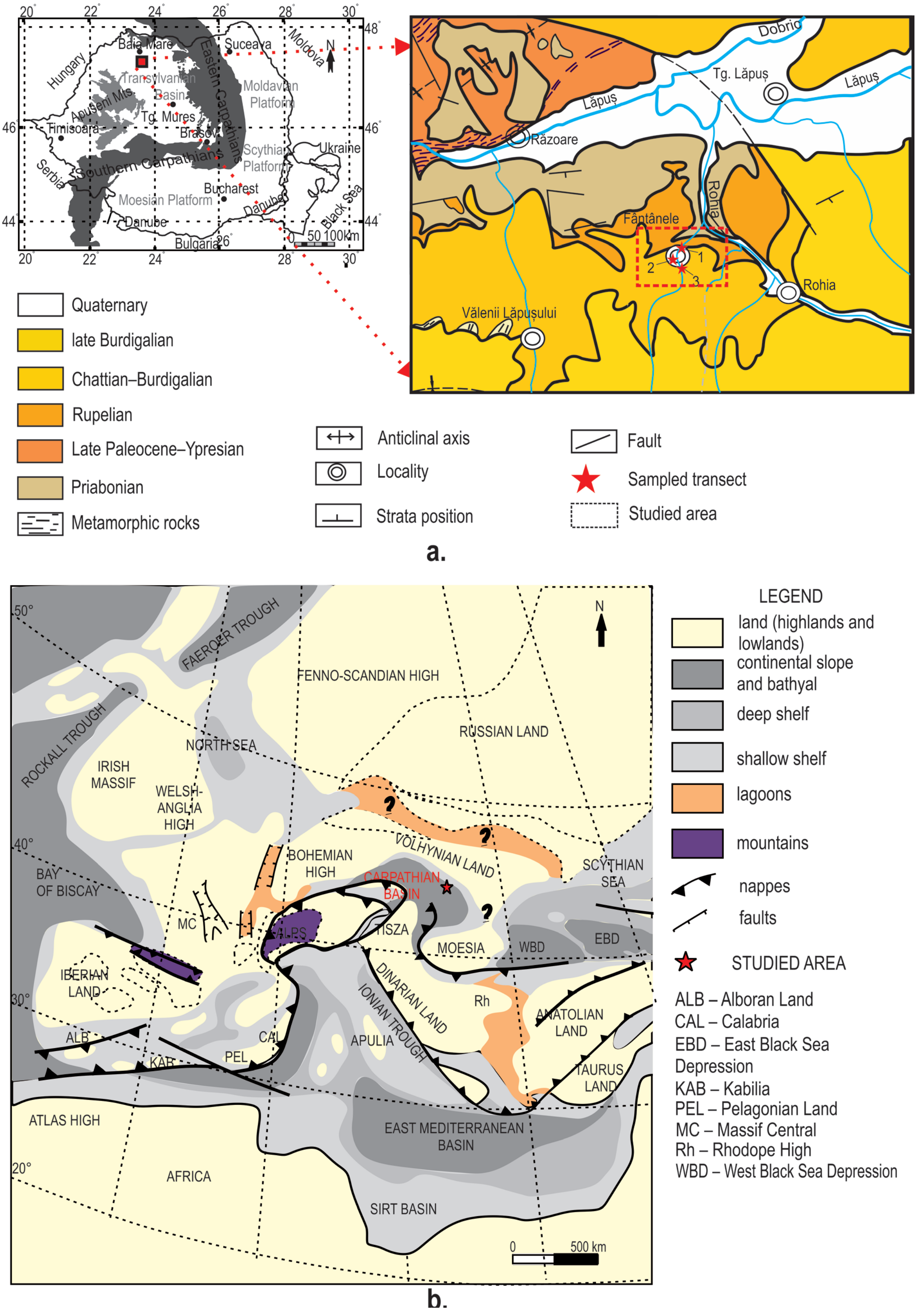

Fig. 1. a — Geological map of Rohia–Fântânele area 1:200,000 (redrawn after Giuşcă & Rădulescu 1967); **b** — Palaeogeographical map (Popov et al. 2004).

(>21 specimens per FOV), C — common (11–20 specimens per FOV), F — few (1–10 specimens per FOV), R — rare (1–10 nannofossils per 10 FOV), VR — very rare (1 specimen in >10 FOV), B — barren (no nannofossils were found) and "Bloom" when >90 % of the assemblage is represented by a single species/group.

Preservation was considered as follows: G — good (all the specimens can be identified at species level and less than 10 % of the assemblage shows fragmentation, etching and/or overgrown), M — moderate (25 % of the specimens show fragmentation, etching and overgrowth, but the species are easily to identify) and P — poor (>25 % of the specimens are broken, sometimes it was not possible to identify some fragments; the exceptions were the single segments of *Braarudosphaera bigelowii* and fragments of *Pontosphaera* spp.). The standard zonations (Fig. 2) implemented in this study follow the concepts of Martini (1971), Okada & Bukry (1980) and additionally, tentative correlation is made to the low to middle latitudes zonation of Agnini et al. (2014). The PAST software (Hammer et al. 2001) was used for statistical treatment of the counts. Multivariate Hierarchical Clustering by Ward's Method and Non-metric Multidimensional Scaling (Hammer & Harper 2006) have been applied to all the counted samples. Before statistical treatment, percentages of the counts were calculated and the Arcsine SQRT (Square Root) formula was applied on the obtained data. The general taxonomy follows the concepts of Perch-Nielsen (1985a,b) and the Nannotax3 website (Young et al. 2017).

Results

Assemblage composition and species diversity

Forty-nine calcareous nannofossil species (Table 1, electr. supplement) were identified in the studied outcrops, 38 of them

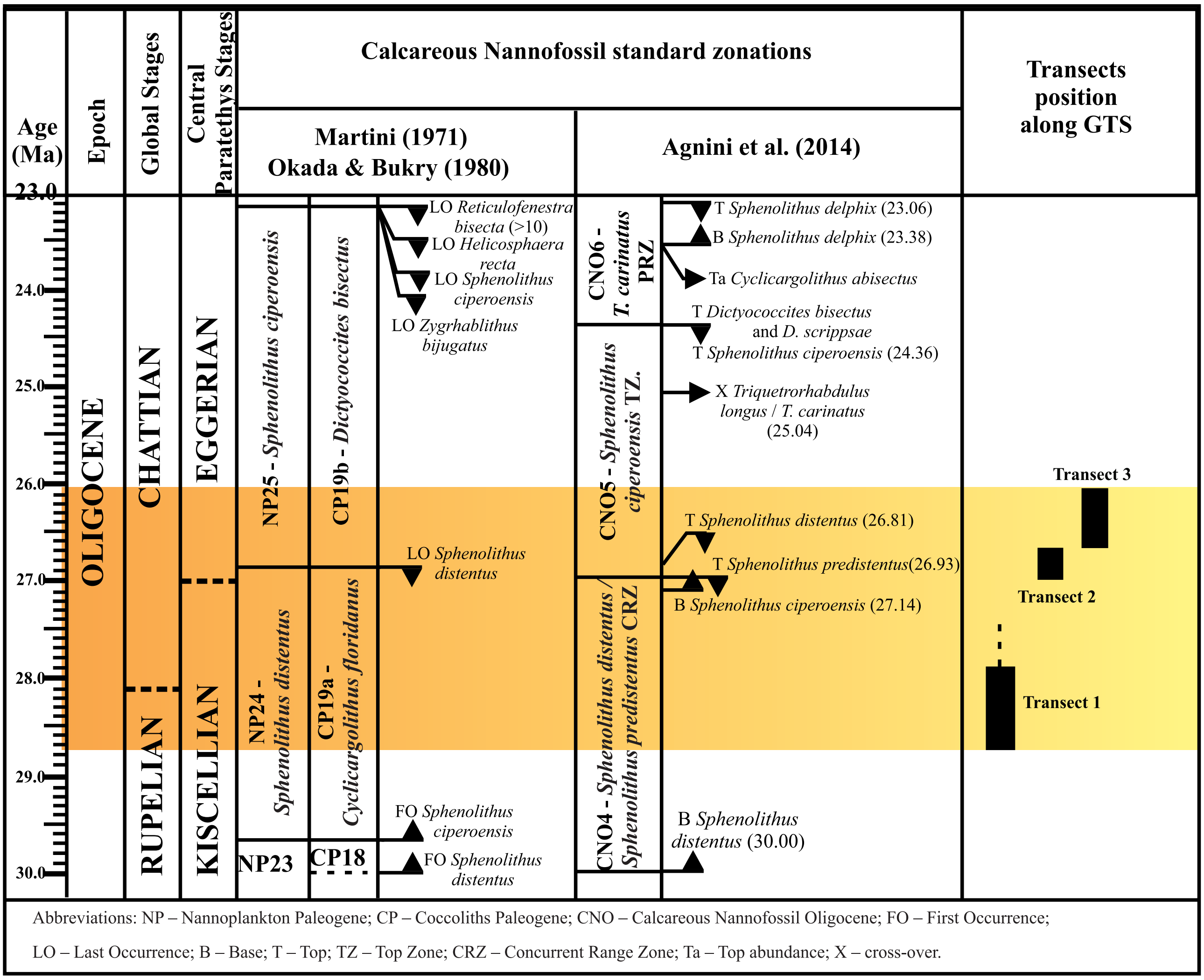

Fig. 2. Biochronological Time Scale for the Oligocene and the Central Paratethys regional stages (Gradstein et al. 2012). The standard calcareous nannofossils follow: NP — Martini (1971); CP — Okada & Bukry (1980); CNO — Agnini et al. (2014).

were in situ while 11 species were reworked from Mesozoic and lower stages of the Palaeogene. The long ranging species such as *Braarudosphaera bigelowii*, *Coccolithus pelagicus*, *Sphenolithus moriformis* and *Zygrhablithus bijugatus* are considered the autochthonous component. The examined material contains well to poorly preserved calcareous nannofossil assemblages, dominated in order of abundance by: *Cyclicargolithus floridanus*, *Reticulofenestra minuta*, *Braarudosphaera bigelowii*, *Pontosphaera multipora*, *Coccolithus pelagicus, Reticulofenestra* gr. 3–5 µm, *Reticulofenestra bisecta*, *Cyclicargolithus abisectus*, *Reticulofenestra lockeri*, *Pontosphaera pygmaea*, *Reticulofenestra daviesii, Reticulofenestra stavensis*, *Helicosphaera recta*, *Sphenolithus moriformis* and *Pontosphaera desueta*. Species with rarer and irregular distribution are: *Coronocyclus* sp., *Helicosphaera euphratis*, *H. intermedia*, *Pontosphaera* cf. *enormis*, *Pyrocyclus orangensis*, *Reticulofenestra callida*, *R. dictyoda*, *R. scrippsae*, *Sphenolithus akropodus*, *S. ciperoensis*, *S. distentus*, *Sphenolithus predistentus*, *Sphenolithus* sp. and *Zygrhablithus bijugatus.* Other important biostratigraphical species such as *Chiasmolithus altus*, *Sphenolithus dissimilis* and *Triquetrorhabdulus longus* are extremely rare and appear in few samples. Reworked taxa represent 0.2 % of the whole assemblage and include species (Table 1, electr. supplement) with their FO (first occurrence) and LO (last occurrence) in the Mesozoic and lower stages of the Palaeogene.

The taxa diversity is expressed as the number of autochthonous species per sample and here it is considered as moderate to low. The maximum diversity of 26 autochthonous species was recorded in sample FA20, in the first outcrop, decreasing in the second one up to a maximum of 17 autochthonous species in sample FA34, while in the last one the maximum diversity of 22 species is recorded in samples FB19 and FB43. A drastic decrease in the number of species (5 species) is recorded in the upper part of the last transect in the samples containing blooms of *Braarudosphaera bigelowii* and *Reticulofenestra minuta.* Microphotographs of the most representative nannofossil taxa are included in Figs. 3 & 4.

Calcareous nannofossils biostratigraphy

Biostratigraphically, the calcareous nannofossil assemblages suggest a late Rupelian to Chattian age (Fig. 2) for the whole sedimentary succession. This attribution is supported by the absence of index species *Reticulofenestra umbilicus,* ranging from the base of NP16 (Middle Eocene) to the lower NP23 (Gradstein et al. 2012). The lowermost part of the Fântânele section (Transect A and partially Transect B) belongs to the NP24 — *Sphenolithus distentus* biozone (Martini 1971) and CP19a — *Cyclicargolithus floridanus* Subzone (Okada & Bukry 1980) of late Rupelian–early Chattian age. The boundary between NP24 (*Sphenolithus distentus* Zone) — NP25 (*Sphenolithus ciperoensis* Zone of Chattian age) biozones is tentatively traced between samples FA34–FA35 from the second transect, where the LO of *Sphenolithus distentus,* was recorded. Above this level the presence of this marker is not observed anymore. The upper part of the second transect and the whole of Transect C belong to the NP25 — *Sphenolithus ciperoensis* biozone of Martini (1971) and to CP19b — *Reticulofenestra bisecta* Subzone of Okada & Bukry (1980). Correlation with the new zonation for low to middle latitudes, proposed by Agnini et al. (2014) suggest that the investigated transects would fall within the interval from CNO4 — *Sphenolithus distentus/Sphenolithus predistentus* CRZ to CNO5 — *Sphenolithus ciperoensis* TZ.

The Upper Oligocene–Lower Miocene markers *Sphenolithus delphix* and *Sphenolithus capricornutus*, used to define the Oligocene/Miocene boundary in the Mediterranean area and other Lower Miocene taxa such as *Helicosphaera carteri, H. mediterranea* and *Discoaster druggii* were not recorded in the investigated samples.

Abundance patterns of the selected coccolith taxa for palaeoecology

The palaeoecological preferences (Table 2, electr. supplement) of the most abundant species and taxonomical groups were investigated and the following were considered for palaeoenvironmental reconstruction: *Cyclicargolithus* spp. (*Cy. floridanus* with an average of 26.06 %. and *Cy. abisectus* with a total of 3.42 %), small reticulofenestrids (*Reticulofenestra minuta* comprise coccoliths <3 µm; 14.78 % from total; *Reticulofenestra* gr. 3–5 µm including small specimens with a pore or a small central opening — total of 4.26 %), *Pontosphaera* spp. (14.55 %), *Braarudosphaera bigelowii* (12.70 %), *Reticulofenestra* spp. (coccoliths >5 µm; 11.57 % from total), *Coccolithus pelagicus* (7.44 %), *Sphenolithus* spp. (2.54 %) and *Helicosphaera* spp. (1.54 %). The abundance patterns of the above mentioned species and groups are plotted along the sampling interval (m) in Figs. 5, 6 and 7.

Multivariate statistics

The Multivariate Hierarchical Clustering (Fig. 8) indicates four main clusters and eight sub-clusters which are well differentiated and are described below. Samples belonging to the first and second outcrops are noted with FA and samples belonging to the third outcrop with FB.

Cluster 1 (assemblages with *Pontosphaera* spp.) comprises 9 samples and groups the highest proportions of *Pontosphaera* spp. with values between 13.21 and 99.34 %. Two sub-clusters 1a and 1b are differentiated by the fluctuations in the amount of *Pontosphaera* spp. Sub-cluster 1a (samples FA3, FA10, FA23, FA24, FB12 and FB41) includes assemblages with *Pontosphaera* spp. in association with increased amounts of *C. pelagicus* (from 12.38 to 61.32 %) and in two samples with *Helicosphaera* spp. (up to 25.23 %). The average participation of the rest of the taxa is less than 6 % per group. Sub-cluster 1b (samples FB9, FB11 and FB13) is characterized by the highest amount of *Pontosphaera* spp. (from 81.41 to 99.34 %).

Cluster II (*Cyclicargolithus* spp. assemblages) concentrates the highest number of samples (in total 28) belonging to

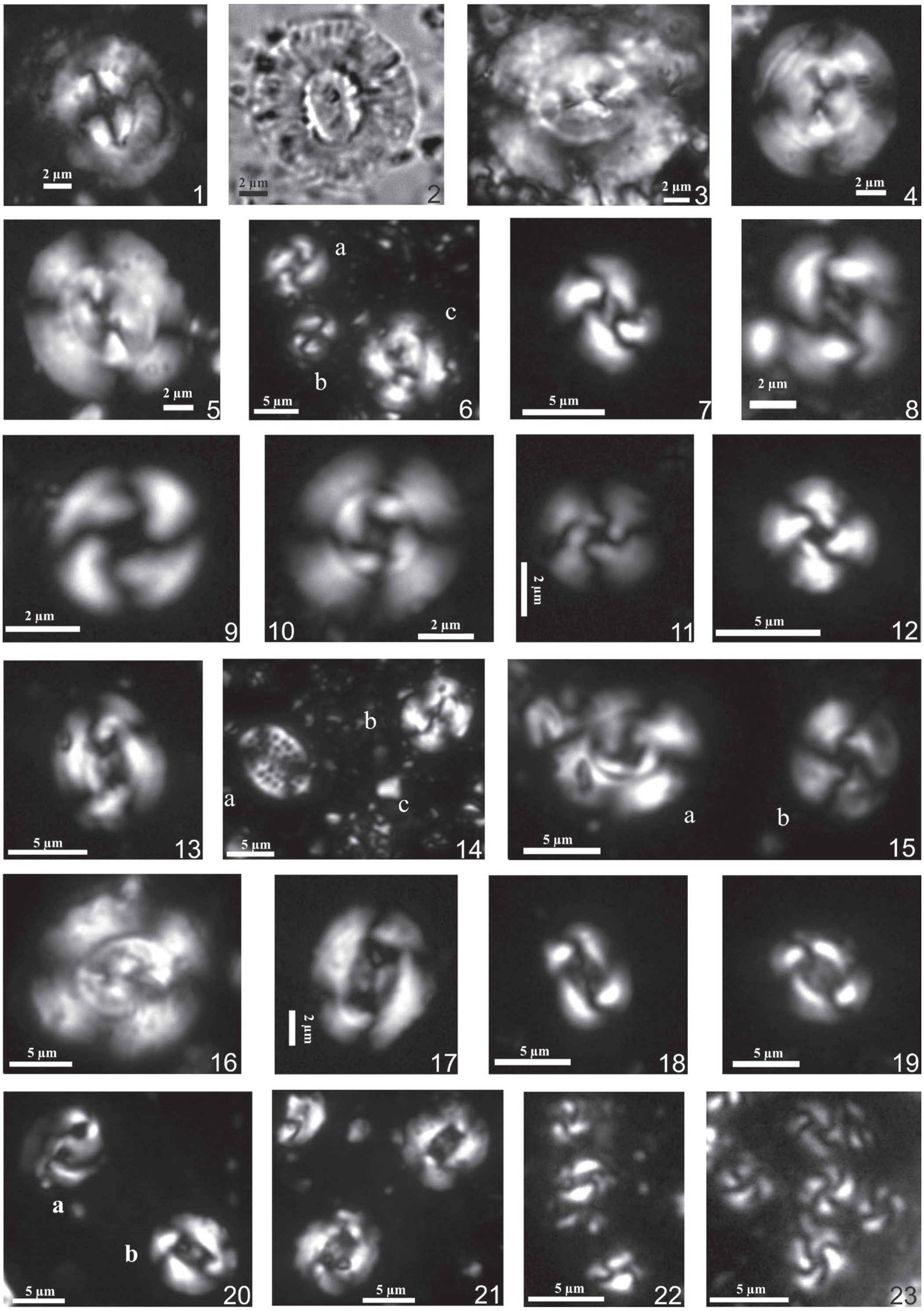

Fig. 3. Calcareous nannofossils from the Vima Formation. The microphotographs are taken under Cross-Polarized Light (XPL) and Bright Field (BF). **1–2** — *Coccolithus pelagicus* (same specimen, XPL and BF, sample FA20); **3** — *Reticulofenestra stavensis* (XPL, sample FA18); **4** — *Reticulofenestra bisecta* (XPL, sample FA21); **5** — *Reticulofenestra bisecta* (XPL, sample FA32); **6** — a) *Reticulofenestra daviesii*; b) *Coccolithus pelagicus*; c) *Reticulofenestra bisecta* (XPL, sample FB20); **7** — *Reticulofenestra lockeri* (XPL, sample FB67); **8** — *Reticulofenestra lockeri* (XPL, sample FA28); **9** — *Pyrocyclus orangensis* (XPL, sample FA11); **10** — *Cyclicargolithus abisectus* (XPL, sample FA35); **11** — *Cyclicargolithus floridanus* (XPL, sample FA18); **12** — *Cyclicargolithus floridanus* (XPL, sample FB43); **13** — *Reticulofenestra lockeri* (XPL, sample FA32); **14** — a) *Pontosphaera multipora*; b) *Reticulofenestra bisecta*; c) *Reticulofenestra minuta* (XPL, sample FA20); **15** — a) *Cyclicargolithus abisectus*; b) *Cyclicargolithus floridanus* (XPL, sample FA28); **16** — *Reticulofenestra stavensis* (XPL, sample FA20); **17** — *Reticulofenestra callida* (XPL, sample FA7); **18** — *Reticulofenestra daviesii* (XPL, sample FB43); **19** — *Reticulofenestra daviesii* (XPL, sample FA13); **20** — a) *Helicosphaera recta;* b) *Reticulofenestra callida* (XPL, sample FB19); **21** — *Reticulofenestra callida* (XPL, sample FA32); **22** — *Reticulofenestra* gr. 3–5 µm (XPL, sample FA20); **23** — *Reticulofenestra* gr. 3–5 µm (XPL, sample FA20).

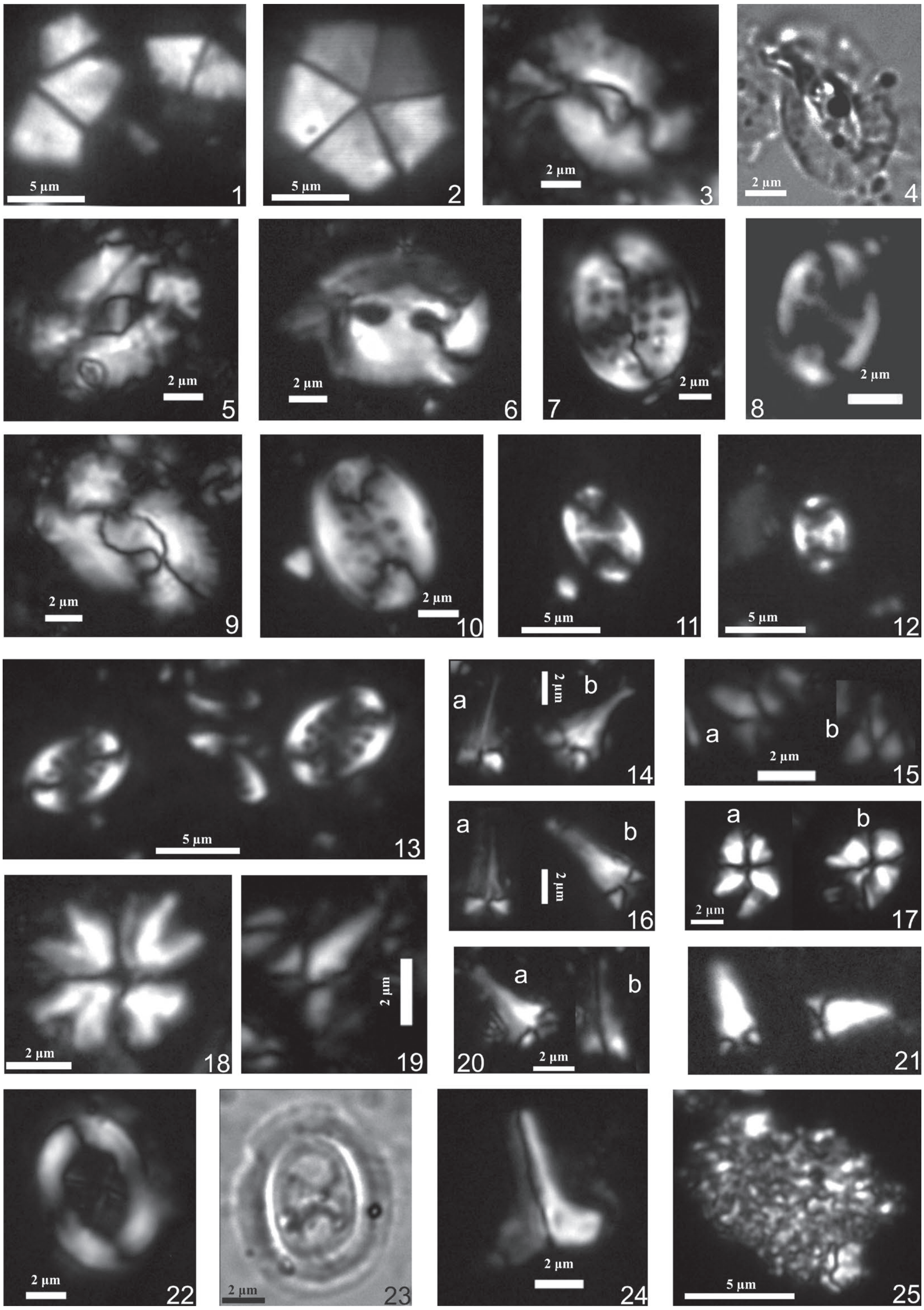

Fig. 4. Calcareous nannofossils from the Vima Formation. The microphotographs are taken under Cross-Polarized Light (XPL) and Bright Field (BF). **1** — *Braarudosphaera bigelowii* (XPL, sample FB73); **2** — *Braarudosphaera bigelowii* (XPL, sample FB73); **3–4** — *Helicosphaera euphratis* (same specimen, XPL and BF, sample FA15); **5** — *Helicosphaera euphratis* (XPL, sample FA20); **6** — *Helicosphaera recta* (XPL, sample FA21); **7** — *Pontosphaera multipora* (XPL, sample FA18); **8** — *Pontosphaera pygmaea* (XPL, sample FA3); **9** – *Helicosphaera intermedia* (XPL, sample FA20); **10** — *Pontosphaera* cf. *enormis* (XPL, sample FA14); **11** — *Pontosphaera pygmaea* (XPL, sample FB43); **12** — *Pontosphaera desueta* (XPL, sample FB16); **13** — *Pontosphaera multipora* (XPL, sample FB13); **14a–b** — *Sphenolithus distentus* (same specimen in two orientations, XPL, sample FA17); **15a–b** — *Sphenolithus distentus* (same specimen in two orientations, XPL, sample FA11); **16a–b** — *Sphenolithus akropodus* (same specimen in two orientations, XPL, sample FA17); **17a–b** — *Sphenolithus dissimilis* (same specimen in two orientations, XPL, sample FB46); **18** — *Sphenolithus moriformis* (XPL, sample FA28); **19** — *Sphenolithus ciperoensis* (XPL, sample FA18); **19a–b** — *Sphenolithus predistentus* (same specimen in two orientations, XPL, sample FA17); **21** — *Sphenolithus predistentus* (XPL, sample FA11); **22–23** — *Chiasmolithus altus* (same specimen, XPL and BF, sample FA30); **24** — *Zygrhablithus bijugatus* (XPL, sample FA13); **25** — *Thoracosphaera* sp. (XPL, sample FB67).

Transect A (FA5–FA8, FA11, FA15–FA19, FA26, FA30–FA32), all positive samples from the second (FA33 to FA35) and some from the third outcrop (FB7–FB8, FB16, FB19, FB22–FB24, FB42, FB46, FB49, FB52). It contains the highest amount of *Cyclicargolithus* spp. (*Cy. floridanus*), which has an average participation in the assemblage of 47.64 % (from 0.31 up to 73.29 %), followed in moderate amounts by *Reticulofenestra* spp. (17.68 %) and by small reticulofenestrids (16.29 %). Low participation in the assemblage was registered for *C. pelagicus* (7.58 %) and for *Pontosphaera* spp. (6.1 %). Very low average quantities occur of *Sphenolithus* spp. (2.9 %), *Helicosphaera* spp. (1.74 %) and *B. bigelowii* (0.69 %). The three sub-clusters identified (2a, 2b and 2c) are defined by the fluctuations in abundance and intra-cluster shifts of the main autochthonous taxa. Sub-cluster 2a exhibits the lowest amounts of *Cy. floridanus* (32.44 %) and the highest amount of small reticulofenestrids (24.70 %), followed by *Reticulofenestra* spp. (17.35 %), *C. pelagicus* (11.99 %), less *Pontosphaera* spp. (6.47 %) and *Sphenolithus* spp. (6.43 %). Increasing of the amount of *Cy. floridanus* (average 48.25 %) and shift in small reticulofenestrids (decrease to 17.84 %) and *Reticulofenestra* spp. (increase to 22.84 %) is noticed in sub-cluster 2b, coupled with a very low amount of the rest of the taxa with group average participation less than 4 %. Sub-cluster 2c exhibits the highest quantity of *Cy. floridanus* (58.96 %), slightly increase of *C. pelagicus* (11.63 %) and *Pontosphaera* spp. (10.35 %) and noticeable decrease of *Reticulofenestra* spp. (8.91 %) and small reticulofenestrids (7.61 %).

Cluster III (small reticulofenestrids assemblages) has 13 samples belonging to Transect A and to Transect C and displays the highest amounts of small reticulofenestrids which account for an average of 47.69 %, followed by *Cyclicargolithus* spp. (*Cy. floridanus*) with a mean of 21.23 %, *Reticulofenestra* spp. (10.72 %), *B. bigelowii* (9.31 %), *C. pelagicus* (6.24 %), *Pontosphaera* spp. (5.46 %), *Sphenolithus* spp. (2.06 %) and *Helicosphaera* spp. (1.92 %). Three sub-clusters (3a, 3b and 3c) were distinguished based on the participation of small reticulofenestrids to the assemblages, with gradual increase from sub-cluster 3a to 3c. Sub-cluster 3a (FA4, FA12–FA14, FA22) is dominated by an association of small reticulofenestrids (36.84 %) and *Cy. floridanus* (33.18 %), with an additional contribution of *B. bigelowii* (12.60 %) and less *Reticulofenestra* spp. (7.87 %), *Pontosphaera* spp. (7.23 %) and *C. pelagicus* (6.90 %). Sub-cluster 3b (FA20-FA21, FA25, FA27–FA28 and FB43) exhibits abundant small reticulofenestrids (53.26 %), with smaller numbers of *Cy. floridanus* (17.97 %), *Reticulofenestra* spp. (13.66 %) and *C. pelagicus* (7.55 %). The rest of the taxa do not reach more than 4.5 % per group. Sub-cluster 3c (FB67–FB68) displays the highest amount of small reticulofenestrids (58.11 %) and additionally *B. bigelowii* (26.13 %).

Cluster IV includes only 4 samples (FB69, FB71–FB73) from the uppermost part of Transect C. It is clearly distinguished from the others due to the blooms of a single species *Braarudosphaera bigelowii* (from 91.88 to 96.33 %).

Discussions

Biostratigraphy and calcareous nannofossil bioevents

The sediments from the Vima Formation were previously investigated by Mészáros & Ghergari (1979) and Mészáros (1984), who identified the following zones: the NP24 biozone based on the co-occurrence of *Cyclicargolithus floridanus, Reticulofenestra dictyoda, Sphenolithus moriformis, Pontosphaera fibula,* and *Reticulofenestra ornata*; the NP25 biozone with dominant species: *Cyclicargolithus floridanus, Coccolithus formosus, Coccolithus pelagicus, Sphenolithus ciperoensis, Cyclicargolithus abisectus, Sphenolithus moriformis, Pontosphaera desueta*, *P. multipora*, *P. obliquipons*, *P. fibula, Syracosphaera clathrata* and *R. ornata*; the NN1 biozone based on the presence of marker species *Triquetrorhabdulus carinatus,* and the NN2 biozone based on the sporadic appearance of index species *Discoaster druggii, Helicosphaera ampliaperta*, *H.* cf. *carteri*, *H. euphratis*, *R. lockeri* and *R. pseudoumbilica.*

The assignments of the Fântânele section deposits to the NP24–NP25 biozones (Martini 1971), to CP19 (Okada & Bukry 1980) and additionally to CNO4–CNO5 (Agnini et al. 2014) are based on the presence of several primary and secondary bioevents considered for the Oligocene biostratigraphical subdivision schemes. Whether or not they can be applied in the present study is discussed below. Several authors (Mészáros 1984; Rusu et al. 1996; Melinte 2005; Melinte-Dobrinescu & Brustur 2008) investigated various locations where the Vima Fm. crops out, in more complete successions compared to the Fântânele section. A recent study on planktonic and benthic foraminifera from the Vima Formation (Székely & Filipescu 2016) indicates an Early Oligocene (Rupelian) age for the base of the first sampled transect, more precisely the Biozone O4 (based on the co-occurrence of *Chiloguembelina cubensis* together with *Paragloborotalia opima*), while for the third investigated transect a Late Oligocene (Chattian) age is suggested, or the foraminiferal biozone O5 (based on co-occurrence of *Paragloborotalia opima* and *Globigerina ciperoensis*).

In the Fântânele section, the marker species ***Sphenolithus ciperoensis*** appears in the Transect A at 7 m (FA15). The absence of this species from the lower part of the studied section raises the question whether the NP23 zone of Martini (1971) and CP18 of Okada & Bukry (1980) are present or not. The presence of the NP23 and CP18–lower CP19a biozones would be in disagreement with the planktonic foraminifera data (Székely & Filipescu 2016) which point to the O4 zone of Wade et al. (2011) of late Rupelian age. In conclusion, it is difficult to consider this event as a first occurrence and its absence from the lowermost part of Transect A might be due to unfavourable environmental conditions or to its scarcity and in general to the reduced number of sphenoliths.

The species ***Cyclicargolithus abisectus*** displays low abundance patterns, both sizes being present (<10 µm and >10 µm). The medium-sized specimens (<10 µm) appear from samples

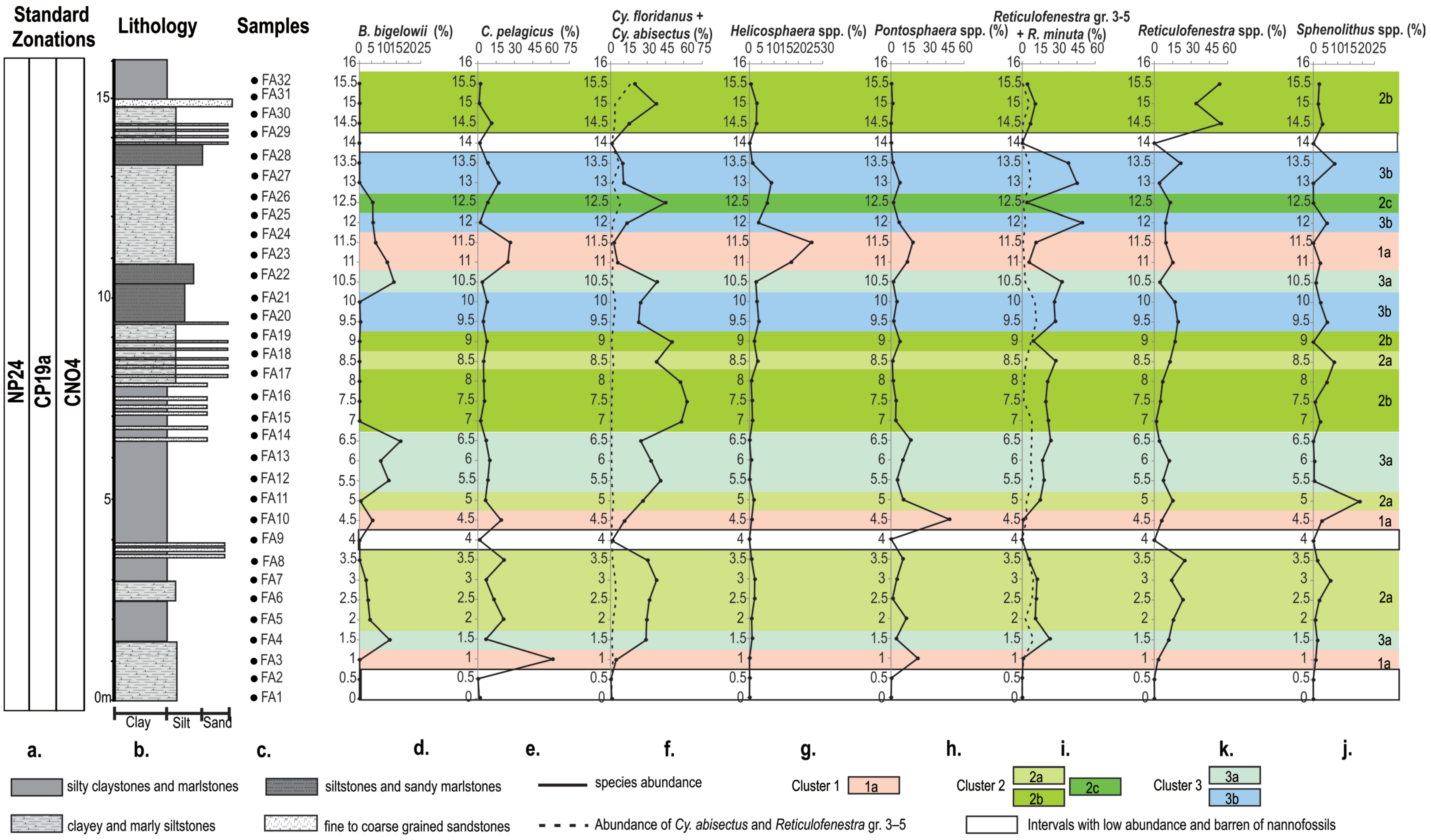

Fig. 5. Transect A — lithology, sample positions and abundance patterns of the most important species and taxonomic groups plotted along the sampling interval (m): **a** — Standard Zonations of Martini (1971), Okada & Bukry (1980) and Agnini et al. (2014); **b** — Lithology; **c** — Samples position; **d** — *Braarudosphaera bigelowii*; **e** — *Coccolithus pelagicus*; **f** — *Cyclicargolithus floridanus*+*Cyclicargolithus abisectus*; **g** — *Helicosphaera* spp.; **h** — *Pontosphaera* spp.; **i** — *Reticulofenestra* gr. 3–5+*Reticulofenestra minuta*; **j** — *Reticulofenestra* spp. >5; **k** — *Sphenolithus* spp.

FA3 upwards and are more continuously distributed along the section than the large-sized ones which are present starting from the middle of Transect A (FA17), in a few samples above this level. In this study the FO is not recognized due to the fact that the above mentioned species has a continuous distribution along the investigated section. Rich assemblages, dominated by *Cy. abisectus* and *R. bisecta*, are mentioned for the late Rupelian (Van Simaeys et al. 2004), from several boreholes in the Belgium Basin (Belgium and Germany). From the Central Paratethys realm, the NP24 zone and assemblages containing this taxon were mentioned from: the Magura Basin (Poland) by Oszczypko-Clowes (2001, 2010), Oszczypko-Clowes & Ślączka (2006), Oszczypko-Clowes & Żydek (2012), the Subtatric Group (Slovakia) by Ozdínová (2013), the Podhale flysch (Poland) by Garecka (2005), from the Skole Unit (Poland) by Garecka (2012), from the Magura Basin (Poland) by Kopciowski & Garecka (1996), Garecka et al. (1998), Garecka & Szydlo (2011, 2015), from the South Slovakian Basin by Ozdínová & Soták (2014), from the NW Transylvanian Basin and from the central and southern Eastern Carpathians (Gheţa et al. 1976; Mészáros & Ghergari 1979; Mészáros 1991; Rusu et al. 1996; Melinte 2005; Melinte-Dobrinescu & Brustur 2008).

The species ***Sphenolithus distentus*** is very scarce in the first two transects, and is absent from the third one. Its LO is tentatively placed at the level of sample FA34 in Transect B.

The **LO of *Sphenolithus predistentus*** is not used in the standard zonations of Martini (1971) and Okada & Bukry (1980), but its biostratigraphical importance was pointed out by several authors (Fornaciari et. al. 1990; Olafsson & Villa 1992; Agnini et. al. 2014). Gradstein et al (2012) indicate that its LO is located at 26.93 Ma, below the LO of *Sphenolithus distentus*. This bioevent is recorded in the Fântânele section at 13.5m (between FA28–FA29) from Transect A. Its absence from Transects B and C makes it suitable to be considered as a possible LO event.

The species ***Helicosphaera recta*** is more or less continuously present in

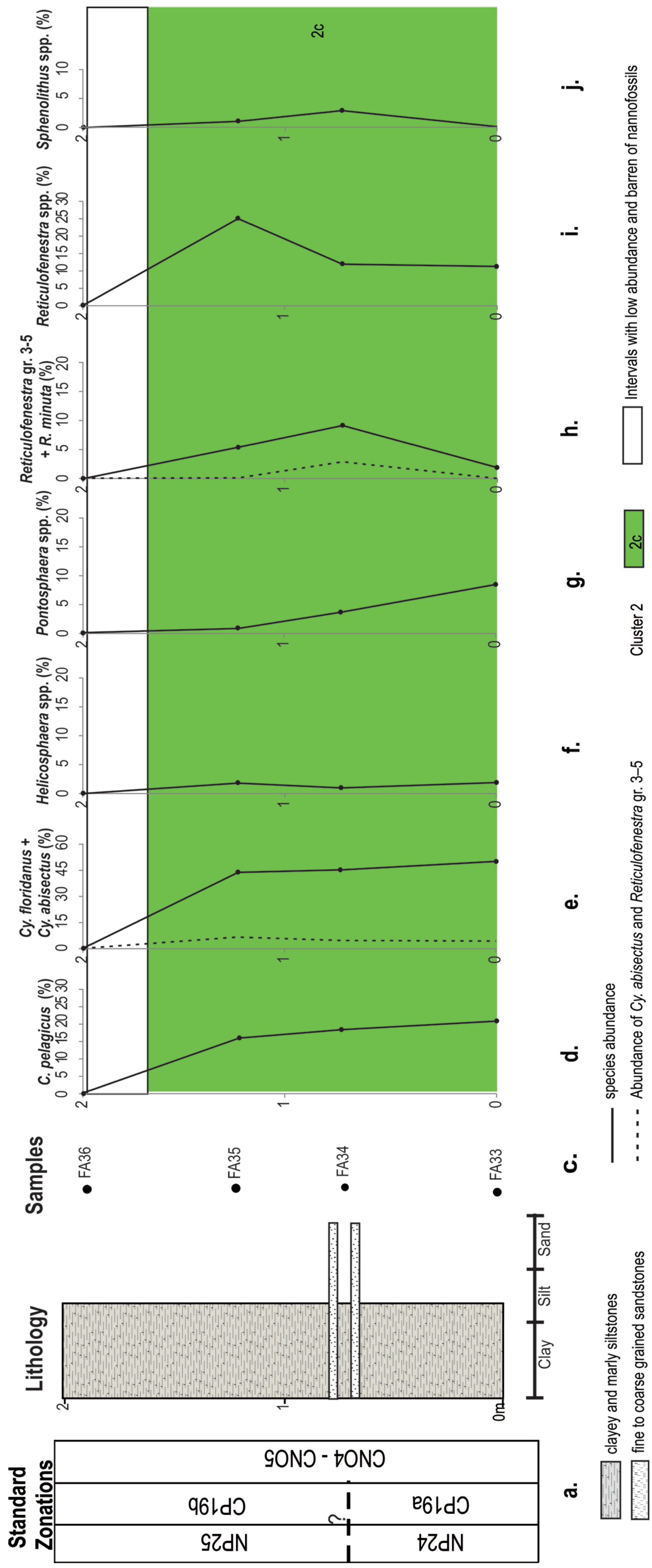

Fig. 6. Transect B — lithology, sample positions and abundance patterns of the most important species and taxonomic groups plotted along the sampling interval (m): **a** — Standard Zonations of Martini (1971), Okada & Bukry (1980) and Agnini et al. (2014); **b** — Lithology; **c** — Sample positions; **d** — *Coccolithus pelagicus*; **e** — *Cyclicargolithus floridanus*+*Cyclicargolithus abisectus*; **f** — *Helicosphaera* spp.; **g** — *Pontosphaera* spp.; **h** — *Reticulofenestra* gr. 3–5+*Reticulofenestra minuta*; **i** — *Reticulofenestra* spp. >5; **j** — *Sphenolithus* spp.

Transects A and B (from sample FA5 of the first outcrop, upwards), and sporadically in Transect C and due to this continuity its FO was not traced in this interval. In other areas of the Central Paratethys domain, this species has been mentioned from the NP24–NP25 zones by Mărunţeanu (1992; from the Romanian Carpathians), Oszczypko-Clowes (2001, 2010), Garecka (2005), Garecka & Szydlo (2011, 2015), and Ozdínová & Soták (2014).

Pontosphaera* cf. *enormis (first observed in sample FA7 from Transect A) occurs rarely and discontinuously. It appears to have a lower occurrence (within NP24) compared to other studies which mention it near the NP24/NP25 boundary (von Benedek & Müller 1974; Martini & Müller 1975; Martini 1981) and from the NP25 Zone (Van Simaeys et al. 2004; Garecka 2005; Melinte 2005; Melinte-Dobrinescu & Brustur 2008; Ozdínová & Soták 2014).

The species ***Chiasmolithus altus*** is very rare and sporadic and is present only in Transect A (samples FA20 and FA30). Previous reports from similar sections in Romania, mentioned its FO in the late Rupelian (Melinte-Dobrinescu & Brustur 2008).

The species ***Triquetrorhabdulus longus*** has a biostratigraphical range from NP24 to NN3 Zones, and a well marked acme in the Late Oligocene (Blaj & Young 2010). It is present in the studied material in only one sample from the third outcrop (FB43).

Rupelian/Chattian boundary

The historically acknowledged Rupelian–Chattian boundary as defined from its typical stratotypes in the North Sea Basin, is associated with several benthic foraminiferal and dinocists events (Köthe 1990; Berggren et al. 1995; De Man et al. 2004; Van Simaeys et al. 2004, 2005a, b; Pross et al. 2010; Wade et al. 2011). New data on the reliability of marker species foraminifer *Chiloguembelina cubensis* as bio-event for defining the R/C boundary were brought by King & Wade (2017). The base of the Chattian at the Monte Cagnero section (Umbria-Marche Basin, Apennines, Italy) was calibrated at 27.82 Ma at the HCO (Highest Common Occurrence) of *Chiloguembelina cubensis* (Coccioni et al. 2017). In terms of calcareous nannofossils the Rupelian–Chattian boundary falls within the upper part of the NP24 biozone (Berggren et al. 1995; Coccioni et al. 2008, 2017). The R/C boundary in the North Sea Basin (Van Simaeys et al. 2004) is marked by cooler

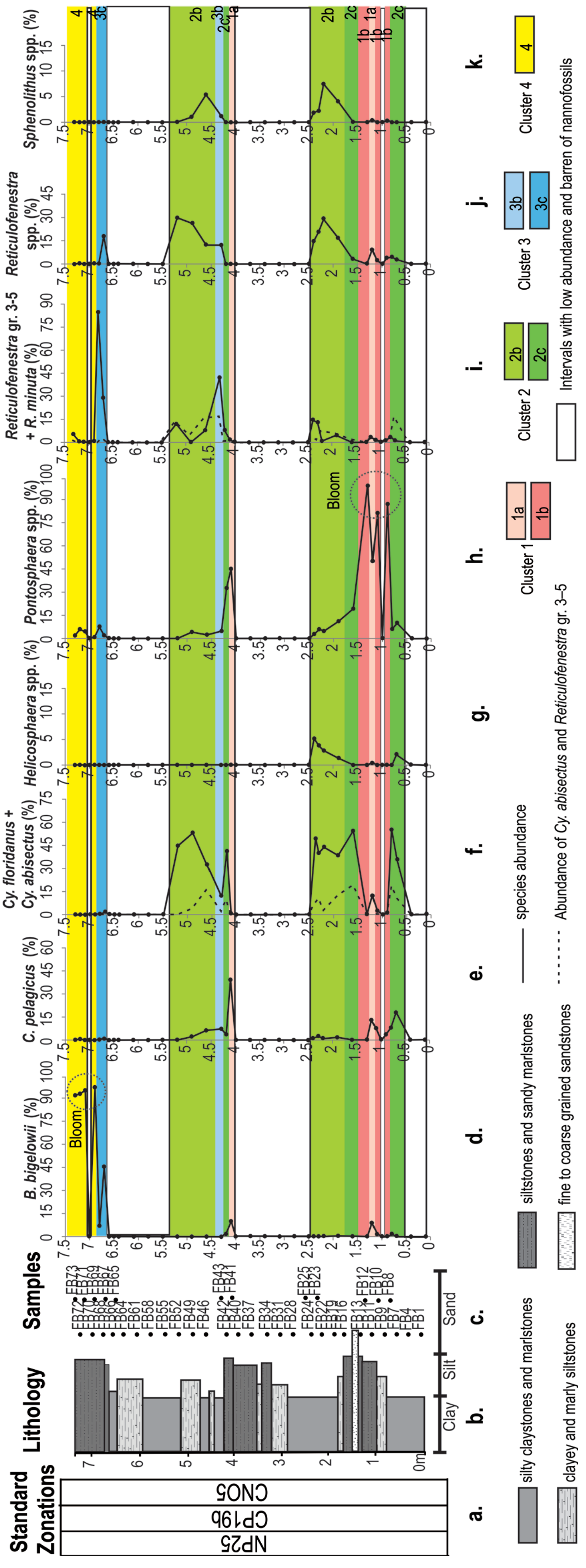

Fig. 7. Transect C – lithology, sample positions and abundance patterns of the most important species and taxonomic groups plotted along the sampling interval (m): **a** — Standard Zonations of Martini (1971), Okada & Bukry (1980) and Agnini et al. (2014); **b** — Lithology; **c** — Sample positions; **d** — *Braarudosphaera bigelowii*; **e** — *Coccolithus pelagicus*; **f** — *Cyclicargolithus floridanus* +*Cyclicargolithus abisectus*; **g** — *Helicosphaera* spp.; **h** — *Pontosphaera* spp.; **i** — *Reticulofenestra* gr. 3–5+*Reticulofenestra minuta*; **j** — *Reticulofenestra* spp. >5; **k** — *Sphenolithus* spp.

climate and more open marine conditions for the late Rupelian, while the lower Chattian is associated with shallower, warmer climate and warmer sea-surface water temperatures and hyposaline shallow marine environments, as documented also by the calcareous nannofossil assemblages (at the base of Chattian) with presence in higher quantities of *Ponstosphaera* spp., *Zygrhablithus bijugatus* and *B. bigelowii*. Generally, the calcareous nannofossil assemblages from the Fântânele section, assigned to the NP24/CP19a zones are comparable in species composition to many other Paratethyan localities, where the NP24 Biozone was identified, being considered as late Rupelian to Chattian. The acknowledgement of NP24/CP19a is associated with the presence of several primary and secondary index species with overlapping ranges which cross the R/C boundary, such as *Sphenolithus ciperoensis*, *S. distentus*, *S. predistentus*, *H. recta* and *Cy. abisectus*. The identification of the NP25/CP19b biozones (of Chattian age) is given by the absence of *S. distentus* and *S. predistentus* in the last part of the second transect and in the third one. The R/C boundary is difficult to trace in the investigated sediments, and this is mainly due to the gaps between the outcrops, areas covered by vegetation, where sampling was not possible. Detailed age assignment and separation of the nannofossil assemblages, to only late Rupelian or to the Chattian part of the NP24 biozone, was also difficult to perform due to the similarities in their composition. The first investigated transect and to the half of the second one, is given a general late Rupelian–early Chattian age (NP24 Zone), while for the second half of Transect B and Transect C, the Chattian age was assumed (NP25 Zone).

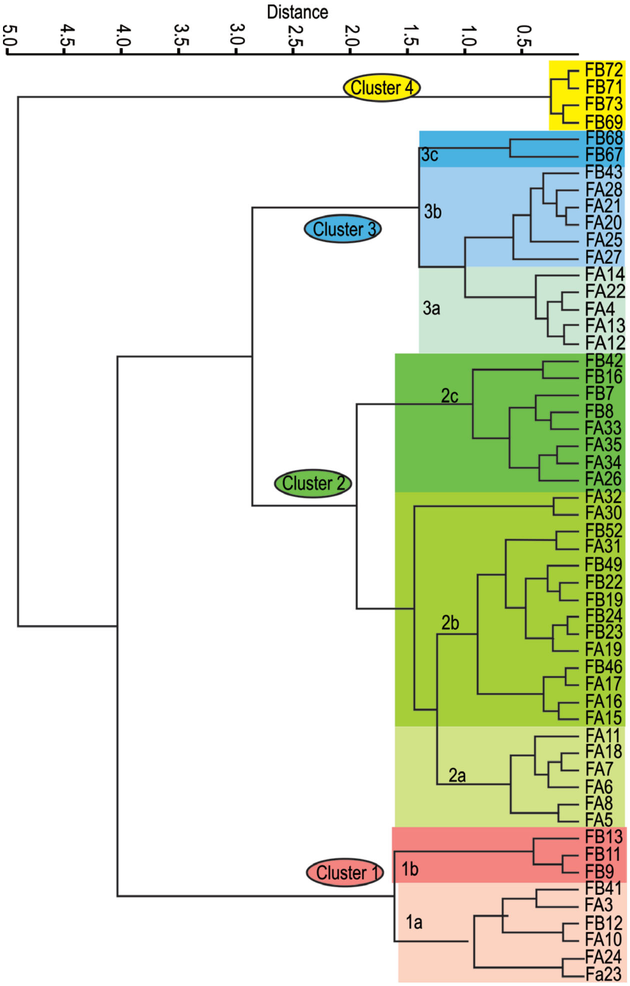

Fig. 8. Multivariate Clustering Analysis by Ward's Method.

Calcareous nannofossils palaeoecology, palaeoenvironment and statistical interpretation

Palaeoenvironmental changes during the deposition of the Fântânele sedimentary succession are recorded here through the variations in calcareous nannofossil abundance and assemblage composition, all together connected to the distinct climatic conditions and to the changed palaeogeographical configuration during the Oligocene (Rögl 1998, 1999; Popov et al. 2004). The calcareous nannofossil assemblages from the Fântânele section indicate similar palaeoenvironmental conditions as recorded by many other authors in other Paratethyan areas, with a temperate to cooler late Rupelian interval and slightly warmer conditions in the Chattian (Báldi-Beke 1984; Rögl 1998; Soták 2010). Similar variations in temperatures and salinities were mentioned by Van Simaeys et al. (2004) as prevailing during the early Chattian in the North Sea Basin, assumed to be connected to the beginning of the Late Oligocene Warming Event (Zachos et al. 2001).

Based on our statistical model (Fig. 9) and calcareous nannofossil trophic preferences (Table 2, electr. supplement), the palaeoenvironmental regime under which the Fântânele section sediments were deposited, can be considered as more open-marine for the latest Rupelian to earliest Chattian interval, with normal salinity, with little or no fluctuations in the nutrient supply content, and temperate to cool sea-surface temperatures, while for the youngest part of the section (NP25, early Chattian) this study confirmed the near-shore shallow to brackish palaeoenvironment identified by Székely & Filipescu (2016), characterized by temperate to slightly warmer SSTs, stronger salinity fluctuations, increased terrigenous material runoff and freshwater influx and fluctuations of the distance to the shore.

As a general trend, the first sampled transect assigned to the NP24/CP19a Zone (late Rupelian–early Chattian) is dominated by two types of assemblages, while those belonging to Clusters 2 and 3 (Figs. 5, 8, 9) are characterized by high amounts of *Cyclicargolithus* spp. (always prevailing *Cy. floridanus*) and small reticulofenestrids (especially *R. minuta*), coupled locally with moderate amounts of temperate — cool and cold-water taxa such as *Reticulofenestra* spp. (*R. bisecta* and *R. daviesii* groups), *C. pelagicus* and *B. bigelowii* (Table 2, electr. supplement). The temperate–warm and subtropical water taxa, such as *Pontosphaera* spp., *Helicosphaera* spp. and *Sphenolithus* spp. (Table 2, electr. supplement) display moderate to very low amounts.

The intervals with prevailing *Cy. floridanus* (FA4–FA8, FA11–FA19, FA22) are associated with stable, meso- to eutrophic open-marine conditions, nutrient-rich waters (Aubry 1992; Monechi et al. 2000), without too much water turbulence and no fluctuations in temperature, salinity and nutrient content (Auer et al. 2014), while those with increased small reticulofenestrids, known to flourish along continental margins (Haq 1980), reflect eutrophic conditions (Wade & Bown 2006) and high primary productivity under increased stress factors such as higher contents of terrigenous material derived from the continent (Auer et al. 2014). As indicated in Figs. 5 and 9, intervals with equal participation of *Cy. floridanus* and *R. minuta* contents (Sub-cluster 3a), are displayed in some samples, where apparently a slight decrease in *Cy. floridanus* amount is balanced by an increase in *R. minuta*, possibly due to a moderate run off of continental material.

Contrasting the general stable open-marine conditions reflected by the diverse nannofossil assemblages of this transect, supported also by recent data on foraminifera (Székely & Filipescu 2016), several short intervals (Fig. 5) reflect a drastic decrease in the calcareous nannofossil content (samples FA1–FA2, FA9 and FA29), while those occupied by the assemblages of sub-cluster 1a, suggest a slight deviation from the normal marine stable palaeoenvironmental conditions, associated with the increased amounts of *C. pelagicus*, *Pontosphaera* spp. and *Helicosphaera* spp. The presence of the above mentioned taxa as the main components within the sub-cluster 1a assemblage, are not easily connected to each other's palaeoecological preferences. The highest amount of *C. pelagicus*, a species known to occupy eutrophic surface waters and upwelling areas (Haq 1980; Rahman & Roth 1990; Kameo & Sato 2000), was recorded in sample FA3 and is associated with the increase of *Pontosphaera* spp. These two species characterize this level before the establishment of the stable marine conditions with dominating *Cy. floridanus.* The next intervals occupied by the sub-cluster 1a assemblage, are at the level of sample FA10, and in samples FA23–FA24, being marked by the replacement of *Cy. floridanus* — small reticulofenestrids assemblages with *C. pelagicus–Helicosphaera* spp.*–Pontosphaera* spp. associations. Higher amounts with the open-marine species *C. pelagicus* suggest periods with less surface water column stratification (Auer et al. 2014), connected to fluctuations in upwelling intensity, possible increasing of cool-nutrient availability and increased wave driven surface water turbulence or seasonal marine oscillations. The high amounts of *Pontosphaera* spp. known to thrive under shallow, warmer conditions (Perch-Nielsen 1985b; Firth 1989), considered to tolerate salinity fluctuations (Krhovský et al. 1992; Nagymarosy 2000), in samples with higher amounts of *C. pelagicus* (sub-cluster 1a), might indicate an opportunistic behaviour of this group and increased tolerance of stress factors, such as variation in the type of nutrient available (possible cooler nutrient), column-water mixing and increased upwelling conditions. The highest amounts of *Helicosphaera* spp. at this level, a taxonomical group with preference for shallow hemipelagic, near-shore upwelling conditions (Bukry et al. 1971; Krhovský et al. 1992), supports our assignment of *Pontosphaera* spp. group, to adapt to increased nutrient supply, increased upwelling and nutrient mixing. A slightly increased water salinity as a stress factor is not excluded for both *Pontosphaera* spp. and *C. pelagicus* and goes somehow along with the position of the sub-cluster 1a samples on the left upper side of the nMDS plot (Fig. 9). The terminal part of Transect A (FA30–FA32) containing samples assigned to sub-cluster 2b (Figs. 5, 9), is marked by dominance of temperate–cool to cold water species of *Reticulofenestra* spp. and *Cy. floridanus*, indicative for more meso- to eutrophic sea-surface waters and full marine conditions. Assemblages with *Cy. floridanus*, *Reticulofenestra bisecta* and *Zygrhablithus bijugatus* were described by Melinte (2005) as occurring together within the Oligocene deposits from Romania and were considered to be indicative for warmer conditions with increased nutrients available.

The stable open-marine palaeoenvironment which characterize Transect A, continue also in the second outcrop (Fig. 6). The nannofossil assemblages of sub-cluster 2c are characterized by high amounts of the open-ocean species *Cy. floridanus*, accompanied by the moderate amounts of *C. pelagicus, Reticulofenestra* spp. and less small reticulofenestrids, indicating more stable marine meso-eutrophic conditions, decreased influx of terrigenous material and implicitly higher distance from the shore.

The depositional regime and palaeoenvironment of Transect C (Fig. 7) indicates in general meso- to eutrophic conditions, with strong fluctuations in calcareous nannofossil abundance and diversity. High-resolution sampling at intervals from 10 to 30 cm was applied, providing more detailed information. As represented on the nMDS plot (Fig. 9), the samples of this transect are scattered, indicating highest variability in calcareous nannofossil composition and abundance, coupled with the most variable palaeoenvironmental conditions. The calcareous nannofossil assemblages are dominated by sub-cluster 1b & 2b & 2c, and cluster 4 (less Cluster 3), indicating abrupt short-term variations in basin conditions, reflected also in the blooms of low diverse monospecific assemblages, dominated by one species or genus, coupled additionally with the presence of more barren intervals (Fig. 7) and supported also by the foraminifera data (Székely & Filipescu 2016). The intervals barren of nannofossils and all those where no counting was possible (FB1–FB4, FB25–FB40, FB55–FB66 and FB70), and only qualitative data were collected, correspond to those of infrequent foraminifera intervals (Székely & Filipescu 2016).

Similar assemblages to those of Transects A and B, dominated by the open-ocean species *Cy. floridanus* (sub-clusters 2b & 2c) are met at several levels (FB7–FB8, FB16–FB24, FB42, FB46–FB52). The highest peaks of this species (FB8, FB16, FB49) are associated with *Reticulofenestra* spp. >5 µm (highest amount in FB22 and FB52), with *Cy. abisectus* (highest amount in FB8, FB16 and FB46), with *Reticulofenestra* gr. 3–5 µm (in FB7 and FB43), less *R. minuta*, *Pontosphaera*

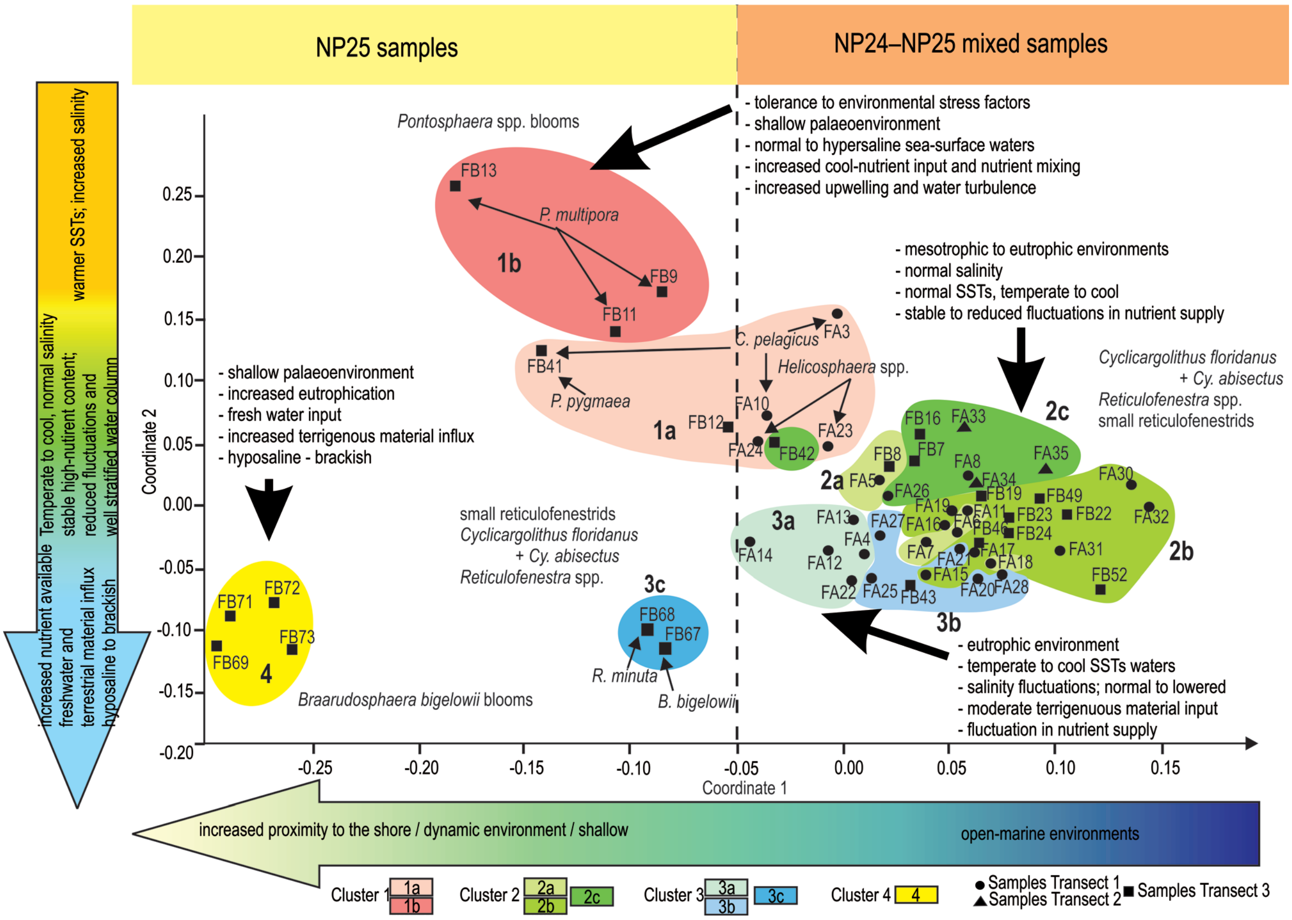

Fig. 9. Non–Metric Multidimensional Scaling (nMDS) showing the clusters distribution according to palaeo-environmental variables.

spp. and *Sphenolithus* spp. (highest peaks in FB22 and FB46). Restoration of short term eutrophic marine conditions, with seasonal high primary productivity is also recorded by the foraminiferal data (Székely & Filipescu 2016).

The short intervals belonging to sub-cluster 1b comprise the most intriguing low diverse assemblages, due to the blooms of *Pontosphaera* spp. (Fig. 7h). Among this genus, *P. multipora* is the dominant species of sub-cluster 1b, while *P. pygmaea* of sub-cluster 1a. It is acknowledged that this genus thrives in shallow, near shore warmer marine environments (Perch-Nielsen 1985b; Firth 1989, present study), under stable marine conditions (Melinte 2005; Bartol et al. 2008; Garecka 2012) and tolerates some salinity fluctuations (Krhovský et al. 1992; Nagymarosy & Voronina 1992, Nagymarosy 2000; Garecka 2012). Several authors indicate adaptability to increased salinity (Báldi-Beke 1984; Melinte 2005; Bartol et al. 2008; Garecka 2012) while others identify adaptation to more hyposaline conditions (Van Simaeys et al. 2004). The shallowing trend indicated by calcareous nannofossil abundance fluctuations were recognized also by means of low abundance and low diverse foraminiferal assemblages (Székely & Filipescu 2016). This interval is comprised between two periods of fully marine, meso-eutrophic palaeoenvironment, and indicative of high nutrient availability, temperate to warmer SSTs and normal to slightly increased salinity (Fig. 9). The presence of *Pontosphaera* spp. in association with the *Cy. floridanus–abisectus* group, indicates that this genus can also adapt to more stable marine eutrophic conditions, with normal salinity. The timing of these blooms, immediately before and after such conditions might be due to regional or local seasonal variations. Two regime models might explain the slightly increased sea surface water salinity and the increased amounts of this genus. The first one might be associated with the prevailing of a warmer drier climate, with reduced connectivity of the area to the more marine palaeo-environment, with no/or very little continental riverine input into the basin. Seasonal warming and intense evaporation might have triggered the creation of shallower intervals with increased sea-surface water salinity, eutrophic near shore palaeoenvironment, as indicated by the positioning of samples FB9, FB11, FB 12 and FB13 on the nMDS plot (Fig. 9). The second possibility might be due to the combination of reduced seasonal fluvial input, with upwelling of denser more saline nutrient-rich waters to the surface. The intriguing and opportunistic behaviour of this genus is given by the many assemblage combinations where it has been found in our material. In the Fântânele section, excepting the cases when this genus is associated with *Cy. floridanus–abisectus* and when found alone, it was recorded in association with high amounts of *C. pelagicus* and less *B. bigelowii*, co-occurring together in sample FB41, which might reflect a certain tolerance to dense cooler nutrient influx (*P. pygmaea* dominates this interval) caused by the increased upwelling, nutrient mixing, not necessarily connected to cooler SSTs waters. The salinity ranges from normal to slightly hypersaline. The co-occurrence together with *R. minuta* in sample FB43, and the positioning on the nMDS plot (Fig. 9), does not necessarily imply a near-shore environment with very shallow water depth, but it seems to be more marine and within the normal sea surface water salinity, with moderate continental material influx and high tolerance of environmental stress.

The uppermost part of this outcrop belonging to cluster 4 (FB69, FB71–FB73) is associated with blooms of monospecific assemblages of *B. bigelowii*. Approximately 10 cm of non-calcareous interval is present at the level of sample FB70. The position of samples FB67–FB68 on the nMDS plot (Fig. 9) marks the beginning of the shallowest period recorded in the Fântânele section, with extreme eutrophication due to increased seasonal terrigenous nutrient and fresh water influx, near shore high energy wave dominated palaeoenvironment, cool nutrient available due to mixing and seasonal upwelling and increased precipitation. All these variables taken together, might have contributed to the lowered sea-surface waters as indicated by the blooms of *B. bigelowii*. In additional, the sample FB68, displays abundant *R. minuta*, a species associated with high productivity eutrophic environment and increased continental influx. *B. bigelowii* displays opportunistic behaviour and flourishes under reduced concurrence and together with *R. minuta*, are considered indicator taxa for tolerance of high environmental stress (Wade & Bown 2006; Bartol et al. 2008; Auer et al. 2014; present study). Samples FB67–FB68 also display a very low abundance of foraminifera, while samples FB69–FB73 are barren in foraminifera (Székely & Filipescu 2016). The absence of planktonic and benthic foraminifera could be explained by the fresh-water influence and lower salinity (Székely & Filipescu 2016), as also suggested by the calcareous nannofossils. The calcareous nannofossil fluctuations from the last outcrop can be connected to increased proximity to the shore, shallowing, and terrigenous material influx and not least to fluctuations in salinity. In the Central Paratethys Realm, blooms of *Braarudosphaera bigelowii* in the Oligocene were considered to have been caused by the partial separation of the Paratethys from the Mediterranean and were connected to the existence of anoxic environmental conditions (Nagymarosy 1991). Monospecific assemblages of *B. bigelowii* are mentioned from the early Rupelian (Rusu et al. 1996; Melinte 2005), in both the Eastern Carpathians and Transylvanian areas.

The absence of the warm open marine *Discoaster* genus (Lohmann & Carlson 1981; Aubry 1992; Young 1998; Villa et al. 2008) coupled with the low amounts of autochthonous subtropical warm water taxa (*Sphenolithus* spp., *Helicosphaera* spp. and *Zygrhablithus bijugatus*) indicate shallow marine conditions, with temperate to cooler SSTs for the first and second outcrops, and with a slightly warmer and shallow marine environment for the youngest one.

Palaeogeographical considerations

The Transylvanian Palaeogene formations crop out and are widespread around the northern parts of the Transylvanian Basin, in the Pienide nappes (Krézsek & Bally 2006). Starting with the late Rupelian the emplacement of the Pienide nappes took place (Sãndulescu et al. 1981), resulting in the deposition of coarse-grained siliciclastic sediments (Tischler et al. 2008). Differences in depositional settings from area to area are acknowledged for the late Rupelian–Chattian interval. The southern part of the basin was exposed and the central part was dominated by continental, inner to outer shelf palaeoenvironments (Petrescu et al. 1989; Rusu 1995; Filipescu 2001). The situation in the northern part of the basin was totally different, a deeper marine environment (Vima Formation) and slope/outer to middle fan dominated (Valea Carelor, Birţu and Borşa Formations) (Mészáros et al. 1971; Dicea et al. 1980). The more marine character of these deposits and the northward thickening of the Oligocene successions in the area are due to a flexural down-bending caused by the emerging of the Pienides nappes (Săndulescu & Micu 1989; Aroldi 2001; Tischler et al. 2008). Several authors considered the late Rupelian sediments to be transgressive (Rusu 1989; Popescu & Brotea 1994; De Broucker et al. 1998; Ciulavu et al. 2000), but the Chattian siliciclastic sediments to be progradational (Krézsek & Bally 2006). During the Chattian, important sedimentary changes occurred in relation to the climate cooling (Abreu & Haddad 1998) and to the global eustatic sea-level fall (Hardenbol et al. 1998).

The palaeoenvironmental reconstruction of the Fântânele section highlights the development of the north-western Transylvanian Basin in the Paratethyan settings during the Oligocene (Székely & Filipescu 2016). Tischler et al. (2008) pointed out that the late Rupelian–early Chattian progradational phases do not match to the global eustatic sea-level changes of Haq et al. (1987). Székely & Filipescu (2016) connected the foraminifera abundances within the Fântânele section with high-frequency sequences associated with 4th or 5th order relative sea-level oscillations for Transects A and B, while the strong progradational trend observed in Transect C suggests an increased continental influence. These data are also supported by the calcareous nannofossil changes along the section, changes which might be due to episodic isolation of the basin and to tectonic activity in the area. A sedimentary hiatus was observed at the top of the Vima Formation (Hofmann 1887; Majzon 1950; Popescu 1971; Popescu & Iva 1971), highlighting the possibility that these sediments could have been eroded as a result of a sea-level fall (Székely & Filipescu 2016) which gave a diachronic upper boundary for the Vima Formation.

Conclusions

Biostratigraphically, based on the presence and overlapping ranges of several marker species, the investigated sediments were dated as belonging to the late Rupelian–Chattian interval. Correlation to the following biozones was possible: the NP24 — *Sphenolithus distentus* Zone, the NP25 — *Sphenolithus ciperoensis* Zone, the CP19a — *Cyclicargolithus floridanus* Subzone, the CP19b — *Dictyococcites bisectus* Subzone, the CNO4 — *Sphenolithus distentus*/*Sphenolithus predistentus* CRZ, and the CNO5 — *Sphenolithus ciperoensis* TZ.

Several bioevents for the Oligocene subdivision were discussed and the following were considered as reliable for the investigated interval: the LO of *Sphenolithus predistentus*, the LO of *Sphenolithus distentus,* the FO of *Pontosphaera* cf. *enormis*. Important marker species such as *Helicosphaera recta* and *Sphenolithus ciperoensis* were recorded.

Variations in the abundance of autochthonous calcareous nannofossils and the clusters distribution along the investigated interval, allowed the palaeoenvironmental reconstruction of the Fântânele Section. Alternations from open marine to shallower conditions are documented here.

Intervals with short-term abrupt changes in nannofossil composition and abundance are associated with the blooms of *Pontosphaera* spp. and *B. bigelowii*. New insights on *Pontosphaera* genus palaeoecology indicates opportunistic behaviour, quick response to fast changes in the environment, increased tolerance of stress factors and great adaptability to a wide range of palaeoenvironmental conditions, from normal fully marine to shallower, to the type and availability of nutrient content, normal to increased salinity, nutrient mixing and increased upwelling intensity in the upper water column.

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Supplementum

Table 1: List of calcareous nannofossils species present in the Fântânele Section together with their counts.

a) Autochtonous calcareous nannofossils	**Number of specimens / specie**
Blackites sp.	7
Braarudosphaera bigelowii (Gran & Braarud, 1935) Deflandre, 1947	1677
Calcidiscus pataecus (Gartner, 1967) de Kaenel & Villa, 1996	2
Chiasmolithus altus (Bukry & Percival, 1971)	4
Coccolithus pelagicus (Wallich, 1877) Schiller, 1930	983
Coronocyclus sp. (Hay, Mohler & Wade, 1966)	26
Cyclicargolithus abisectus (Muller, 1970) Wise, 1973	452
Cyclicargolithus floridanus (Roth & Hay, in Hay et al., 1967) Bukry, 1971	3441
Discoaster deflandrei (Bramlette & Riedel, 1954)	1
Helicosphaera euphratis (Haq, 1966)	21
Helicosphaera intermedia (Martini, 1965)	11
Helicosphaera recta (Haq, 1966) Jafar & Martini, 1975	163
Helicosphaera sp.	9
Pontosphaera desueta (Müller, 1970) Perch-Nielsen, 1984	134
Pontosphaera cf. *enormis* (Locker, 1967) Perch-Nielsen, 1984	55
Pontosphaera multipora (Kamptner, 1948 ex Deflandre in Deflandre & Fert, 1954) Roth, 1970	1300
Pontosphaera pygmaea (Locker, 1967) Bystricka & Lehotayova, 1974	433
Pyrocyclus orangensis (Bukry, 1971) Backman, 1980	46
Reticulofenestra bisecta (Hay, Mohler & Wade, 1966) Roth, 1970	467
Reticulofenestra callida (Perch-Nielsen, 1971) Bybell, 1975	88
Reticulofenestra daviesii (Haq, 1968) Haq, 1971	199
Reticulofenestra dictyoda (Deflandre in Deflandre & Fert, 1954) Stradner in Stradner & Edwards, 1968	46
Reticulofenestra lockeri (Müller, 1970)	476
Reticulofenestra minuta (Roth, 1970)	1952
Reticulofenestra scissura (Hay, Mohler & Wade, 1966)	6
Reticulofenestra scrippsae (Bukry & Percival, 1971)	44
Reticulofenestra stavensis (Levin & Joerger, 1967) Varol, 1989	202
Reticulofenestra gr. 3-5 µm (Hay, Mohler & Wade, 1966)	563
*Sphenolithus akropodus (*de Kaenel & Villa, 1996)	29
Sphenolithus ciperoensis (Bramlette & Wilcoxon, 1967)	10
Sphenolithus dissimilis (Bukry & Percival, 1971)	1
Sphenolithus distentus (Martini, 1965) Bramlette & Wilcoxon, 1967	26
Sphenolithus moriformis (Bronnimann & Stradner, 1960) Bramlette & Wilcoxon, 1967	136
Sphenolithus predistentus (Bramlette & Wilcoxon, 1967)	80
Sphenolithus sp. (Deflandre in Grassé, 1952)	14
Thoracosphaera sp. (Kamptner, 1927)	10
Triquetrorhabdulus longus (Blaj & Young, 2010)	1
Zygrhablithus bijugatus (Deflandre in Deflandre &Fert, 1954) Deflandre, 1959	64
Total	**13180**
b) Reworked calcareous nannofossils	
Calculites obscurus (Deflandre, 1959) Prins & Sissingh *in* Sissingh, 1977	3
Cyclagelosphaera reinhardtii (Perch-Nielsen, 1968) Romein, 1977	1
Cyclicargolithus luminis (Sullivan, 1965) Bukry, 1971	3
Neochiastozygus sp. (Perch-Nielsen, 1971)	1
Pontosphaera distincta (Bramlette & Sullivan, 1961) Roth & Thierstein, 1972	1
Prediscosphaera cretacea (Arkhangelsky, 1912) Gartner, 1968	3
Prinsius sp. (Hay & Mohler, 1967)	1
Rhabdosphaera sp. (Haeckel, 1894)	2
Sphenolithus obtusus (Bukry, 1971)	2
*Toweius rotundus (*Perch-Nielsen in Perch-Nielsen et al., 1978)	1
Watznaueria barnesiae (Black in Black & Barnes, 1959) Perch-Nielsen, 1968	9
Total	**27**

Table 2: Published references emphasising species known palaeoecological preferences and the findings from this study: [1] Gran & Braarud (1935); [2] McIntyre & Bé (1967); [3] Bukry (1971); [4] Bukry & Percival (1971); [5] Bukry et al. (1971); [6] Haq & Lipps (1971); [7] Takayama (1972); [8] Okada & Honjo (1973); [9] Bukry (1974); [10] Roth & Berger (1975); [11] Haq et al. (1977); [12] Schmidt (1978); [13] Okada & McIntyre (1979); [14] Haq (1980); [15] Lohmann & Carlson (1981); [16] Báldi-Beke (1984); [17] Perch-Nielsen (1985b); [18] Flores & Sierro (1987); [19] Chepstow-Lusty et al. (1989); [20] Firth (1989); [21] Rahman & Roth (1990); [22] Wei & Wise (1990); [23] Nagymarosy (1991); [24] Wei & Thierstein (1991); [25] Aubry (1992); [26] Chepstow-Lusty et al. (1992); [27] Krhovský et al. (1992); [28] Nagymarosy & Voronina (1992); [29] Pujos (1992); [30] Sissier et al. (1992); [31] Wei et al. (1992); [32] Giraudeau et al. (1993); [33] Giraudeau & Rogers (1994); [34] Roth (1994); [35] Winter et al. (1994); [36] Flores et al. (1995); [37] Ziveri et al. (1995); [38] Fornaciari et al. (1996); [39] De Kaenel & Villa (1996); [40] Chapman & Chepstow-Lusty (1997); [41] Cunha & Shimabukuro (1997); [42] Flores et al. (1997); [43] Wells & Okada (1997); [44] Aubry (1998); [45] Young (1998); [46] Peleo-Alampay et al. (1999); [47] Svábenická (1999); [48] Cachão & Moita (2000); [49] Kameo & Sato (2000); [50] Monechi et al. (2000); [51] Nagymarosy (2000); [52] Negri & Villa (2000); [53] Pagani et al. (2000); [54] Takahashi & Okada (2000); [55] Oszczypko-Clowes (2001); [56] Bralower (2002); [57] Geisen et al. (2002); [58] Kameo (2002); [59] Kelly et al. (2003); [60] Ćorić & Rögl (2004); [61] Eisenach & Kelly (2004); [62] Gibbs et al. (2004); [63] Persico & Villa (2004); [64] Van Simaeys et al. (2004); [65] Thierstein et al. (2004); [66] Tremolada & Bralower (2004); [67] Ziveri et al. (2004); [68] Flores et al. (2005); [69] Melinte (2005); [70] Gamboa & Shimabukuro (2006); [71] Villa & Persico (2006); [72] Wade & Bown (2006); [73] Bartol et al. (2008); [74] Ćorić & Hohenegger (2008); [75] Villa et al. (2008); [76] Silva et al. (2008); [77] Narciso et al. (2010); [78] Shcherbinina (2010); [79] Garecka (2012); [80] Plancq et al. (2013); [81] Auer et al. (2014); [82] Ozdínová & Sotak (2014); [83] Kallanxhi et al. (2016); [84] Holcová (2017); [85] present study. Note: some of the references from table 3 of Villa et al. (2008) are included here.

Species versus their known palaeoecology	**Palaeoenvironment (eutrophic, mesotrophic, oligotrophic)**	**Type of nutrient t / Trophic preferences**	**Temperature: warm, temperate, cold**	**Salinity: brackish–hyposaline, normal, hypersaline**	**Geological setting**	**Others**
Braarudosphaera bigelowii	Eutrophic (1, 7, 9, 30, 41, 46, 59, 61, 70, 73, 82, 85)	High-nutrient input (23, 65, 77) Terrigenous material influx (47, 81, 85) Cold nutrient-rich waters (60)	Warmer (63) Cool (85)	Hyposaline–brackish (1, 3, 7, 9, 23, 28, 46, 51, 60, 77, 81, 85) Hypersaline (83) Absent in high-salinity (9)	Neritic (1, 7, 9) Shallow / increased proximity to the shore (23, 28, 51, 64, 73, 81, 85) Open-marine (30, 46, 59, 61, 70) Coastal areas (46)	Increased environmental stress (1, 7, 9, 73, 81, 85) Opportunistic / reduced competition (30, 46, 59, 61, 65, 70, 73, 85)
Coccolithus pelagicus	Eutrophic (21, 57) Oligotrophic (82)	Cool high-nutrient input (2, 13, 34, 48, 60, 81) High terrigenous material influx (57)	Cold (13, 35, 57, 67) Temperate (55, 63, 71, 75, 82) Warm (22)	Hyposaline (2) Different salinity ranges (76)	Open-ocean (2, 81, 84) Turbulence / mixing / non-stratification (57, 74, 81) Upwelling (21, 32, 33, 60, 81, 84)	Middle–high latitudes (11, 22, 43, 48)
***Cyclicargolithus* genus**						Eurytopic (77)
Cy. floridanus	Eutrophic (22, 25, 50, 81, 82) Mesotrophic to eutrophic (85)	No changes in temperature / no to reduced mixing in nutrient (81, 83, 85) Decrease in abundance when influx of warm, low nutrient (53)	Temperate (22, 55, 82, 85) Temperate–cold (25) No-temp affiliation (63) Warm (69)		Open-marine (14, 80, 81) Mid-latitudes (20)	Eurytopic (78, 85) No / reduced turbulence (81, 85)
***Discoaster* spp.**	Oligotrophic (14, 15, 18, 19, 25, 26, 31, 44, 45, 75)	Absent / rare in high fertility waters (19, 40)	Warm (14, 15, 18, 19, 25, 26, 31, 44, 45)		Deep-marine, stable (14, 15, 18, 19, 25, 26, 31, 39, 44, 45, 75) Absent in marginal seas (17)	

Table 2 (continued)

Species versus their known palaeoecology	**Palaeoenvironment (eutrophic, mesotrophic, oligotrophic)**	**Type of nutrient t / Trophic preferences**	**Temperature: warm, temperate, cold**	**Salinity: brackish–hyposaline, normal, hypersaline**	**Geological setting**	**Others**
***Helicosphaera* spp.**	Eutrophic (17, 72) Oligotrophic (81)	High-productivity waters (17, 29, 67, 68, 69, 77) High terrigenous nutrient influx (5, 77)	Warm (5, 6, 52, 69, 82) Warm–temperate (17, 22, 67, 85)	Hyposaline–brackish (29, 68, 72, 77) Normal to slightly increased salinity (85)	Shallow / hemipelagic / near continental (5, 6, 17, 20, 27, 51, 67) Upwelling (17, 37, 67, 79, 85)	
***Pontosphaera* spp.**	Eutrophic (25, 85)	Nutrient mixing and sea surface turbulence (85)	Warm (64,79) Temperate–warm (85)	Tolerate slight salinity fluctuations (27, 28, 79, 82) Hyposaline (64) Hypersaline (16, 73, 79, 82) Normal–hypersaline (85)	Shallow/ near shore (17, 20, 27, 28, 51, 64, 79, 85) Stable marine conditions (69, 73, 79)	Eurytopic (85) Opportunistic (85)
Pontosphaera multipora		Adapt to nutrient mixing and sea surface turbulence (85)	Warm (64) Temperate–warm (85)	Normal (28) Normal–hypersaline (85)	Shelf areas (17) Shallow/ near shore (51, 85)	Opportunistic (85)
Pontosphaera pygmaea		Adapt to nutrient mixing and sea surface turbulence (85)	Warm (64) Temperate–warm (85)	Normal–hypersaline (85)	Shallow/ near shore (51, 85)	Opportunistic (85)
***Reticulofenestra* genus**	Eutrophic (52, 68, 73)	Cold high-nutrient input (14, 49)				Eurytopic (78)
Reticulofenestra bisecta	Eutrophic (82, 85)	High-nutrient input (69, 85)	Warm (52, 69) Warm–temperate (22) Temperate (31, 55,63, 71, 75, 82) Temperate–cool (85) Cold (51)		Neritic / near-continental (27, 69)	High latitudes (11, 20)
Reticulofenestra callida			Cold (22, 51)			
Reticulofenestra daviesii			Cold (24) Cool (31, 50, 63, 71, 75)			
Reticulofenestra lockeri	Eutrophic (51) Oligotrophic (82)	High-nutrient input (51, 79)	Cold (22, 51, 82)	Hypersaline (79)	Shallow (79)	
Reticulofenestra minuta	Eutrophic (14, 72, 85) More oligotrophic (60, 74)	Terrigenous high-nutrient input (14, 72, 81, 85) Oscillations in nutrient (42, 43, 58, 83) High productivity environments (72, 85)	Warmer (60, 72, 74)	Brackish to hypersaline (72) Hyposaline (74) Normal to hyposaline (85)	Near-shore / shallow / continental margin (5, 14, 27, 72, 81)	Better stratified column water / stable (60, 74) Environmental stress / instability (72, 81, 84, 85) Opportunistic behaviour (72)
Small *Reticulofenestra* (<5)	Eutrophic (58, 85)	High-nutrient input (8, 25, 36, 54, 85)				Environmental stress / instability (84, 85)

Table 2 (continued)

Species versus their known palaeoecology	**Palaeoenvironment (eutrophic, mesotrophic, oligotrophic)**	**Type of nutrient t / Trophic preferences**	**Temperature: warm, temperate, cold**	**Salinity: brackish–hyposaline, normal, hypersaline**	**Geological setting**	**Others**
Reticulofenestra scrippsae					Neritic+open-marine (4)	
Sphenolithus genus	Oligotrophic (17, 22,44, 62, 63) Eutrophic (72)	Nutrient input (81)	Warm (17, 22, 38, 44, 56, 63, 75)		Deep-marine (38, 39) Shallow, near-continental, stable (17, 72)	
S. moriformis	Oligotrophic (62)		Warm (25, 31, 50, 62, 66, 71, 75)		Near-shore (81)	
Zygrhablithus bijugatus	Oligotrophic (22) Eutrophic (66, 75)		Warm (62, 64, 69) Temperate (75) Cool (66)		Near-shore (27, 50, 51, 69)	

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