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Late Albian calcareous dinocysts and calcitarchs record linked to environmental changes during the final phase of OAE 1d – a case study from the Tatra Mountains, Central Western Carpathians

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Calcareous dinocysts and calcitarchs have been investigated for the first time within the Upper Albian limestone and marl succession of the Zabijak Formation from the High-Tatric Unit in the Tatra Mountains (Central Western Carpathians), related to the Oceanic Anoxic Event 1d (OAE 1d). Four groups of morphotaxa of calcareous dinocysts have been distinguished. They totally dominate the assemblages, and belong to the pithonellids. They are represented by *Pithonella sphaerica* (Kaufmann in Heer) and *P. ovalis* (Kaufmann in Heer), which dominate, as well as *P. trejoi* Bonet and *P. lamellata* Keupp in Keupp and Kienel, which are less abundant. Two other morphotaxa, *Colomisphaera gigantea* (Borza) and *Cadosina oraviensis* Borza, occur sporadically in the assemblages. Both forms represent the calcitarch group, which assembled calcispheres of unknown taxonomic affinity. The calcareous dinocyst and calcitarch diversity is low to moderate, compared to the general species richness known from Late Albian assemblages in other Western Tethyan sections. This is interpreted as a result of nutrient input fluctuations due to changes in the circulation pattern of surface and intermediate waters. The changes in the *P. sphaerica*/*P. ovalis* ratio along the Upper Albian section are here correlated with short-term (third-order) sea level fluctuations including transgressive and regressive events and a highstand. Pelletization processes might have influenced cyst abundance on the sea floor, especially during periods with oligotrophic surface waters.

Key words: calcareous dinocysts, calcitarchs, nutrient input and sea level fluctuations, Upper Albian, OAE 1d, Tatra Mountains.

INTRODUCTION

The Late Albian was a time of enhanced marine burial of sedimentary organic carbon as related to inorganic carbon, which is characterized by a positive excursion in $\delta^{13}C$ values in marine deposits, known from various Tethyan, North Atlantic, Pacific and epicontinental environments, and attributed to Oceanic Anoxic Event 1d (e.g., Coccioni et al., 2001; Strasser et al, 2001; Kennedy et al., 2004; Bornemann et al., 2005; Jarvis et al., 2006; Gale et al., 2011; Papp et al., 2013; Scott et al., 2013; Horikx et al., 2014; Melinte-Dobrinescu et al., 2015). Such strata (a limestone and marl succession) with a positive $\delta^{13}C$ excursion, deposited on the northern shelf of the Alpine–Carpathian microcontinent, were also recorded from the Central Western Carpathians (the Tatra Mountains; Bąk et al., 2016). They contain marine and land-derived organic matter, strongly degraded under oxic conditions. These carbonate deposits, Late Albian in age, are enriched in calcareous dinocysts. However, there are relatively few publications which deal with calcareous dinocysts from the Cretaceous Tethyan realm of the Carpathians, with the exception of Upper Jurassic through Lower Cretaceous assemblages (mostly Tithonian–Aptian) recorded in numerous Western Carpathian settings (e.g., Nowak, 1963, 1968, 1974; Borza, 1964, 1969, 1986; Řehánek, 1987; Reháková and Michalík, 1994, 1996; Lintnerová et al., 1997; Michalík et al., 1999, 2009; 2016; Reháková, 2000a, b; Pszczółkowski and Myczyński, 2004; Olszewska, 2005; Olszewska et al., 2008; Pszczółkowski et al., 2016).

In this paper, we provide the first overview of calcareous dinocysts and calcitarchs, totally dominated by pithonellids from the Upper Albian carbonate deposits of the High-Tatric Unit in the Central Western Carpathians. Using new palaeontological data related to these microfossils from the Tatra Mountains, we make suggestions as to the possible environmental conditions prevailing on the northern shelf of the Alpine – Carpathian microcontinent (Fig. 1) that influenced the development of these organisms during the time corresponding to Oceanic Anoxic Event 1d.

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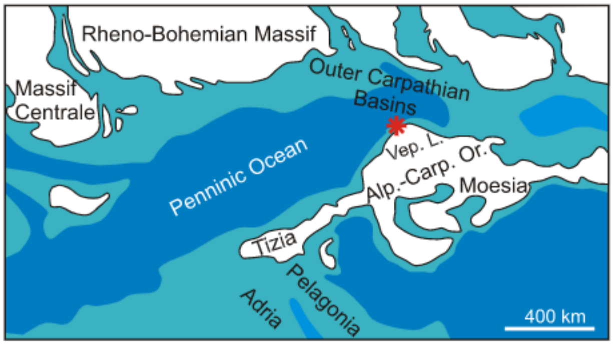

Fig. 1. Upper Albian (~100 Ma) palaeogeographic map showing the location of the strata studied (red asterisk) in the Western Tethys (map redrawn after http://deeptimemaps.com – simplified); names of regions partly after Michalik et al., 2007)

Alp.-Carp. Or. – Alpine–Carpathian Orogen;
Vep. L. – Veporic Land

CALCAREOUS DINOFLAGELLATES AND CALCITARCHS

Single-celled spherical to ovoid, calcareous microfossils known in the fossil record from the Paleozoic to the Cenozoic have been usually referred to as “calcispheres” (Williamson, 1880). During over a century of palaeontological studies, many microfossils previously assigned to “calcispheres” have been classified to various taxonomic groups (see Kaźmierczak and Kremer, 2005). They were considered to belong to various groups of foraminifers, calcareous algal spores, protozoans, spores of dasyclad algae or nannoplankton. Many forms have been proved to represent dinoflagellate calcareous cysts as resting, reproductive or coccoid stages of their life cycle (Meier et al., 2009) belonging to the Family Thoracosphaeraceae (Elbrächter et al., 2008). Despite many previous investigations, the biological affinities of many “calcispheres” remain unknown. For these forms Versteegh et al. (2009) proposed a new incertae sedis group of the Calcitarcha that includes all calcareous microfossils with a central cavity and currently lacking taxonomic allocation.

Pithonellids, which are the dominant calcareous microfossils in the assemblage studied, have been considered to belong to calcareous dinoflagellates (Elbrächter et al., 2008; Wendler et al., 2013; Wendler and Bown, 2013). Two other forms – *Colomisphaera gigantea* (Borza) and *Cadosina oraviensis* Borza – which are present in the material studied, represent the calcitarch group in which are assembled “calcispheres” of unknown taxonomic affinity.

GEOLOGICAL SETTING

The Central Western Carpathians are composed of three principal superunits: the Tatric, Veporic, and Gemeric basement cover crustal imbricates (Plašienka, 1999). The Tatric superunit (Tatricum) frames the outer (northern) part of the Central Western Carpathians block (microcontinent), formed dominantly by pre-Alpine crystalline basement complexes and a Late Paleozoic–Mesozoic (up to Lower Turonian) sedimentary cover. The deposits studied belong to the High-Tatric units occurring in the Tatra Mountains which are a part of the Tatric superunit (Plašienka, 2003). The High-Tatric units are exposed in three tectonic-facies units: Kominy Tylkowe, Czerwone Wierchy and Giewont (e.g., Kotański, 1961). The Kominy Tylkowe Unit (called the autochthonous unit) rests directly on the crystalline basement, and comprises a Lower Triassic (?Permian) through mid-Cretaceous sedimentary succession (e.g., Rabowski, 1959; Kotański, 1961; Lefeld, 1968; Jurewicz, 2005; Jezierska et al., 2016, Wolska et al., 2016). Its youngest part, the Zabijak Formation (Krajewski, 2003) contains echinodermal-foraminiferal limestones of the Żeleźniak Member, which are overlain by marls and marly limestones of the Kamienne Member. The Żeleźniak Member and the lowermost part of the Kamienne Member, both late Albian in age (Bąk and Bąk, 2013) contain abundant calcareous dinocysts which are an object of this study.

MATERIAL AND METHODS

The section studied is located in the Żeleźniak gully, a left tributary of the Kościeliska Valley in the Polish part of the Tatra Mountains (Fig. 2). The exposure is situated at the bottom of the gully, and on its slopes (Fig. 2C), extending for a distance of 100 m below a 3 m high waterfall. The lower part of the section comprises the uppermost part of a limestone succession (Żeleźniak Member), ~30 cm thick. This is overlain by grey and dark grey marls followed by green marls (Kamienne Member).

We studied calcareous dinocysts and calcitarchs in thin-sections 5 x 3 cm in size made from rock samples. Four rock samples represent a 30 cm thick echinodermal-foraminiferal limestone layer, and 13 samples represent a 4 m marly interval that comprises 2 m of dark grey marls followed by 2 m of green marls (Fig. 3). The rock material from the same stratigraphical position has been a subject of earlier studies, which concerned bio- and chemostratigraphy, as well as organic matter analyses (Bąk, 2015; Bąk et al., 2015; Bąk et al., 2016).

Contents of planktonic foraminifers, pellets and phosphates are shown as percent values of the total microfacies components. The total content of pithonellids and calcitarchs was estimated on the basis of regular traverses at 200 μm intervals across a slide area of ~6 cm^2. Taxonomic studies were based on observations of their morphological features such as shape, size, aperture, and wall structure (mostly, the wall crystal orientation) following the determinations known from literature (e.g., Keupp, 1987, 1990; Reháková, 2000a, b; Wendler et al., 2002a, 2013; Kohring et al., 2005; Wendler and Bown, 2013; Omaña et al., 2014).

STRATIGRAPHY

The planktonic foraminiferal assemblages studied in the Żeleźniak Gully section and the nearby sections (Bąk and Bąk, 2013; Bąk, 2015) show that the whole interval corresponds to the lower part of the *Parathalmanninella appenninica* Zone (Upper Albian; Fig. 3; for discussion – see Bąk et al., 2016). The positive excursion in $\delta^{13}C$ values recorded in the limestone layer and first marly interval (Bąk et al., 2016), with values comparable to that seen in the GSSP section at Mont Risou, east of Rosans, Hautes-Alpes (Kennedy et al., 2004; Gale et al., 2011), and Speaton, Yorkshire, England (Mitchell et al.,1996), indicate that this part of the section corresponds to Oceanic Anoxic Event 1d.

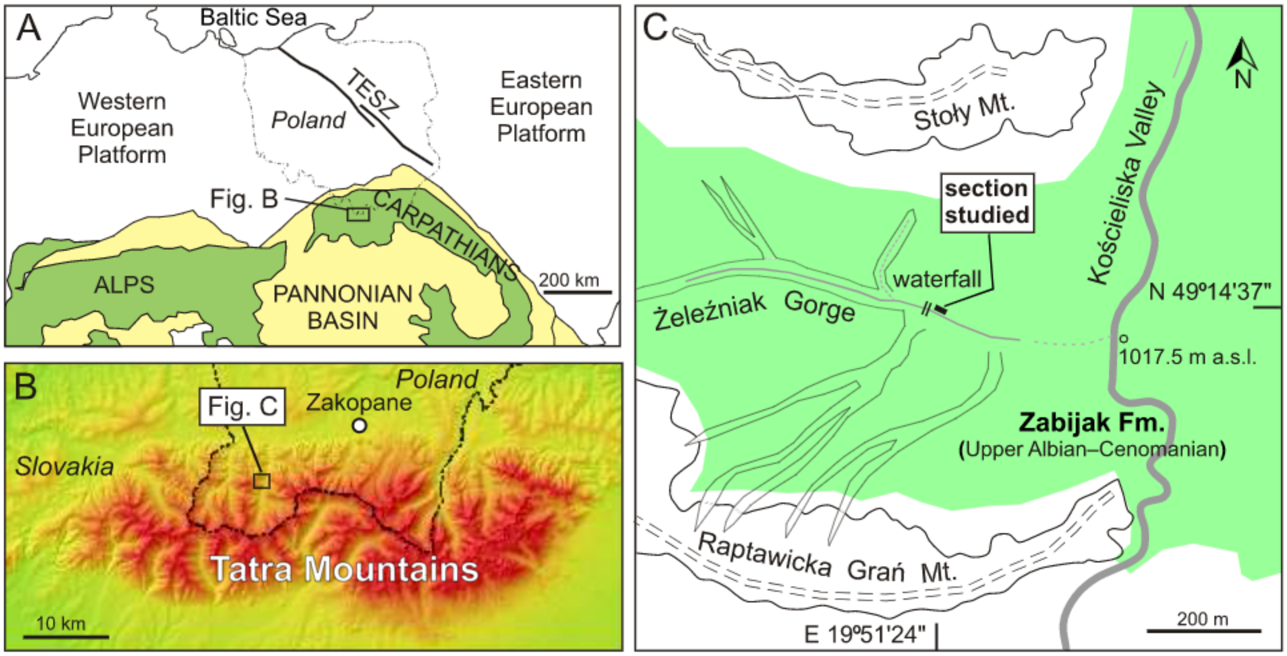

Fig. 2A – Carpathians against the background of a simplified geological map of the Alpine orogeny and their foreland; B – location of the area studied in the Tatra Mountains (Inner Carpathians) on a contour map (map after Bryndal, 2014); C – location of the section studied in the Żeleźniak Gorge

RESULTS

Calcispheres appear in all samples across the section studied (Fig. 3). Their total content ranges from 5 up to 20% of microfacies constituents in limestone and grey marl corresponding to the OAE 1d interval. Above this interval, in green marlstones, their content diminishes and fluctuates between 3 and 7%. A characteristic feature of these deposits is the occurrence of planktonic foraminifers, dominated by hedbergellids and less common heterohelicids (Fig. 4A, B), as well as of two types of pellet – homogeneous and not digested, including nearly complete tests of planktonic foraminifers and pithonellids (Fig. 4C, D).

Six morphotaxa of “calcispheres” were recognized within the section studied (Figs. 3 and 5). The assemblages are dominated by calcareous dinocysts, which are represented by the genus *Pithonella* Lorenz, 1902 (Fig. 5) belonging to *P. ovalis* (Kaufmann in Heer), and *P. sphaerica* (Kaufmann in Heer), which comprise >95% of the individuals observed. Less abundant are *P. trejoi* Bonet and *P. lamellata* Keupp in Keupp and Kienel. There are also forms which are here classified as *Colomisphaera gigantea* (Borza) and *Cadosina oraviensis* Borza belonging to calcitarchs but displaying the pithonellid wall spectrum. The first one includes a large forms currently questionably classified to the Ciliates. The specimens of *Cadosina oraviensis* Borza contain forms with walls that appear to be dominated by an organic substance. The precise taxonomic position of these morphotaxa is impossible to determine at this state of study due to the low number of individuals.

The species richness of the calcitarch and calcareous dinocyst assemblages ranges from 3 to 6 in an individual sample (Figs. 3 and 6). They are generally moderately- to well-preserved even if the rock matrix was recrystallized (Fig. 5).

Based on the changes in assemblage distribution, three intervals can be discriminated in the section investigated. Interval 1 and Interval 2 correspond to the OAE 1d event. Interval 1 comprises light grey echinoderm-foraminiferal limestone containing numerous pellets and phosphates (Fig. 6). “Calcisphere” assemblages are represented only by pithonellids ranging from 2 to 4 species per sample. *Pithonella ovalis* prevails over other taxa. Lying above, Interval 2 contains grey marls including abundant pellets (Fig. 6) and land-derived floral components (Bąk et al., 2016). Calcareous dinocysts and a calcitarch assemblage is rich in this interval consisting of up to 55% of all constituents (sample Z8) and highly diverse (species diversity up to 6; Fig. 6); *Pithonella sphaerica* with thick, double-layered, calcareous walls dominates here consisting of nearly 70% of the assemblages. Interval 3 is represented by green marls lying above the OAE 1d deposits. It is again characterized by the dominance of *P. ovalis* with an overall lower species number, up to 3 (Fig. 6).

The *P. sphaerica*/*P. ovalis* ratio that is used as a bathymetric indicator in marine environments (e.g., Dias-Brito, 2000; Wendler et al., 2002b) fluctuates along the section studied (Fig. 6) ranging from 0.2 to 2.7 (average value per intervals, described above). The highest values corresponds to the dark grey marls of the OAE 1d interval.

The fluctuations in pithonellid distribution correspond also to fluctuations in the total number of pellets visible in thin-section views, especially in those samples which contain whole or partly broken planktonic foraminiferal tests. However, this distribution does not coincide with total calcium carbonate content (Bąk et al., 2016; Fig. 6).

DISCUSSION

The “calcispheres” from the section studied are dominated by the pithonellid group (>95% of the whole assemblages). The interpretation of palaeoenvironment based on pithonellid ecology match observations by previous authors that these photosynthetic organisms lived in surface waters and are associated with sediments deposited in the shelf to shallow bathyal environments (e.g., Banner, 1972; Zügel, 1994; Wendler et al.,

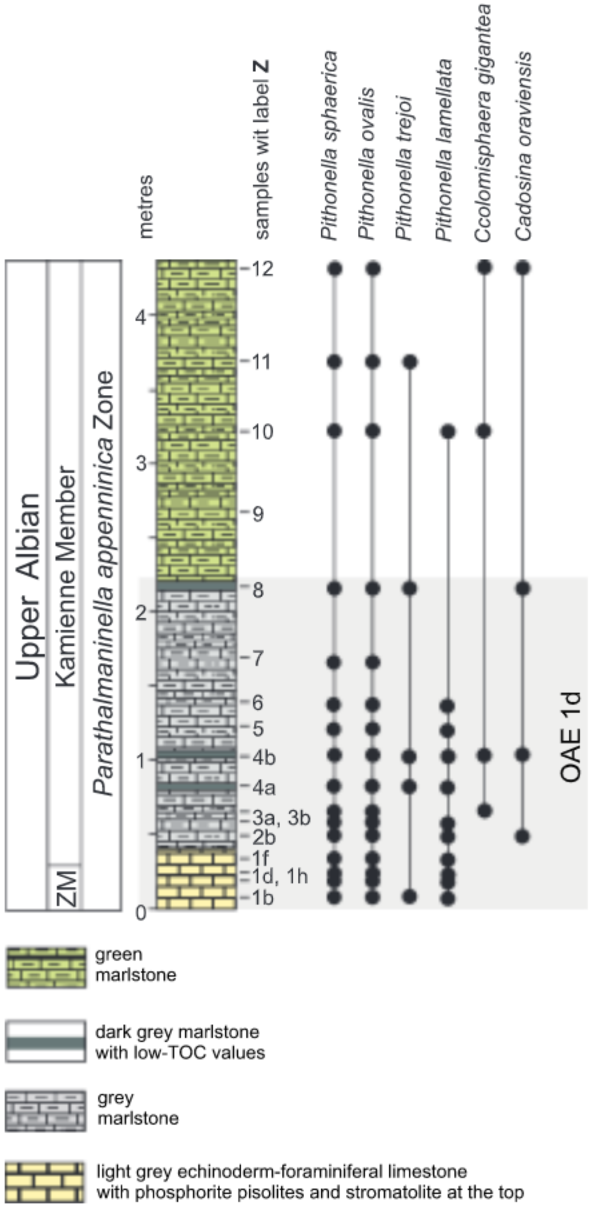

Fig. 3. Lithological log of the Upper Albian succession from the Żeleźniak Gully section, High Tatric units, Tatra Mountains, plotted against the distribution of pithonellids and calcitarchs

ZM – Żeleźniak Member

2002a, b; Omaña et al., 2014; Wiese et al., 2015). There are statements that *Pithonella ovalis* is a characteristic species of the offshore facies and marks transgressive intervals. In turn, *Pithonella sphaerica* commonly occurs in an environment that is slightly influenced by coastal conditions (e.g., Zügel, 1994).

During the Late Cenomanian–Early Turonian, both these taxa showed significant and temporal blooms, known as the global bioevent associated with OAE 2 (e.g., Wendler et al., 2002a, b). The abundance of pithonellids was strongly related to nutrient availability in surface waters. Jarvis et al. (1988) stated that this group appeared to have been an opportunistic group and their abundance in sediments probably reflects an increased nutrient supply; moreover, the marked increase of them coincides with a decline in organic-walled dinoflagellate cysts. Alternative suggestions have been presented by Dias-Brito (2000) and Wiese et al. (2015), who concluded that the pithonellids are typical of distal, most likely nutrient-depleted, shelf environments. In turn, Omaña et al. (2014) describing the large quantity of forms from the genus *Pithonella* in the Cenomanian–Turonian deposits of carbonate platform from Mexico suggested that these microfossils were opportunists living in an unstable environment. Another palaeoecological aspect concerning these microfossils was suggested by Keupp (1987). He remarked a change of "calcispheres" towards pithonellid dominated assemblages during the Cenomanian transgression. Similarly, Wendler et al. (2002a, b) used the ratio of *P. sphaerica* to *P. ovalis* (*Ps*/*Po*) as an indicator in the interpretation of relative distances from the coastline. They postulated that a high *Ps*/*Po* ratio (~10) characterizes marginal shelf assemblages, while a low *Ps*/*Po* ratio (~3), may suggest that the assemblages came from the outer shelf.

CALCAREOUS DINOCYSTS VS. SEA LEVEL CHANGES AND NUTRIENT AVAILABILITY

Taking into account the *Ps*/*Po* ratio in three intervals distinguished along the section studied, we interpret that the pithonellids represent the outer shelf assemblages *sensu* Wendler et al. (2002a, b; average *Ps*/*Po* ratio ranges between 0.2 and 2.7) that was also earlier suggested based on the composition of benthic foraminiferal assemblages (Bąk, 2015).

The occurrence of pithonellids during the period related to Interval 1 corresponds to a transgressive phase that culminated in the highstand event. It is supported in the Tatric area by facies represented by the echinoderm-foraminiferal limestone, rich in its topmost part in phosphates with hardgrounds, stromatolites, and phosphate pisolites (summary in Krajewski, 2003). This short-term (third-order) transgressive event began during the *P. ticinensis* Chron (after KAl7 using a numbering system of Cretaceous eustatic events after Haq, 2014; Fig. 6) and culminated during the *P. appenninica* Chron. The upper water column was characterized by high productivity in surface waters, potentially induced by wind-driven coastal upwelling (Bąk et al., 2016). In this environment, input of undigested pellets to the sea bottom derived directly from superficial waters was moderate, which correlates with the moderate species diversity of calcareous dinocysts (Fig. 6). Such a moderate value of "calcisphere" diversity is probably diminished due to long-lasting material reworking and dissolution on the sea floor, caused by a long period of sediment exposure and nondeposition before the diagenesis of the sediment (Bąk, 2011).

The pithonellids from Interval 2 display the highest values of the *Ps*/*Po* ratio in the section studied (av. value ranges from 1.4 to 2.7; Fig. 6). This coincides with the high abundance of all types of "calcispheres", and additionally, is linked with the abundance of planktonic foraminiferal tests belonging mostly to the hedbergellids and heterohelicids (Figs. 4A, B and 6). The latter microfossils were typical components of mid-Cretaceous superficial oceanic water occurring abundantly during blooms of "calcispheres", related to transgressive events (e.g., Keupp, 1987; Omaña et al., 2014). However, taking into account the change in the sedimentation regime during this period, recorded in the composition of the dark grey marl succession that overlies the echinoderm-foraminiferal limestone, it seems that the blooms of "calcispheres" were linked rather to a high land-derived nutrient delivery in superficial water. These deposits contain numerous clay minerals and two types of organic matter (OM), including marine with abundant non-digested or partly digested pellets, and land-derived, with components of near-shore alluvial plains in the surrounding landscape, i.e.,

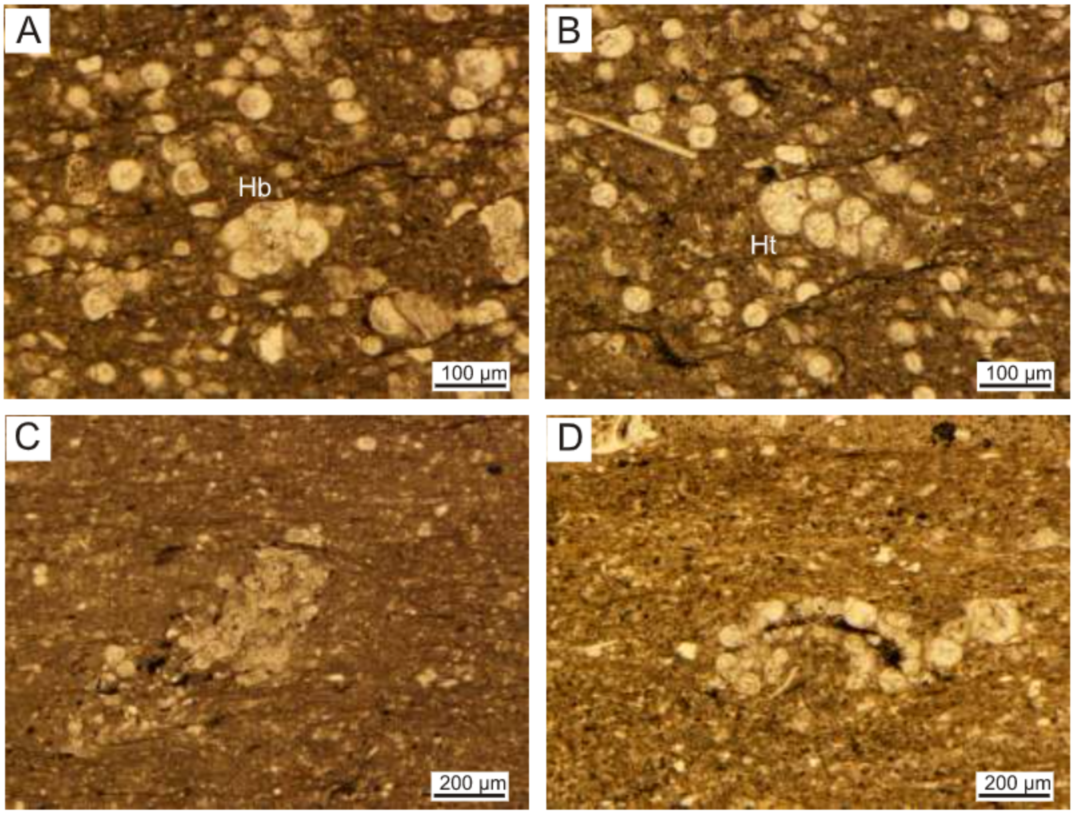

Fig. 4. Characteristic microfacies in the Upper Albian marl succession from the Żeleźniak Gully section, High Tatric Unit, Tatra Mountains

A, B – photomicrographs of foraminiferal-pithonellid microfacies in dark grey marlstone from the uppermost part of the OAE 1d interval; Hb – *Hedbergella*, Ht – *Heterohelix*; sample Z8; **C, D** – pellets produced by microzooplankton with visible intrinsic constituents, which are planktonic foraminifers and pithonellids, C – sample Z6, D – sample Z11

vascular plant remnants, spores of lake-derived green algae and particles of freshwater blue algae (for details – see Bąk et al., 2016). Nutrients derived from rivers may have stimulated the growth of phytoplankton and, thus, zooplankton activity and enhanced the deposition of POC (fecal pellets and aggregates). The occurrence of autochthonous barite crystals and homogeneous pellets in these deposits may indicate relatively high productivity in the surface waters. In turn, the change in the water regime from weakening coastal upwelling to downwelling during that time caused water stratification that is interpreted here based on the enhanced content of undigested pellets in the deposits along the Interval 2 (Fig. 6). The flux of such pellets into the bottom sediments might have been a consequence of secondary digestion by microzooplankton in the water column below the thermocline/nutricline, and additionally, by microbial decomposition at the sea bottom (Pomeroy et al., 1984).

Fluctuations in the total number and diversity of pithonellids and calcitarchs in Interval 2 is another feature of these assemblages. This may record changes in surface water currents related to changes in wind direction, causing variable seasonal anoxia and water-column stratification. The highest number of highly diverse "calcispheres" that coincides with the reduced percentage of planktonic foraminifers occurring in the dark grey marls with organic-rich laminae containing land-derived OM (samples Z4b and Z8; Fig. 6) is an example of conditions with a less oxygenated sea floor, caused by copious input of OM from alluvial plains covered by wetlands. It seems, therefore, that the nutrients brought by rivers to the sea may have the greatest influence on the growth of pithonellids and calcitarchs.

It should be stressed that the source of echinoderm particles, which were numerous in the underlying succession of the limestones, disappeared at the beginning of Interval 2 due to burial by land-derived clay material, transported together with land-derived organic detritus. This shows that the growth of "calcispheres", described from Interval 2, occurred during the continuing highstand event.

The abundance and diversity of pithonellids and calcitarchs assemblage diminished during Interval 3. This coincides with the low average value of the *Ps*/*Po* ratio (0.6–1.2) and the reduced content of undigested pellets in the green marlstones (Fig. 6). Most probably, the "calcispheres" from these sediments represent the assemblages that correspond to the period during which the water stratification was broken down and the upwelling regime was renewed. This has been confirmed by many geochemical indices based on analysis of OM in the green marlstones, which show a decrease in the supply of land-derived OM to the basin floor, and additionally suggest more highly oxygenated conditions on the basin floor (Bąk et al., 2016). All this may indicate that the weaker growth of "calcispheres" during this period corresponds to the beginning of a third-order regression event, still with enhanced nutrient availability in surface water.

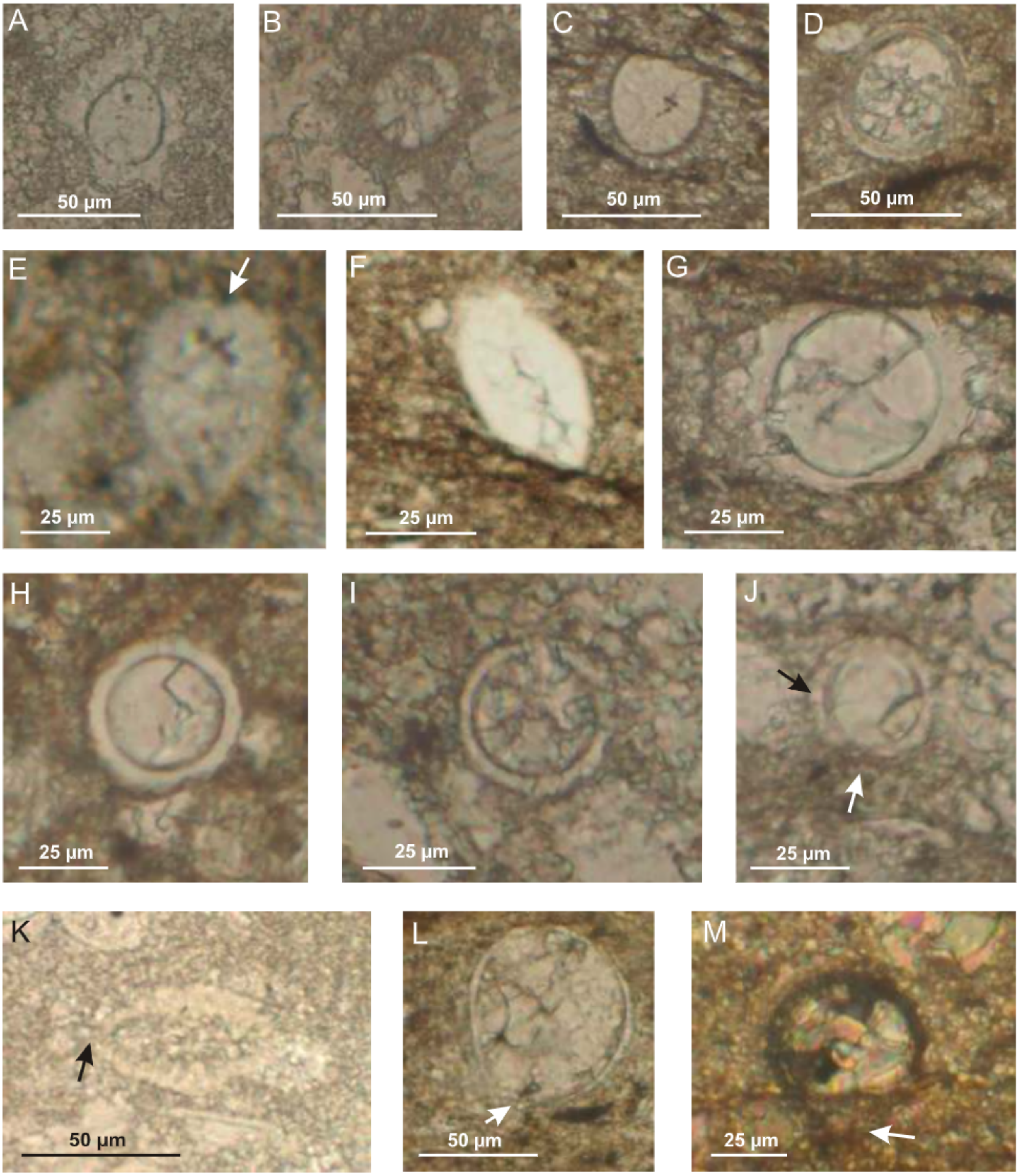

Fig. 5. Calcareous dinoflagellate cysts and calcitarchs from the Upper Albian deposits in the Żeleźniak Gully section, High Tatric units, Tatra Mountains

A–D – *Pithonella lamellata* Keupp in Keupp and Kienel, A – sample Z1d; B – sample Z1h; C – sample Z2b; D – sample Z4b; **E, F** – *Pithonella ovalis* (Kaufmann in Heer) – longitudinal section showing the eliptical shape, thick wall and small aperture at the end (arrow), E – sample Z3b, F – sample Z6; **G–J** – *Pithonella sphaerica* (Kaufmann in Heer), G – axial section, sample Z2b; H – sample Z4b; I – sample Z4b; J – axial section showing the double layer of the thick wall divided by a dark line (black arrow) and aperture (white arrow), sample Z5; **K** – *Pithonella trejoi* Bonet – longitudinal section with aperture (arrows), Z1b; **L** – *Colomisphaera gigantea* (Borza) with aperture (arrow) – a large form of the pithonellid wall spectrum, sample Z12; **M** – *Cadosina oraviensis* Borza – form with pithonellid wall spectrum, rich in an organic substance, arrow points to the aperture, sample Z2b

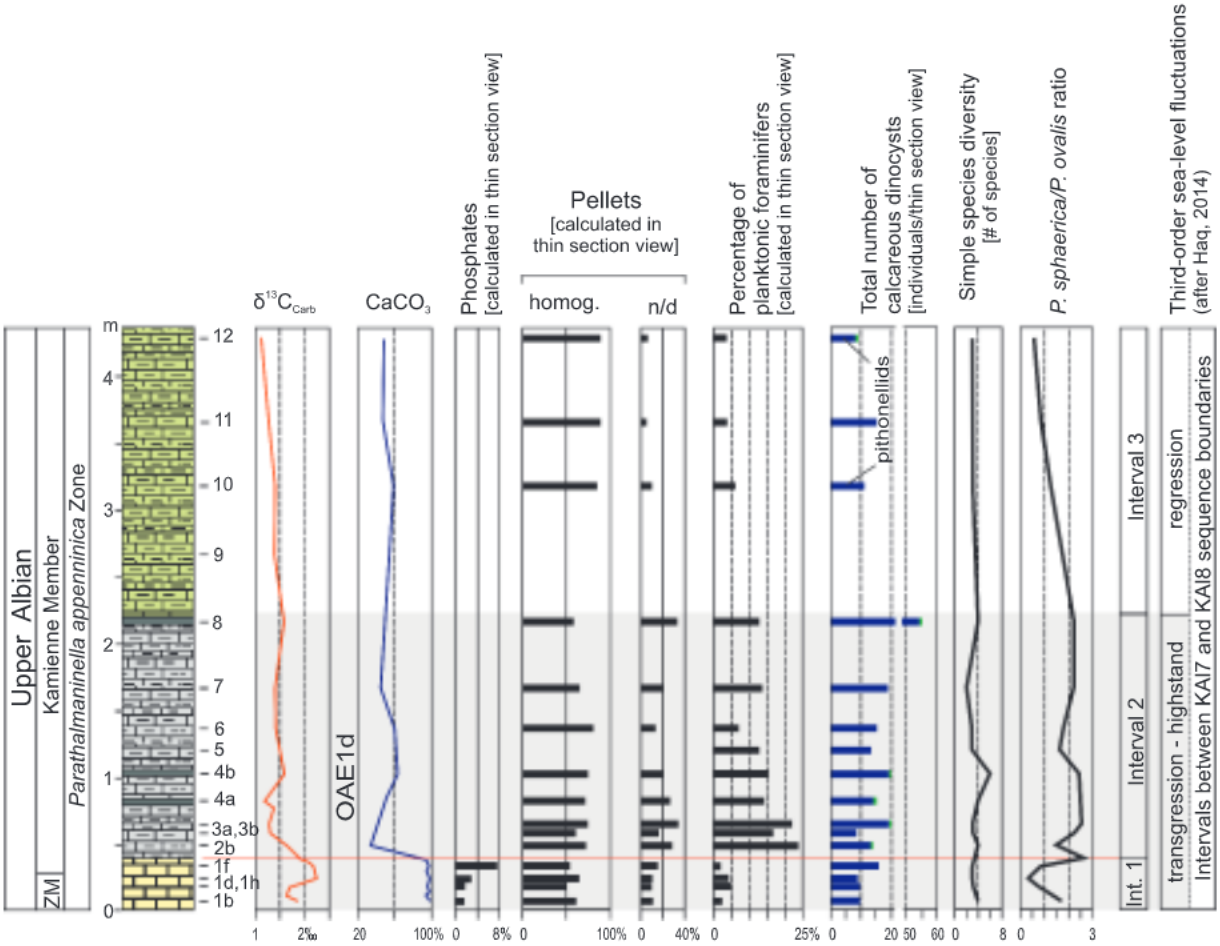

Fig. 6. Lithological log of the Upper Albian succession from the Żeleźniak Gully section, High Tatric Unit, Tatra Mountains, plotted against selected geochemical and micropalaeontological indices

$\delta^{13}C_{carb}$, CaCO$_3$, phosphates and pellets contents – after Bąk et al. (2016); homog. – homogeneous; n/d – undigested; OAE 1d – Oceanic Anoxic Event 1d – grey background; for explanations of lithologic log – see Figure 3

CONCLUSIONS

The “calcispheres” recorded from the Upper Albian deposits of the Tatra Mountains are of relatively low to moderate diversity, and consist of four species of pithonellids and two species belonging to the calcitarchs. The assemblages are dominated by pithonellids, the relative abundance of which exceeds 95%. The distribution of “calcispheres” in the section studied can be related to changes in nutrient input that occurred periodically, being related to changes in sea level during the Late Albian. The alternating abundance of *P. sphaerica* and *P. ovalis* gives a proximal/distal proxy that shows short-term third-order fluctuations of sea level during that time, which took place between two mid-Cretaceous sea level fall events, described as KAl7 and KAl8 following the chronostratigraphy by Snedden and Liu (2011). A dominance of *P. ovalis* is characteristic for both transgressive and regressive intervals, indicating a general outer shelf position. Periods of moderate abundances of “calcispheres” can be interpreted to reflect increasing marginal upwelling near the northern slopes of the submerged Tatric Ridge, where surface and nutrient-rich waters were mixed. During the highstand period, water stratification was conducive to oligotrophy, creating the most favourable conditions for the increased deposition of pithonellid cysts.

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