Lower Cretaceous palaeokarst in a klippe of the Czorsztyn Succession north of Zázrivá (Pieniny Klippen Belt, Orava sector, northern Slovakia)

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Spodnokriedový paleokras v bradle čorštynskej jednotky severne od Zázrivej (pieninské bradlové pásmo, oravský úsek, severné Slovensko)

Abstract: New locality with well preserved palaeokarst surface was discovered north of the Zázrivá village in the Orava sector of the Pieniny Klippen Belt. The klippe belongs to the Czorsztyn Succession and is known among the local settlers as "Erdútsky kostol". The outcropping succession starts with red nodular limestone of the Czorsztyn Limestone Formation of the Kimmeridgian to the Middle Tithonian age, followed by the Dursztyn Limestone Formation. The latter consists of red bedded micritic limestones of the Korowa Limestone Member and white micritic limestones of the Sobótka Limestone Member. Stratigraphically, the succession covers the time span from the Kimmeridgian to the Early Berriasian. The Sobótka Limestone Member displays unusual succession of calpionellids and is terminated by uneven palaeokarstic surface dominated by hummocky karren forms with rounded tops which are typical for karst evolved under thick soil cover. The karstic surface is covered by a condensed succession of the Late Albian red pelagic marly limestones and marlstones (Chmielowa Formation). The stratigraphic gap encompasses a time span from the Berriasian to the Late Albian.

Key words: Jurassic, Cretaceous, Western Carpathians, Pieniny Klippen Belt, Czorsztyn Succession, microfacies, palaeokarst

1. INTRODUCTION

The Pieniny Klippen Belt (PKB in following text) is a narrow mélange zone placed between the Western Carpathian internides and externides. It consists of a palaeogeographic unit called Pieninicum (Oravicum of Mahel', 1986) and some units which originally belonged to the internides (e.g., Manín, Drietoma, Kostelec, and Haligovce units). These non-Oravic units were ranked by Mahel' (1980) to the so-called Peri-Klippen Zone. The Oravic crustal segment was characterized by a central elevation called the Czorsztyn Swell (represented by relatively shallow-marine Czorsztyn Succession) surrounded by deeper basins (represented by deep-marine Kysuca, Pieniny, Orava, and Magura successions; Birkenmajer, 1977). The Czorsztyn Swell all through its history was a submarine pelagic swell with only one exception. This was a break in sedimentation during the Early Cretaceous (Valanginian to Aptian). Earlier theories considered this break as caused by submarine non-deposition and erosion (Birkenmajer, 1958, 1975). The main reason for this opinion was that this break was followed by deep-marine pelagic deposition of Albian red marls. Some other authors proposed an emersion and subsequent flooding of the Czorsztyn Swell (Andrusov et al., 1959; Mišík, 1994). Only through reevaluation of more than 40 localities and research done at 5 new ones, where the pre-Albian surfaces were preserved, showed that these "non-deposition" surfaces bear many features characteristic for palaeokarst surfaces (Aubrecht et al., 2006). These brought us to idea that the non-deposition was caused by emersion of the Czorsztyn Swell, accompanied by karstification and erosion. This emersion period ended by sudden flooding (ingression) during the latest Aptian–Early Albian.

The most spectacular locality exposing the Early Cretaceous palaeokarst surfaces was in the quarry of Horné Sŕnie cement factory. However, continuing mining destroyed the most spectacular parts and the locality now gradually disappears. Some years ago, a new spectacular site was found north of the Zázrivá Village (Fig. 1) in the Orava sector of the PKB (northern Slovakia). Presence of the Czorsztyn Succession in this sector is surprising as this part of the PKB is almost essentially composed of klippen belonging to deeper, basinal successions, such as Kysuca and Orava successions. The studied klippe (49°17'50.9''N, 19°13'13.5''E) occurs near the forest road, east of the large Kozinec Klippe belonging to the Orava Succession. The limestone succession here lacks the typical envelope of Cretaceous marls. Instead, they are surrounded by flysch deposits of the Magura Nappe (Flysch Zone, Outer Carpathians). Klippe is known among local people as "Erdútsky kostol" (Erdútka Church) (Fig. 2). In this paper we present the first detailed study of this klippe which is recently the best example of the Early Cretaceous palaeokarst event in the Czorsztyn Succession in the whole PKB.

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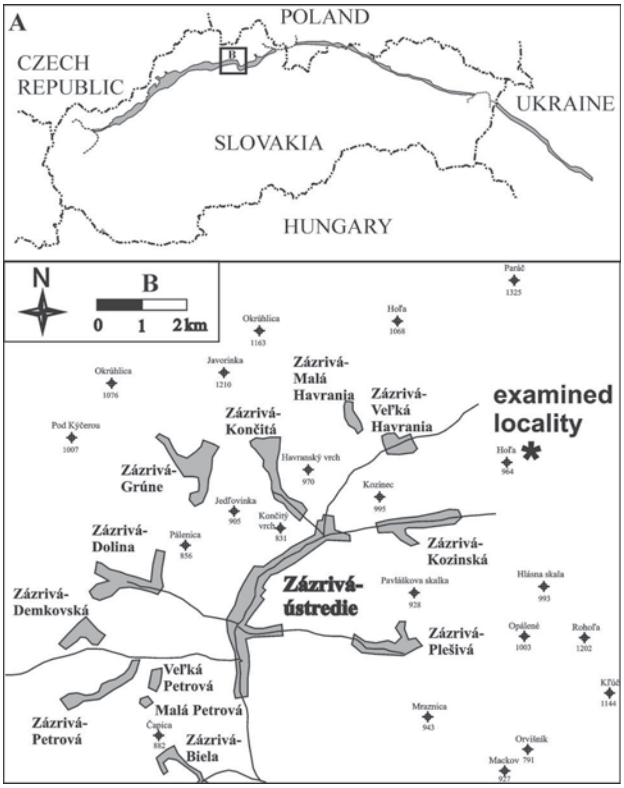

Fig. 1: Position of the examined locality. A – position of the locality within the Pieniny Klippen Belt, B – enlarged map of the territory of Zázrivá Village.
Obr. 1: Pozícia skúmanej lokality. A – pozícia lokality v rámci bradlového pásma, B – zväčšená mapa oblasti obce Zázrivá.

2. METHODS

Lithological section located in more complete and better accessible western part of the klippe was sampled for the microfacies analysis (standard thin-section evaluation). Ammonite fauna was sampled from the top of the klippe formed by Ammonitico Rosso. The Albian red marls were treated with detergents (Rewoquad) applied on samples of the weight between 20–30 g. Afterwards, the samples were wet sieved over 70 and 63 μm screens and dried. Residues were weighted and microfossils were picked under binocular microscope. Foraminifers were studied under scanning elektron microscope (SEM, JXA 840).

The biostratigraphical analysis follows the calcareous dinoflagellate zonation by Reháková (2000) and calpionellid zonation by Reháková (1995). Semiquantitative terms abundant, common, present, and rare we used in the allochems quantification.

3. LITHOLOGICAL DESCRIPTION OF THE KLIPPE

The klippe is in tectonically overturned position, exposing deposits of the Czorsztyn Succession (Fig. 2,3). It starts with deposits of the Czorsztyn Limestone Formation (Fig. 2B). Lower part, 2.90 m thick, is represented by red nodular limestones with large nodules and corroded ammonites. Upper part of the formation is composed of red to greyish nodular limestone with smaller nodules. This part is 1.20 m thick.

The Czorsztyn Limestone Formation is stratigraphically overlain by limestones of the Dursztyn Limestone Formation (Fig. 2C) starting with red, thin-bedded limestone, which can be attributed to the Korowa Limestone Member. Its thickness reaches almost 4 metres, gradually passing to massive, grey to white limestones of the Sobótka Limestone Member, 1.23 m in thickness. This member is terminated by uneven palaeokarst surface, covered by red marly limestones and marlstones of the Chmielowa Formation.

4. PETROGRAPHIC, MICROFACIES AND FAUNISTIC DESCRIPTION OF THE INDIVIDUAL LITHOSTRATIGRAPHIC UNITS AND PALAEOKARST SURFACE

4.1. The Czorsztyn Limestone Formation

The lower part of the nodular limestone (the Ammonitico Rosso-type facies) represents biomicrite with *Saccocoma* microfacies (packstone), containing also abundant thin-shelled bivalves, calcified radiolarians and fragments of benthic crinoids (Fig. 5A). Benthic foraminifers *Lenticulina* sp., *Spirillina* sp., and *Nodosaria* sp. are common. Echinoid spines, thick shelled bivalves, ghost after aragonitic mollusc shells, brachiopods, ostracods, and spores of *Globochaete alpine* Lombard are rare. Syntaxial calcite overgrowths were observed on some *Saccocoma* and benthic crinoid fragments. The limestone contains cysts of calcareous dinoflagellates; *Shizosphaerella minutissima* (Colom) and *Cadosina parvula* Nagy (Fig. 5B) indicating the Parvula Acme Zone (Early Kimmeridgian). Some bioclasts and intraclasts are bored by various microorganisms and coated by Fe-Mn-oxides. Among intraclasts, single clast of *Saccocoma-Globuligerina* wackestone was documented (Fig. 5C).

The upper part of the nodular limestone represents biomicrite, locally biosparite (packstone-grainstone) with *Saccocoma* microfacies (sample EK2/7, see Fig. 3). Spores of *Globochaete alpina* become more abundant in its upper part (EK2/6), which is formed by *Globochaete*-radiolarian microfacies with less frequent fine *Saccocoma* debris (see Fig. 3 and 5D). Fragments of benthic crinoids, thin-shelled bivalves and benthic foraminifers (*Spirillina* sp. and *Textularia* sp.) are common, juvenile ammonites, gastropods, ostracods, echinoid spines, punctate brachiopods, and aptychi are present. The limestone is bioturbated, which is evidenced by presence of fucoids. Allochems are strongly corroded and impregnated by Fe-Mn oxides; late-diagenetic stylolites are locally present. The calcareous dinoflagellate association consists of *Colomisphaera carpathica* (Borza), *Colomisphaera nagyi* (Borza), *Shizosphaerella minutissima*, and *Cadosina parvula*. Their distribution in this part of the formation suggests strong condensation. First, dominance of *Cadosina parvula* still indicates the Parvula Acme Zone of the Early Kimmeridgian; however, appearance in abundance of *Colomisphaera tenuis* (Nagy) in the last ammonitico rosso sample (EK2/6) already indicates Tenuis Zone of the Middle Tithonian (Fig. 5E).

Other six dinoflagellate zones (Moluccana, Borzai, acme Pulla, Tithonica, Malmica, and Semiradiata Zones) were recognized between these two zones by Reháková (2000). They were not documented in our section but this can be due to too large distance between successive samples EK2/7 and EK2/6.

The Czorsztyn Limestone Formation also yielded some ammonite fauna. Stratigraphically oldest uncovered ammonitico rosso bed contains relatively rich, although badly preserved ammonites and aptychi. Ammonites are generally fragmented and/or corroded from one side. The association includes *Taramelliceras* gr. *pugile* (Neumayr), *Aspidoceras apenninicum* Zittel, *Subplanites* sp. and *Biplisphinctes* cf. *spathi* Oloriz, and it is indicative of the Late Kimmeridgian, more precisely Eudoxus Zone or Beckeri Zone.

Fig. 2: "Erdútka Church" klippe. A – Overall view on the klippe. B – View on the western side of the klippe showing red nodular Czorsztyn Limestone Formation on the top (a) and pale Dursztyn Limestone Formation below (b). C – Central part of the klippe with pale, bedded Korowa and Sobótka limestone members (Dursztyn Lst. Fm.). Note the whole klippe is in overturned position.
Obr. 2: Bradlo "Erdútsky kostol". A – Celkový pohľad na bradlo. B – Pohľad na západnú stranu bradla s červeným hľuznatým čorštynským vápencom navrchu (a) a svetlým durštynským vápencom pod ním (b). C – Stredná časť bradla so svetlými vrstevnatými korovskými a sobotskými vápencami durštynského súvrstvia. Bradlo je v prevrátenej pozícii.

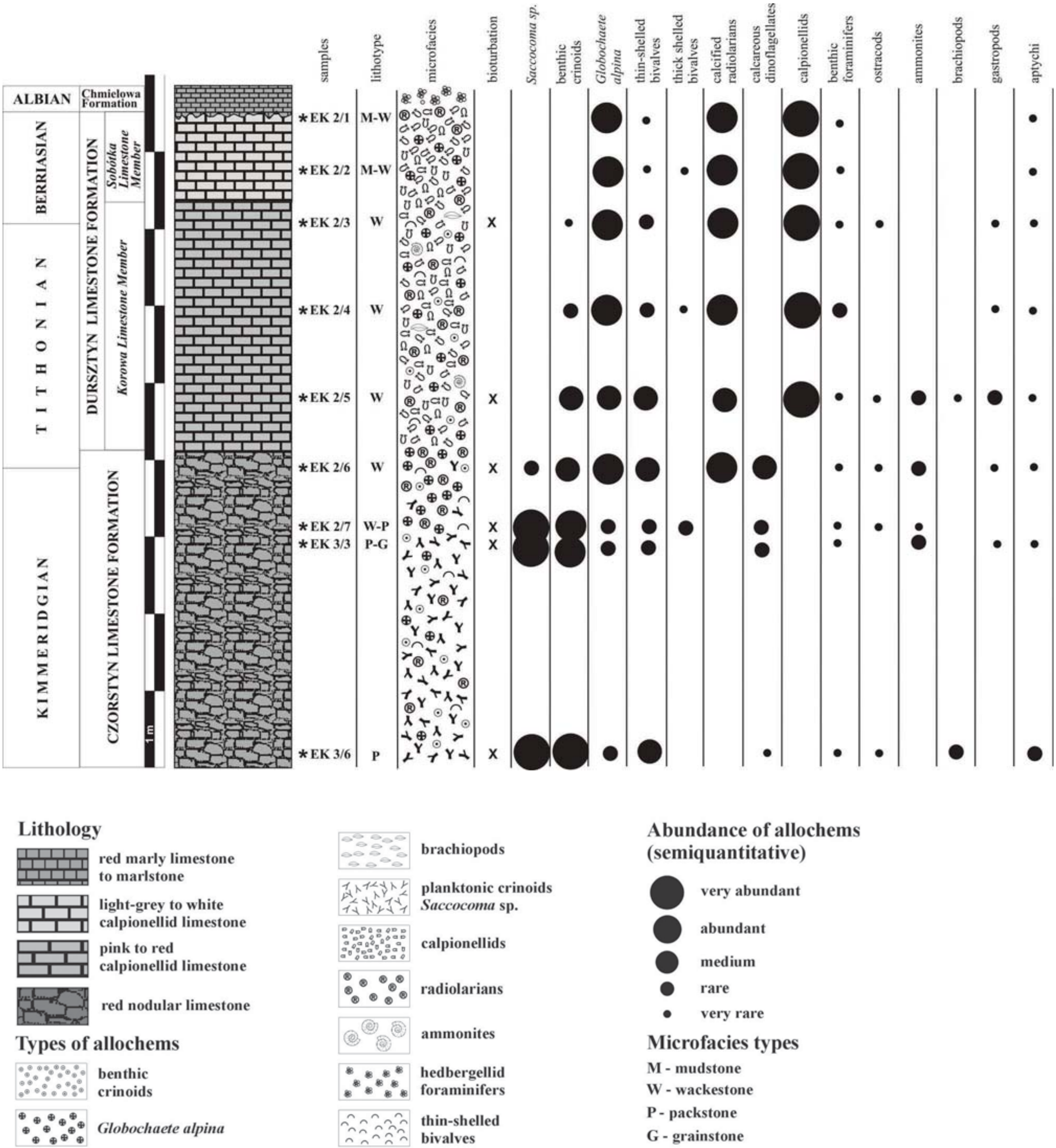

Fig. 3: Lithological section of the examined locality, showing facies and distribution of the allochems.

Obr. 3: Litologický profil skúmanej lokality s vyobrazením fácií a distribúciou komponentov tvoriacich vápence.

4.2. The Dursztyn Limestone Formation

4.2.1. The Korowa Limestone Member

The biomicrite limestone (wackestone to packstone) is characterized by calpionellid microfacies, which is accompanied by abundant calcified radiolarians and *Globochaete alpina* (Fig. 5F). Thin-shelled bivalves and fragments of benthic crinoids are scarce in the lower part of the member. *Saccocoma* particles, tiny gastropods, juvenile ammonites, aptychi, ostracods, brachiopods shells (including punctate brachiopods), foraminifers (*Spirillina* sp., *Textularia* sp., *Lenticulina* sp., *Nodosaria* sp.), and “microforaminifers” are present. We use the term “microforaminifers” for ferroan coatings of the juvenile chambers of foraminiferal tests, which were preserved after dissolution and protected against destruction (Mišík & Soták, 1998). Gastropod shells show geopetal structures. Fragments of thicker shells (bivalves, ammonites) are corroded and impregnated by Fe-Mn oxides. Locally, signs of bioturbation occur. Limestone intraclasts with the allochems identical to those of the surrounding sediment were observed. The calpionellid association consists of *Calpionella alpina* Lorenz (Fig. 6A), *Crassicollaria intermedia* (Durand Delga), *Crassicollaria massutiniana* (Colom) (Fig. 6B), *Crassicollaria brevis* Remane (Fig. 6C), *Crassicollaria parvula* Remane, *Crassicollaria colomi* (Doben) (Fig. 6A), *Tintinopsella doliphormis* (Colom), and *Tintinopsella carpathica* (Murgeanu & Filipescu). Rare calcareous dinoflagellates are represented by *Colomisphaera carpathica* (Borza), *Shizosphaerella minutissima* (Colom), and *Cadosina semiradiata semiradiata* Wanner. In the lower part of the member (EK2/5), the *Crasscollaria intermedia* Subzone of the *Crassicollaria* Zone was recognized (Late Tithonian). In the middle part (EK2/4), *Crassicollaria brevis* becomes very frequent and indicates *Crassicollaria brevis* Subzone of the *Crassicollaria* Zone. *Calpionella alpina* Subzone of the *Calpionella* Zone (Early Berriasian) was documented in the upper part of the member (EK2/3, Fig. 4). It is accompanied by still abundant *Crassicollaria parvula* and *Crassicollaria massutiniana*.

4.2.2. The Sobótka Limestone Member

Limestone is represented by biomicrite (wackestone to mudstone) with calpionellid-*Globochaete* microfacies. Higher up, the amount of calcified radiolarians decreases; these are associated with juvenile gastropods, brachiopods, juvenile ammonites, fragments of thin- and thick-shelled molluscs (bivalves, ammonites), benthic crinoidal particles, ophiurians, calcareous foraminifers, such as *Lenticulina* sp., and *Spirillina* sp., and "ghosts" after originally aragonitic shell fragments. The matrix contains following calpionellid assemblage: *Calpionella alpina, Calpionella grandalpina* Nagy, rare *Crassicollaria massutiniana*, *Crassicollaria parvula* (Fig. 6D), *Crassicollaria colomi*, *Crassicollaria brevis*, *Tintinopsella doliphormis*, and more abundant *Tintinopsella carpathica,* accompanied by dinoflagellates *Cadosina semiradiata semiradiata* (Fig. 6E) and *Colomisphaera nagyi*. Based on the dominant presence of *Calpionella alpina*, this member can be assigned to *Calpionella* Zone, *Calpionella Alpina* Subzone of the Early Berriasian. The member is terminated by uneven palaeokarst surface.

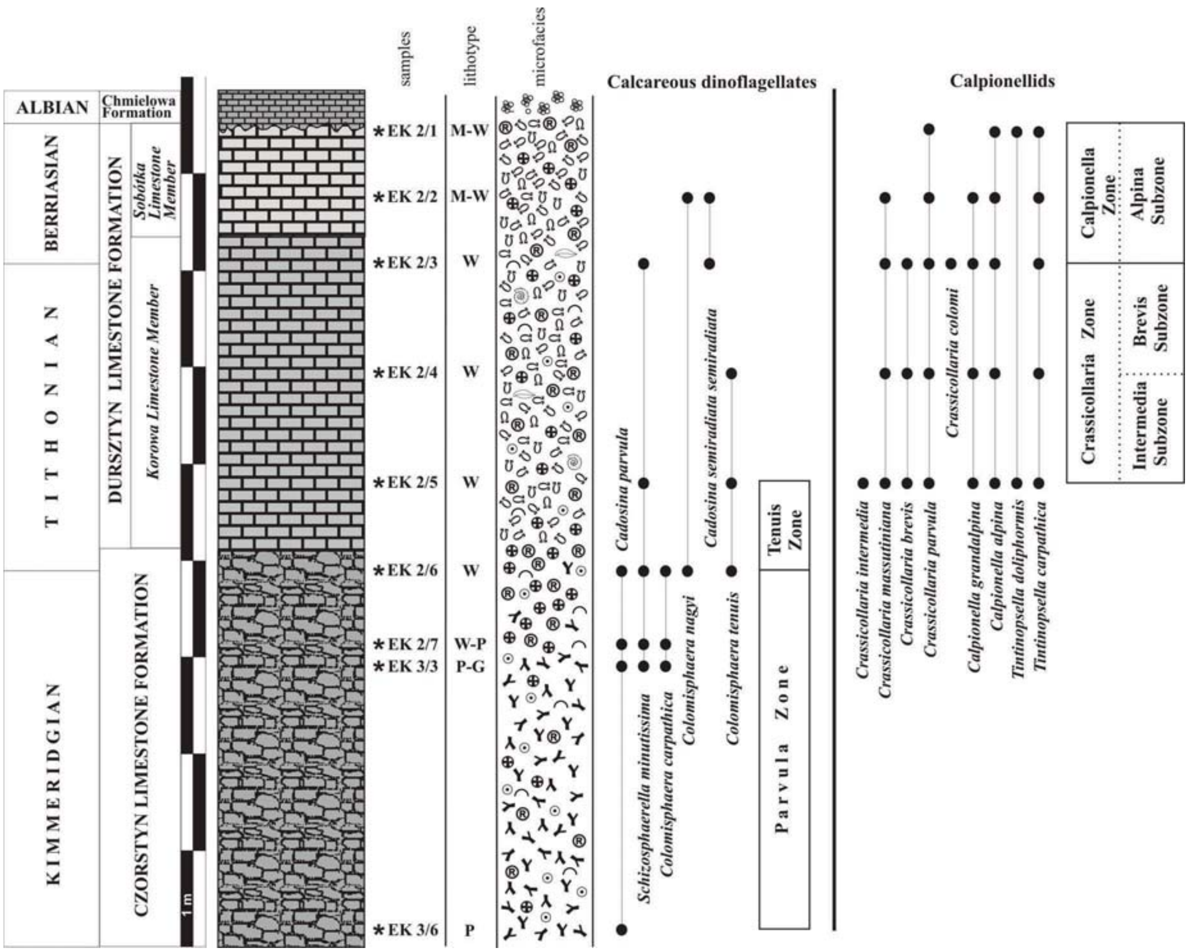

Fig. 4: Distribution of calpionellids and calcareous dinoflagellates within the studied section. For explanations – see Fig. 3.

Obr. 4: Distribúcia kalpionelíd a vápnitých dinocýst v študovanom profile. Vysvetlivky – viď Obr. 3.

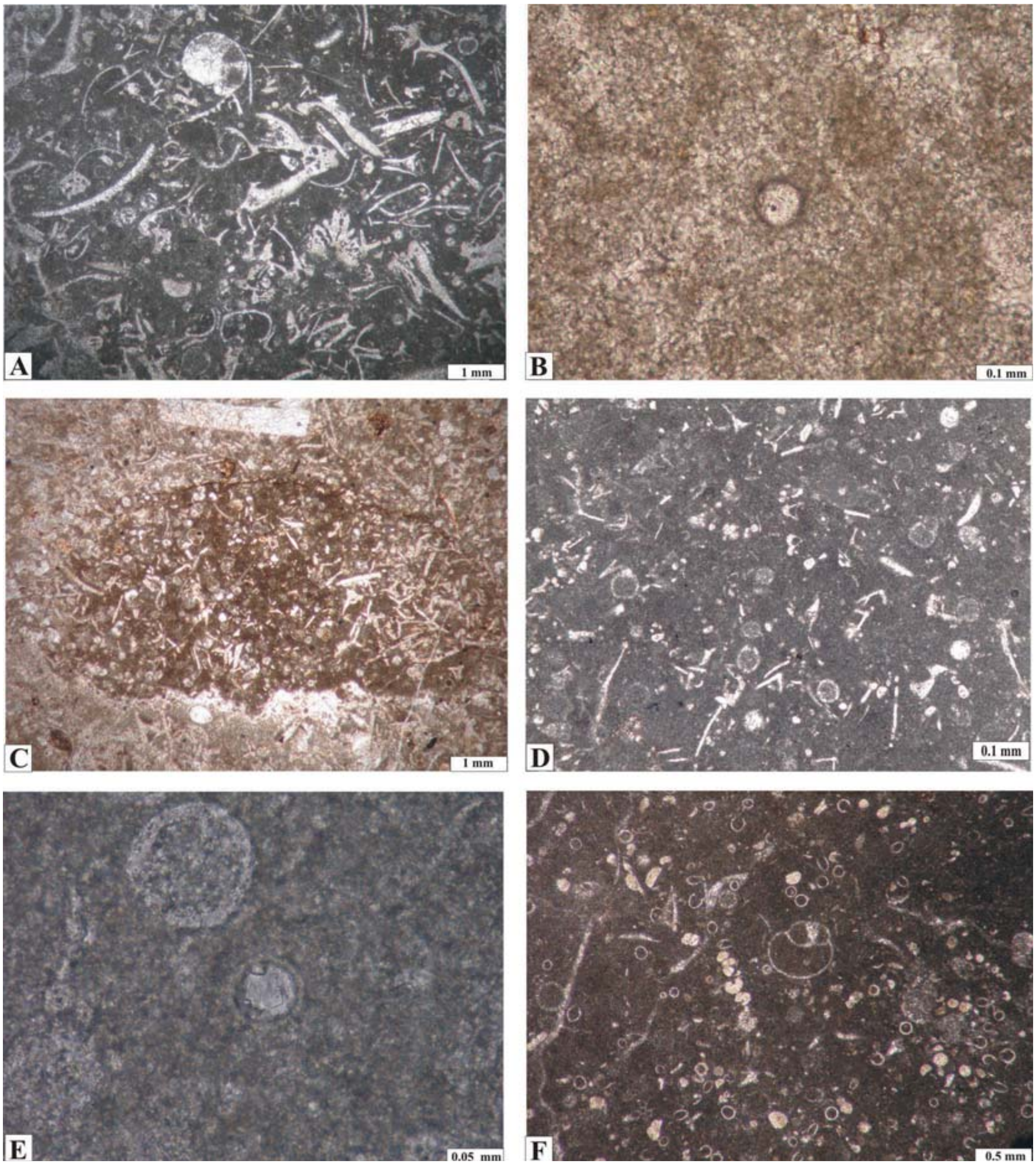

Fig. 5: A – Czorsztyn Limestone Formation, *Saccocoma* packstone with thin- and thick-shelled molluscs, calcified radiolarians, *Globochaete* spores, and juvenile ammonites, Late Kimmeridgian (0.2 m above the base of the section). B – *Cadosina parvula* (Nagy), Czorsztyn Limestone Formation, Early Kimmeridgian–Middle Tithonian (2.9 m). C – Czorsztyn Limestone Formation, intraclast with planktonic foraminifers *Globuligerina* sp. in the *Saccocoma* packstone, Late Kimmeridgian (0.2 m). D – Czorsztyn Limestone Formation, *Globochaete*-radiolarian microfacies with less frequent, fine *Saccocoma* debris, Middle Tithonian (3.8 m). E – *Colomisphaera tenuis* (Nagy), Czorsztyn Limestone Formation, Middle Tithonian (3.8 m). F – Korowa Limestone Member, calpionellid wackestone with *Globochaete alpina* Lombard spores, calcified radiolarians and gastropods, Late Tithonian (4.8 m).

Obr. 5: A – Čorštynský hľuznatý vápenec, sakokómový packston s tenko aj hrubostennými mäkkýšmi, kalcifikovanými rádioláriami, spórami *Globochaete* a juvenilnými amonitmi, vrchný kimeridž (metráž 0,2 m nad bázou profilu). B – *Cadosina parvula* (Nagy), čorštynský hľuznatý vápenc, spodný kimeridž-stredný titón (metráž 2,9 m). C – Čorštynský hľuznatý vápenec, intraklast s planktonickou foraminiferou *Globuligerina* sp. v sakokómovom packstone, vrchný kimeridž (metráž 0,2 m). D – Čorštynský hľuznatý vápenec, globochetovo-rádioláriová mikrofácia s menším počtom sakokómových fragmentov, stredný titón (metráž 3,8 m). E - *Colomisphaera tenuis* (Nagy), čorštynský hľuznatý vápenec, stredný titón (metráž 3,8 m). F – korovský vápenec, kalpionelový wackeston s *Globochaete alpina* Lombard, kalcifikovanými rádioláriami a gastropódmi, vrchný titón (metráž 4,8 m).

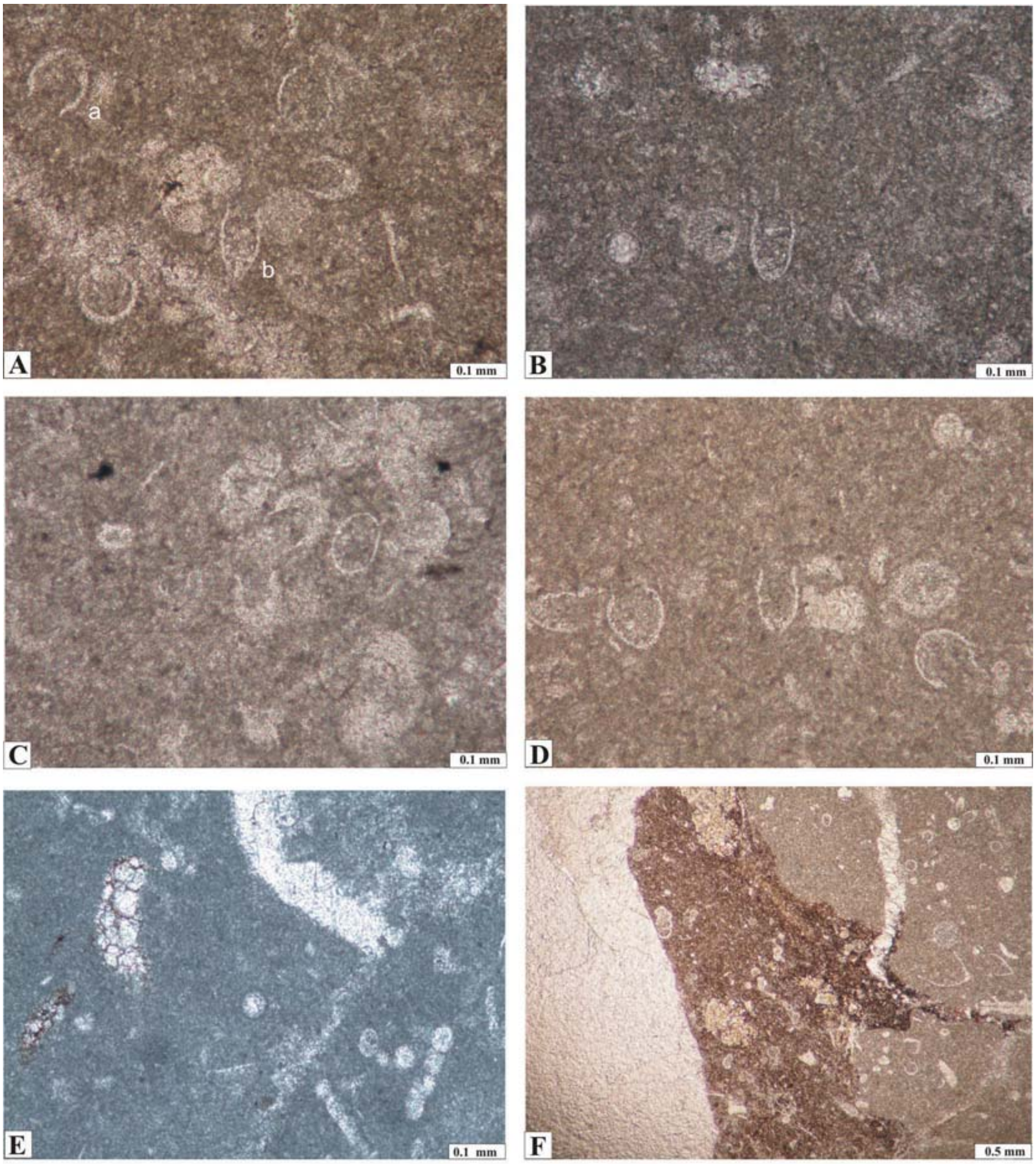

Fig. 6: A – *Calpionella alpina* Lorenz (a) and *Crassicollaria colomi* Doben (b), Sobótka Limestone Member, Early Berriasian (7.7 m). B – *Crassicollaria massutiniana* (Colom), Korowa Limestone Member, Late Tithonian (5.7 m). C – *Crassicollaria brevis* Remane, Korowa Limestone Member, Late Tithonian (6.0 m). D – *Crassicollaria parvula* Remane, Sobótka Limestone Member, Early Berriasian (7.7 m). E – *Cadosina semiradiata semiradiata* Wanner, Korowa Limestone Member, Late Tithonian (7.1 m). F – Transition between the Sobótka Limestone Member (calpionellid microfacies) and the Chmielowa Formation (with hedbergellid foraminifers), Late Albian (8.5 m).

Obr. 6: A – *Calpionella alpina* Lorenz (a) a *Crassicollaria colomi* Doben (b), sobótsky vápenec, spodný berias (metráž 7,7 m). B – *Crassicollaria massutiniana* (Colom), korovský vápenec, vrchný titón (metráž 5,7 m). C – *Crassicollaria brevis* Remane, korovský vápenec, vrchný titón (metráž 6,0 m). D – *Crassicollaria parvula* Remane, sobótsky vápenec, spodný berias (metráž 7,7 m). E – *Cadosina semiradiata semiradiata* Wanner, korovský vápenec, vrchný titón (metráž 7,1 m). F – prechod medzi sobótskym vápencom (kalpionelová mikrofácia) a chmielovským súvrstvím (s hedbergelidnými foraminiferami), vrchný alb (metráž 8,5 m).

Fig. 7: Field photos of the pre-Albian palaeokarst surface between the Dursztyn Limestone Formation and the Chmielowa Formation. A – Overal view on the palaeokarst surface preserved at the bottom of the klippe. B – View on the palaeokarst surface in vertical position on the fallen block below the klippe. C – Detailed view on a hummock palaeokarst body protruding from the stratigraphically older underlying limestones (h). The palaeokarst surface is covered by Late Albian to Cenomanian marls (m). D – Another hummock on which rainwater grooves are visible (arrow), being perpendicular to the palaeokarst surface. E – Hummock on the fallen block below the klippe. Arrow marks remnants of the red marlstones of the Chmielowa Formation. F – Palaeokarstic depression in the eastern part of the klippe. The depression was originally filled by marls of the Chmielowa Formation, which were removed and the palaeokarstic surface is visible. Note the whole klippe is in overturned position.

Obr. 7: Terénne fotografie predalbského paleokrasového povrchu medzi durštynským vápencom a chmielovským súvrstvím. A – Celkový pohľad na paleokrasový povrch zachovaný na báze skúmaného bradla. B – Pohľad na paleokrasový povrch vo vertikálnej pozícii na bloku padnutého pod bradlom. C – Detailný pohľad na homoľovitý paleokrasový útvar vyčnievajúci zo staršieho vápenca v stratigrafickom podloží (h). Na paleokrasový povrch nasadajú sliene vrchnoalbského až cenomanského veku (m). D – Iný homoľovitý útvar, na ktorom vidno ronové ryhy po dažďovej vode (šípka) orientované kolmo na paleokrasový povrch. E – Homoľovitý útvar na bloku padnutom pod bradlom. Šípka označuje zvyšky nasadajúcich červených slieňov chmielovského súvrstvia. F – Paleokrasová depresia vo východnej časti bradla. Depresia bola vyplnená chmielovským súvrstvím, po odstránení ktorého sa obnažil paleokrasový povrch. Bradlo je v prevrátenej pozícii.

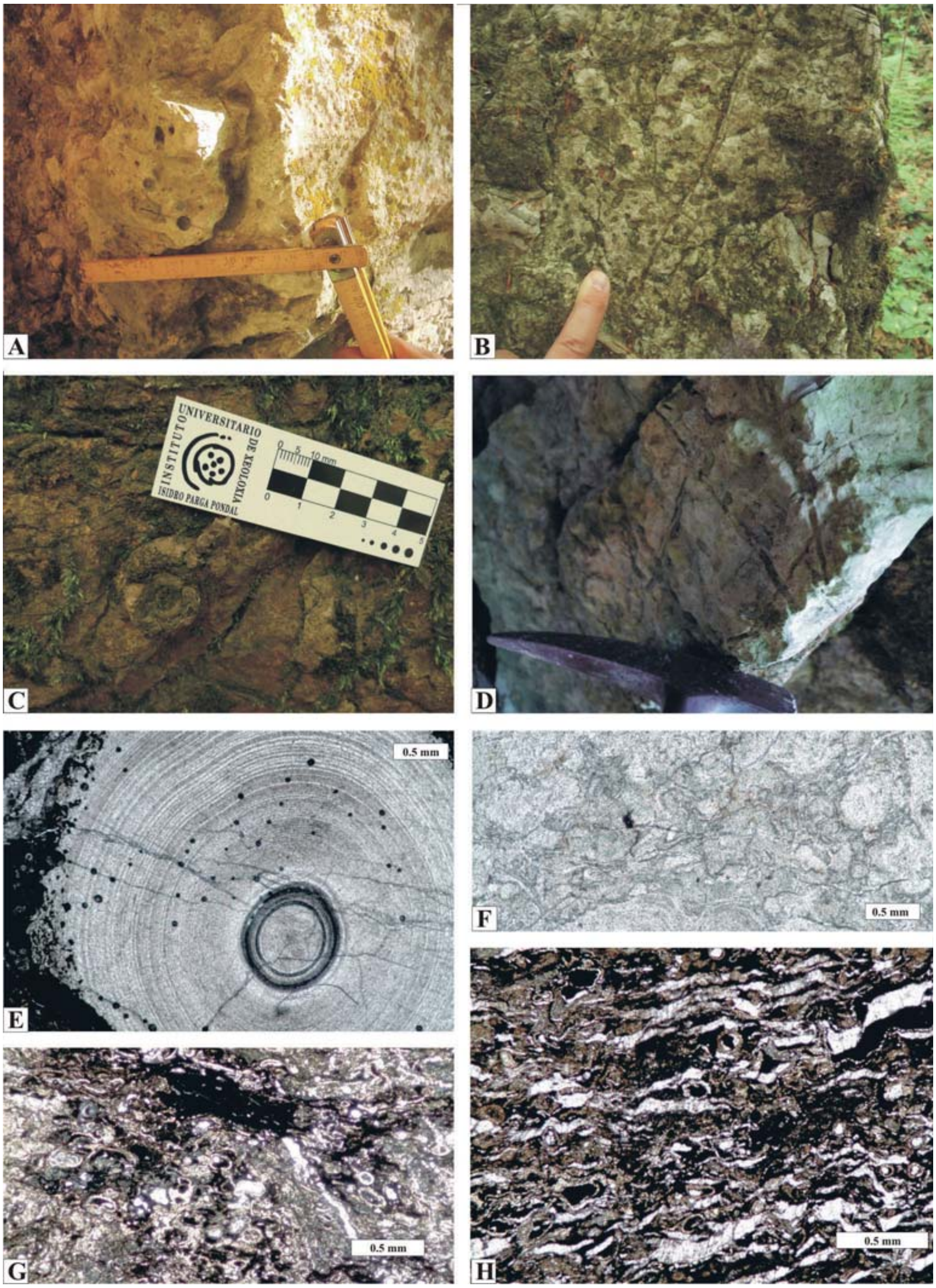

Fig. 8: A – Palaeokarst surface at the base of the klippe bored by bivalves (trace fossil *Gastrochaenolites*). B – Similar borings on the surface of the fallen block below the klippe filled with younger, Albian sediment. C – Ammonite at the base of the Upper Albian sediments on the palaeokarst surface. Fallen block below the klippe. D – Pre-Albian calcite veinlets (appear as straight grooves on the photo) bored by bivalves. Palaeokarst depression in the eastern part of the klippe (see Fig. 7F). E – Cross-section of corroded and bored belemnite rostrum in the basal parts of the Chmielowa Formation. Thin-section, plain polarized light. F – Phosphatic stromatolite at the base of the Chmielowa Formation. Thin-section plain polarized light. G, H – Chambers of sessile foraminifers (oval cross-sections) in the Fe-Mn stromatolite at the base of the Chmielowa Formation. Thin-section plain polarized light.

Obr. 8: A – Paleokrasový povrch na báze bradla navŕtavaný lastúrnikmi (ichnofosília *Gastrochaenolites*). B – Podobné navŕtavania vyplnené mladším albským sedimentom na povrchu bloku padnutého pod bradlom. C – Amonit na báze vrchnoalbských sedimentov na paleokrasovom povrchu. Padnutý blok pod bradlom. D – Predalbské kalcitové žilky (na obrázku pripomínajú rovné ryhy) navŕtavané lastúrnikmi. Paleokrasová depresia vo východnej časti bradla (viď Obr. 7F). E – Prierez korodovaným a navŕtavaným rostrom belemnita v bazálnych častiach chmielovského súvrstvia. Výbrus, rovnobežné nikoly. F – Fosfatický stromatolit na báze chmielovského súvrstvia. Výbrus, rovnobežné nikoly. G, H – Komôrky sesílnych foraminifer v Fe-Mn stromatolite na báze chmielovského súvrstvia. Výbrus, rovnobežné nikoly.

4.3. Palaeokarst surface

On the stratigraphic top of the Sobótka Limestone Member, shallow karren surface (Fig. 7) developed (maximum 30–40 cm deep). It is visible not only at the base of the klippe but even better on a large fallen block some tens of meters below the klippe. The surface is similar to that described from the Horné Sŕnie locality (Aubrecht et al., 2006), i.e. relatively flat surface is covered by loafs and hummocks with rounded tops (Fig. 7C–E). On some hummocks, rainwater grooves perpendicular to the palaeokarst surface were observed (Fig. 7D). In the eastern part of the klippe, the palaeokarst surface penetrated deeper to the underlying limestone, forming smooth depression (Fig. 7F). Shallow bivalve borings (*Gastrochaenolites*) are common on the paleokarst surface (Fig. 8A,B). The underlying Sobótka Lst. Mb. is dissected by some blocky-calcite veinlets which do not continue to the Albian sediments and are bored by bivalves (Fig. 8D), i.e. they are pre-Albian. Similar cases were also described from Lednica and Horné Sŕnie localities (Aubrecht et al., 2006).

4.4. The Chmielowa Formation

The Chmielowa Formation is represented by red to pink marly limestones, followed by marlstones. The base of the formation displays complex and condensed stratigraphy (Fig. 10). The upper surface of the underlying Sobótka Limestone Member is irregular also in microscale (Fig. 6F), it is bored (microboring filled with opaque Fe-Mn minerals, Fig. 9A,B), covered with Fe-Mn-encrustations and phosphatic stromatolites with frequent sessile foraminifers (Fig. 8F–H). The lowermost part of the Chmielowa Formation locally contains pebble-size detritic admixture, composed mostly of clasts of the underlying limestones with calpionellids (Fig. 9C). Single clast of garnet gneiss was also found (Fig. 9D). Numerous belemnites (Fig. 8E) and some ammonites (Fig. 8C) were observed in the basal part as well. The transgressive deposits are rich in bioclastic material of various origins. Significant part of the allochems is represented by planktonic foraminifera, accompanied by less common fragmented crinoidal particles and other unidentified calcitic

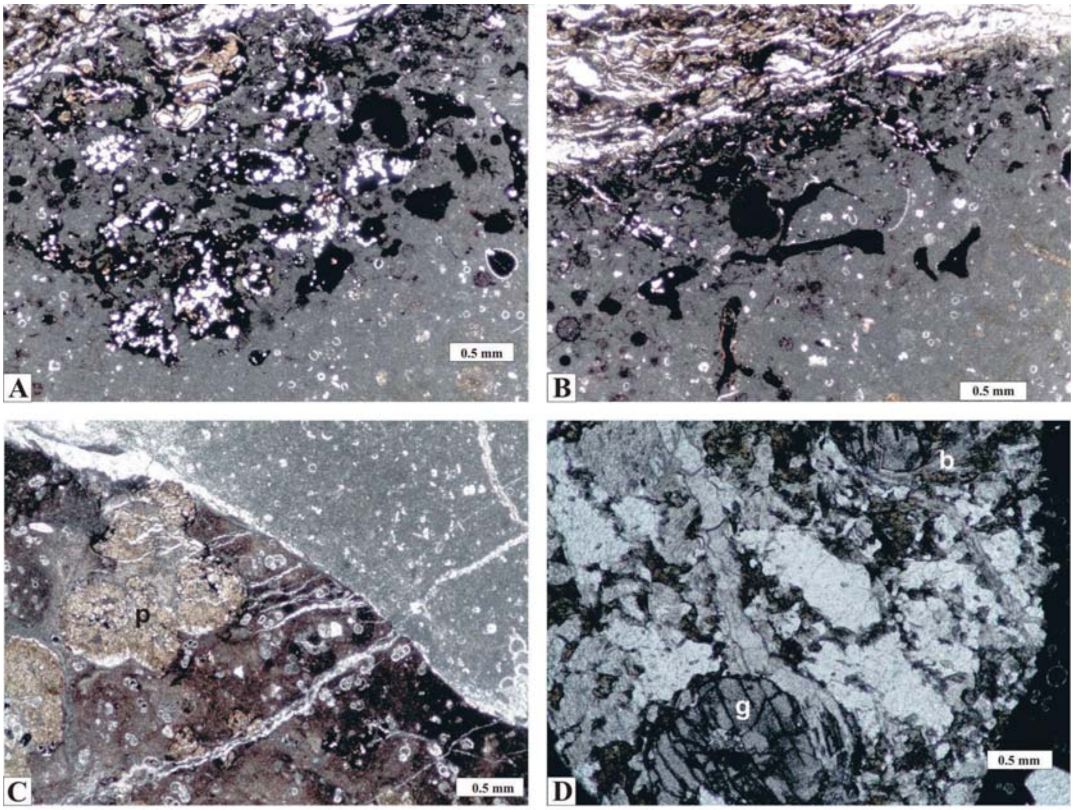

Fig. 9: A, B – Bored limestone of the Sobótka Limestone Member below the base of the Chmielowa Formation. The borings are filled with opaque Fe-Mn minerals. Thin-section, plain polarized light. C – Clast of the underlying calpionellid wackestone (the Sobótka Limestone Member, upper right part of the thin-section) in the red marly limestone of the Chmielowa Formation (lower left part). The latter also contains clusters of phosphates (p). Plain polarized light. D – Small pebble of garnet gneiss in the Chmielowa Formation. The rock consists of quartz (white to pale-grey), garnet (g) and biotite (b). Thin-section, plain polarized light.

Obr. 9: A, B – Navŕtavaný sobótsky vápenec v podloží chmielovského súvrstvia. Navŕtavania sú vyplnené opaknými Fe-Mn minerálmi. Výbrus, rovnobežné nikoly. C – Klast podložného kalpionelového wackestonu (sobótsky vápenec, horná pravá časť výbrusu) v červenom slienitom vápenci chmielovského súvrstvia (dolná ľavá časť). V chmielovskom súvrství vidno aj zhluky fosfátov (p). Výbrus, rovnobežné nikoly. D – Valúnik granátovej ruly v chmielovskom súvrství. Hornina pozostáva z kremeňa (biely až svetlosivý), granátu (g) a biotitu (b). Výbrus, rovnobežné nikoly.

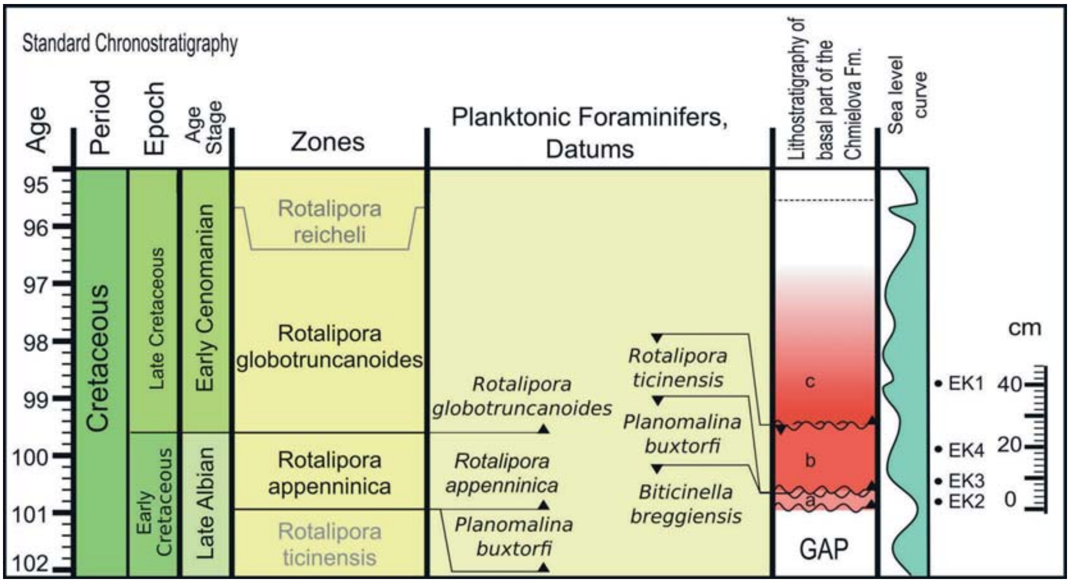

Fig. 10: Chrono-, bio-, and lithostratigraphy of the Upper Albian – Lower Cenomanian deposits of the Chmielowa Formation; a–c foraminifera associations, a – association of Rotalipora appenninica Zone with *Planomalina buxtorfi* (Gandolfi), b – association of Rotalipora appenninica Zone lacking *Planomalina buxtorfi* (Gandolfi), c – association of Rotalipora globotruncanoides Zone with *Rotalipora globotruncanoides* Sigal; (standard chronostratigraphy after Gradstein et al., 2004; foraminiferal zones and datums after Robaszynski, 1998; high-resolution sea level curve after Hardenbol et al., 1998).

Obr. 10: Chrono-, bio- a litostratigrafia vrchnoalbsko-spodnocenomanských sedimentov chmielovského súvrstvia. a–c asociácie foraminifer, a – asociácia zóny Rotalipora appenninica s *Planomalina buxtorfi* (Gandolfi), b – asociácia zóny Rotalipora appenninica bez prítomnosti *Planomalina buxtorfi* (Gandolfi), c – asociácia zóny Rotalipora globotruncanoides s *Rotalipora globotruncanoides* Sigal; (štandardná chronostratigrafia podľa Gradstein et. al., 2004, zonácia a dátumy podľa Robaszynski, 1998; vysokorozlišovacia krivka úrovne hladiny svetového oceánu podľa Hardenbol et al., 1998).

bioclasts. Few centimeters thick layer of red to pink limestone in the direct contact with the underlying Sobótka Limestone Member yielded planktonic foraminiferal association (observed in thin section only). According to the presence of *Planomalina buxtorfi* (Gandolfi) (Fig. 12C–D), *Rotalipora ticinensis* (Gandolfi) (Fig. 11E–H, 12A,D) and *Rotalipora appenninica* Renz (Fig. 11B–D, 12A), it can be assigned to Rotalipora appennica Interval Zone (after Robaszynski, 1998, Fig. 10 – association a). Other planktonic taxa were represented by smaller globular chambered hedbergellid forms such as *Biticinella breggiensis* (Gandolfi) (Fig. 12B). Calcareous and agglutinated benthic foraminifers occur commonly.

This thin limestone layer is overlain by dark red biodetritic marlstones. Washed samples contained poorly preserved Late Albian planktonic foraminifera associations with common *Rotalipora appenninica* and scarce *Rotalipora ticinensis*. Other planktonic foraminifera were represented by *Praeglobotruncana* cf. *stephani* (Gandolfi), *Praeglobotruncana delrioensis* Plummer, *Muricohedbergella delrioensis* (Carsey), *Muricohedbergella planispira* (Tappan) and ?*Macroglobigerinelloides* sp. The association can be assigned to the Rotalipora appenninica Interval Zone (after Robaszynski, 1998, Fig. 10 – association b). The benthic foraminiferal associations contain poorly preserved calcareous forms such as *Gavelinella intermedia* (Berthelin), *Lenticulina gautina* (Berthelin), *Pleurostomella* sp. and ?*Laevidentalina* sp. as well as agglutinated forms, such as common *Tritaxia gaultina* (Morozova), less common *Marsonella oxycona* (Reuss), *„Marsonella“ trochus* (d´Orbigny), *Dorothia gradata* (Berthelin), and scarce *Arenobulimina preslii* (Reuss), *Spiroplectinata complanata* Grabert, *Ammosphaeroidina* sp., and *Spiroplectammina* sp. Sometimes, adherent foraminifers can be found on the test surface of *Spiroplectinata* (Fig. 11A). These suspension feeders colonize some larger epibenthic foraminifera using them as a hard substrate. The position of the adherent foraminifera on the earlier chambers indicates rather post-mortem colonization (Tyszka & Thies, 2001). Among other microbioclasts fish teeth were also observed.

Next sample yielded markedly better preserved foraminiferal association than the previous one, with common *Rotalipora appenninica* and *Rotalipora globotruncanoides* Sigal (Fig. 11I–K). Other planktonic foraminifera are represented by *Praeglobotruncana* cf. *stephani*, *Praeglobotruncana delrioensis*, *Muricohedbergella delrioensis*, *Muricohedbergella planispira*, *Muricohedbergella simplex* (Morrow) (Fig. 11L), and ?*Macroglobigerinelloides* sp., associated with benthic forms, common *Tritaxia gaultina*, *Gavelinella* cf. *cenomanica* (Brotzen), *Gavelinella intermedia* (Berthelin), *Lenticulina* sp. and scarce *Ammosphaeroidina* sp. and *Spiroplectammina* sp. The first occurrence of *Rotalipora globotruncanoides* marks the base of the Cenomanian with Rotalipora globotruncanoides Interval Zone (Robaszynski, 1998; Fig. 10 – association c).

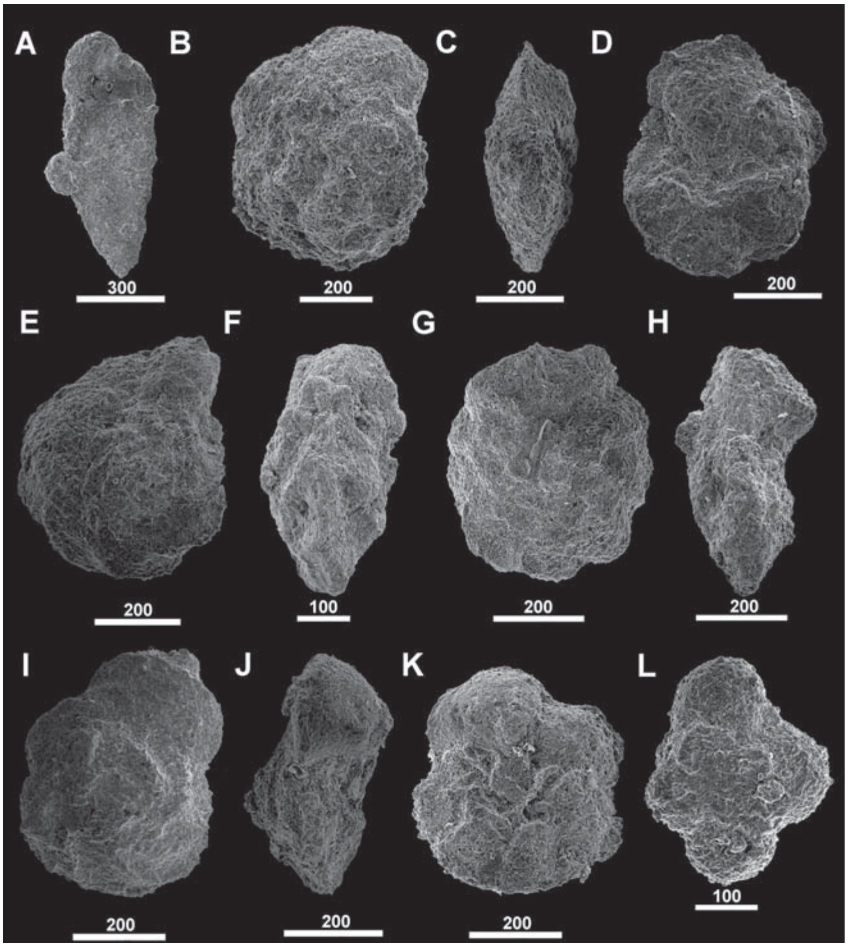

Fig. 11: Foraminifera from the red biodetritic marlstones of the Chmielowa Formation. A – *Spiroplectinata complanata* Grabert with adherent foraminifer attached to the test. Sample EK4. B–D – *Rotalipora appenninica* (Renz), B – dorsal, C – peripheral, D –umbilical view. Sample EK1. E–H – *Rotalipora ticinensis* (Gandolfi), E – dorsal, F,H – peripheral, G – umbilical view. Sample EK4. I–K – *Rotalipora globotruncanoides* Sigal, I – dorsal, J – peripheral, K – umbilical view. Sample EK1. L – *Muricoedbergella simplex* (Morrow), dorsal view. Sample EK4. For sample numbers see Fig. 10. Scale is in microns.

Obr. 11: Foraminifery z červených biodetritických slieňovcov chmielovského súvrstvia. A – *Spiroplectinata complanata* Grabert s adherentnou foraminiferou prisadnutou k schránke. Vzorka EK4. B–D – *Rotalipora appenninica* (Renz), B – dorzálny, C – periferálny, D – umbilikálny pohľad. Vzorka EK1. E–H – *Rotalipora ticinensis* (Gandolfi), E – dorzálny, F,H – periferálny, G – umbilikálny pohľad. Vzorka EK4. I–K – *Rotalipora globotruncanoides* Sigal, I – dorzálny, J – periferálny, K – umbilikálny pohľad. Vzorka EK1. L – *Muricoedbergella simplex* (Morrow), dorzálny pohľad. Vzorka EK4. Viď obr. 10 pre číslovanie vzoriek. Mierka je v mikrónoch.

5. DISCUSSION

The stratigraphic gap between the Berriasian and Albian at the examined locality represents nearly 30 Ma (Gradstein et al., 2004). In fact, the biostratigraphically documented time span of the emersion is from the Hauterivian to the latest Aptian, i.e. about 20 Ma (Aubrecht et al., 2006). The karstification and erosion at the here studied locality reached an average depth (not deeper than Berriasian strata) which is typical of many other localities, such as Lednica, Vršatec, Kamenica, Dolný Mlyn, etc. However, the palaeokarst features are well developed (pronounced karren surface, rainwater grooves, etc.), just like at Horné Sŕnie site, where the erosion was extremely deep, reaching the Bajocian crinoidal limestones (Aubrecht et al., 2006). At both localities, tops of the hummocks and karren ridges are rounded which is typical for karren formed under soil cover (Ginés, 2004). This indicates that the emerged Czorsztyn Swell was covered with rich vegetation. Former research showed that after short Late Aptian period of relative shallow submergence, the area was emerged and karstified again (Aubrecht et al., 2006) followed by rapid Albian flooding with pelagic sedimentation. Our results from Erdútka site show the manifestation of the Late Albian flooding only. The basal part of the Chmielowa Formation is considerably condensed, indicating strong bottom currents being active long time after drowning (at Horné Sŕnie, locally even Turonian sediments rest on the karren surface). Mechanism of the flooding rests unknown. Because of character of the Czorsztyn Swell, it is more substantiated to presume sudden crustal collapse and sinking of the whole ridge than breakage of some barrier which preserved a dry land on the swell (Aubrecht et al., 2009). The clast of garnet-gneiss most likely came directly from the emerged crystalline rocks of the swell. Exotic ophiolitic detritus which appears in the Chmielowa Formation in the Czorsztyn Succession elsewhere (Aubrecht et al., 2009) was not detected at the studied locality.

The unusual vertical succession of calpionellid associations in the Erdútsky kostol section is worth to note, especially from the point of view of the recently largely discussed precise location of the Jurassic-Cretaceous boundary. The boundary is usually placed between the Crassicollaria and Calpionella zones, on the basis of the “explosion” event of small, globular *Calpionella alpina* (Lakova, 1994; Reháková, 1995; Grün & Blau, 1997; Reháková & Michalík, 1997; Houša et al., 1999; Skourtsis-Coroneous & Solakius, 1999; Michalík et al., 2009; Reháková et al., 2009), accompanied by sudden decrease in abundance of *Crassicollaria intermedia*, *Crassicollaria massutiniana*, and *Crassicollaria brevis*. Co-occurrence of several *Crassicollaria* species together with abundant *Calpionella alpina* within the studied section caused that the boundary between the Crassicollaria and Calpionella zones is rather difficult to trace here. Similar case with unusual succession of calpionellids was studied by Tavera et al. (1994) from Puerto Escaño section in southern Spain (province of Córdoba). They considered several possibilities where to place the Jurassic-Cretaceous boundary based on calpionellid associations: a) interval of „relative explosion" of *Calpionella alpina*, which does not yet display the change towards small spherical forms, accompanied by sudden decrease of *Crassicollaria*; b) younger beds where small isometric forms of *Calpionella alpina* are accompanied by *Crassicollaria parvula* and *Crassicollaria brevis*; c) the interval of a complete disappearance of the genus *Crassicollaria* within the Calpionella Zone. He finally decided to place the boundary on the base of the "relative explosion" of small isometric forms of *Calpionella alpina*, accompanied by *Crassicollaria parvula* and *Crassicollaria brevis*. *Crassicollaria parvula* is the only *Crassicollaria* species which is documented without ambiguity to be autochtonous in the lower part of the Calpionella Zone (Ondrejíčková et al. 1993; Lakova et al., 1999; Houša et al., 1996, 1999, 2004; Michalík et al., 1990[b], 2009; Grabowski et al., 2010[a,b]; Pruner et al., 2010). Other *Crassicollaria* species often observed in the samples of Calpionella alpina Subzone are considered as being redeposited. Except some cases where we can really see that these are located inside tiny litoclasts (e.g., Pruner et al., 2010), it is generally very difficult to prove it, mainly because of almost total similarity of mudstone facies in both time intervals, uppermost Tithonian and lowermost Berriasian. Although this was not the purpose of here presented study, we would like to note that the Erdútsky kostol can be very interesting exactly from this point of view. However it need high-resolution sampling.

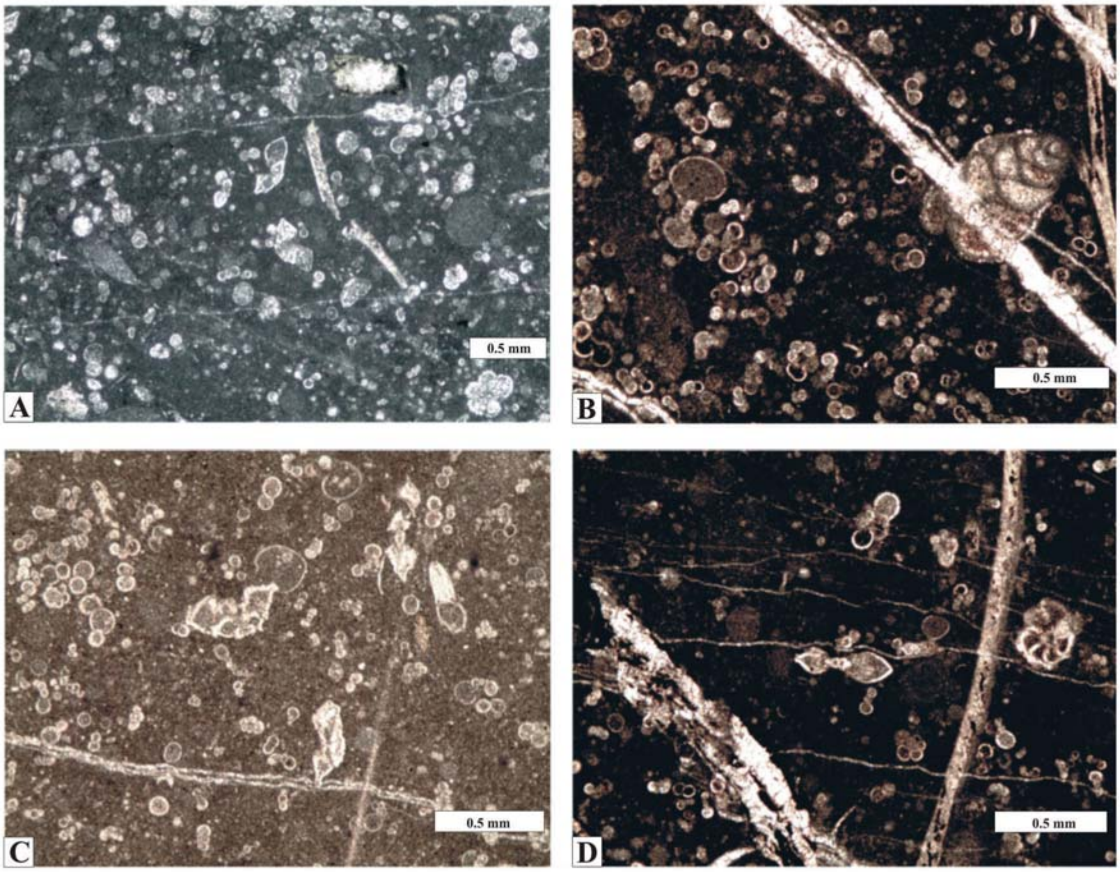

Fig. 12: Planktonic foraminifera and microfacies from the reddish to pink limestones of the Chmielowa Formation from the direct contact with limestones of the Sobótka Limestone Member. A – Foraminiferal and radiolarian wackestone/packstone with *Rotalipora* cf. *appenninica* (Renz) and *Rotalipora* cf. *ticinensis* (Gandolfi) in the middle. B – Foraminiferal wackestone with *Biticinella breggiensis* (Gandolfi) (middle left) and *Dorothia* sp. (middle right). C – Foraminiferal and radiolarian wackestone with *Planomalina buxtorfi* (Gandolfi). D – Foraminiferal wackestone/packstone with *Rotalipora ticinensis* (Gandolfi) and *Planomalina buxtorfi* (Gandolfi). All photos from the sample EK2 (see Fig. 10).

Obr. 12: Planktonické foraminifery a mikrofácie z červenkastých až ružových vápencov chmielovského súvrstvia z priameho kontaktu s vápencami sobótskeho súvrstvia. A – Foraminiferovo-rádioláriový wackeston až packston s *Rotalipora* cf. *appenninica* (Renz) a *Rotalipora* cf. *ticinensis* (Gandolfi) v strede. B – Foraminiferový wackeston s *Biticinella breggiensis* (Gandolfi) (v strede vľavo) a *Dorothia* sp. (v strede vpravo). C – Foraminiferovo-rádioláriový wackeston s *Planomalina buxtorfi* (Gandolfi). D – Foraminiferový wackeston až packston s *Rotalipora ticinensis* (Gandolfi) a *Planomalina buxtorfi* (Gandolfi). Všetky obrázky sú zo vzorky EK2 (viď obr. 10).

Anyway, if we follow above mentioned opinion, we can place this boundary in upper part of the Korowa Limestone Member (see Fig. 4) where the disappearance of the *Crassicollaria brevis* was observed. *Crassicollaria massutiniana* and *Crassicollaria parvula* are still abundant which is interpreted as effect of submarine erosion of older strata (Michalík & Reháková, 2011). Synsedimentary erosion at the Jurassic-Cretaceous boundary was recorded in several Central Carpathian sections; e.g., Hlboča and Strážovce sections (Michalík et al., 1990[a,b]; Michalík & Reháková, 2011).

6. CONCLUSIONS

1. North of Zázrivá (Orava section of the Pieniny Klippen Belt), a klippe of the Czorsztyn Unit with nicely preserved Early Cretaceous palaeokarst was found. The stratigraphic range of the here outcropping succession is from the Kimmeridgian to the Cenomanian, with stratigraphic gap from the Early Berriasian to the Late Albian.
2. The succession consists of red nodular limestones (Czorsztyn Limestone Formation) and red to white calpionellid limestones (Dursztyn Limestone Formation – Korowa and Sobótka limestone members), terminated by palaeokarst surface of hummocky karren shape with rounded tops, indicating a soil-covered karstification. Pelagic red marly limestones and marlstones containing Late Albian to Cenomanian foraminifers were deposited after the hiatus period. Pelagic character of these deposits suggests a rapid flooding, which can be explained by crustal collapse of the Czorsztyn Swell.
3. Precise position of the boundary between Crassicollaria Zone and Calpionella Zone and thus also between Jurassic and Cretaceous within the studied section is rather difficult to locate in the light of acquired data. The section was not sampled for detailed microbiostratigraphy and the few analysed samples are not sufficient. Temporary it can be placed to uppermost part of the Korowa Limestone Member.

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Resumé: Čorštynský chrbát tvoril najvyvýšenejšiu časť paleogeografickej domény oravika, ktorej sedimenty dnes tvoria podstatnú časť pieninského bradlového pásma. Počas väčšiny svojej histórie bol chrbát ponorený. Epizódy vynorenia sa odohrali len krátko po jeho vzniku v strednej jure (v bajoku), avšak najdlhšie obdobie vynorenia sa odohralo v spodnej kriede, od valanžinu do najvrchnejšieho aptu (Aubrecht et al., 2006). Epizódu zavŕšila rýchla ingresia spojená so sedimentáciou červených pelagických slieňov, ktorá trvala až do konca kriedy. Epizóda spodnokriedového vynorenia sa prejavila eróziou a krasovatením, čo bolo dokumentované na viacerých lokalitách. Najlepšie zachovaný paleokrasový povrch sa nachádzal na lokalite Horné Sŕnie (Aubrecht et al., 2006), avšak bol zničený postupnou ťažbou. V poslednej dobe sa však našla podobná lokalita s dobre zachovaným paleokrasom severne od Zázrivej na Orave (Obr. 1).

Bradlo čorštynskej jednotky medzi miestnymi obyvateľmi známe ako „Erdútsky kostol" je v prevrátenej vrstevnej pozícii (Obr. 2,3). Jeho stratigrafia začína čorštynskými červenými hľuznatými vápencami (Obr. 2B). Ich spodná, hrubohľuznatá časť predstavuje biomikrit-packston so sakokómovou mikrofáciou (Obr. 5A). Stratigraficky významná je prítomnosť vápnitých dinocýst *Shizosphaerella minutissima* (Colom) a *Cadosina parvula* Nagy (Obr. 5B), ktoré indikujú acme zónu Parvula (spodný kimeridž). Vrchná časť hľuznatého vápenca predstavuje biomikrit-packston, miestami až grainston opäť so sakokómovou mikrofáciou, avšak vo vyššej časti s pribúdajúcim množstvom spór *Globochaete alpina* Lombard, ktorá tvorí globochétovo-rádioláriovú mikrofáciu s menším množstvom článkov sakokóm (Obr. 5D). Vápenec obsahuje vápnité dinocysty *Colomisphaera carpathica* (Borza), *Colomisphaera nagyi* (Borza), *Shizosphaerella minutissima* a *Cadosina parvula*. Posledná spomínaná prevláda v nižšej časti a indikuje acme zónu Parvula (spodný kimeridž). Vo vrchnej časti *Colomisphaera tenuis* (Nagy) (Obr. 5E) indikuje zónu Tenuis (stredný titón). Z čorštynského vápenca sa podarilo získať aj pomerne zle zachovanú faunu amonitov. Stratigraficky najstaršia zachovaná vrstva obsahovala pomerne hojnú faunu zle zachovaných amonitov a aptychov. Z amonitov sa podarilo určiť druhy *Taramelliceras* gr. *pugile* (Neumayr), *Aspidoceras apenninicum* Zittel, *Subplanites* sp. and *Biplisphinctes* cf. *spathi* Oloriz. Fauna indikuje vrchný kimeridž, konkrétne zónu Eudoxus, alebo Beckeri.

Nad čorštynskými vápencami sa v stratigrafickom nadloží nachádza durštynské vápencové súvrstvie (Obr. 2C), zložené zo starších vrstevnatých červených až ružových korovských vápencov a mladších bielych sobotských vápencov. Korovský vápenec predstavuje biomikrit-wackeston až packston s kalpionelovou mikrofáciou s množstvom rádiolárií a globochét (Obr. 5F). Sakokómy sú už pomerne zriedkavé. Fauna kalpionelidov obsahuje druhy *Calpionella alpina* Lorenz (Obr. 6A), *Crassicollaria massutiniana* (Colom) (Obr. 6B), *Crassicollaria brevis* Remane (Obr. 6C), *Crassicollaria parvula* Remane (Obr. 6D), *Tintinopsella doliphormis* (Colom), *Tintinopsella carpathica* (Murgeanu & Filipescu) a *Crassicollaria colomi* Doben (Obr. 6A). Vápenec obsahuje aj pomerne zriedkavé vápnité dinocysty *Colomisphaera carpathica*, *Shizosphaerella minutissima* a *Cadosina semiradiata semiradiata* Wanner (Obr. 6E). Spoločenstvo krasikolárii v spodnej časti vápenca je príznačné pre zónu Crassicollaria, podzónou Intermedia. V strednej časti začína byť hojná *Crassicollaria brevis* Remane, ktorá indikuje zónu Crassicollaria, podzónu Brevis. Vo vrchnej časti sa znovu objavuje planktonická asociácia kalpionelidov charakteristická pre zónu Calpionella, podzónu Alpina, sprevádzaná stále hojnými druhmi *Crassicollaria parvula* a *Crassicollaria massutiniana* (Obr. 4).

Sobótsky vápenec predstavuje biomikrit–wackeston až mudston s kalpionelovo-globochétovou mikrofáciou. Kalpionelidy sú zastúpené druhmi *Calpionella alpina, Calpionella grandalpina* Nagy, zriedkavo *Crassicollaria massutiniana*, *Crassicollaria parvula*, *Crassicollaria colomi*, *Crassicollaria brevis*, *Tintinopsella doliphormis* a častejším druhom *Tintinopsella*

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carpathica. Vyskytujú sa aj vápnité dinocysty, ako *Cadosina semiradiata semiradiata* a *Colomisphaera carpathica*. Na základe prevládania druhu *Calpionella alpina* sobotské vápence patria do spodného beriasu (zóna Calpionella, podzóna Alpina).

Sobótsky vápenec je ukončený nepravidelne zvlneným paleokrasovým povrchom (Obr. 7), v ktorom dominujú zaoblené homoľovité formy škrapov (Obr. 7C–E), ktoré sú typické pre povrchový kras vyvinutý pod hrubou vrstvou pôdy. Na niektorých pozitívnych formách reliéfu vidno dažďové ryhy, ktoré sú kolmé na podložie (Obr. 7D). Paleokrasový povrch je navŕtavaný lastúrnikmi (Obr. 8A,B) a obrastaný železito-mangánovými a fosfatickými stromatolitmi. V podložnom korovskom vápenci sa našli aj niektoré kalcitové žilky (Obr. 8D), ktoré nepokračujú do nadložných albských sedimentov; musia byť teda staršie. Nad paleokrasovým povrchom leží kondenzovaný súbor červených pelagických slienitých vápencov a slieňovcov (chmielovské súvrstvie) (Obr. 7A). Súvrstvie obsahuje bohatú faunu planktonických (Obr. 10) a bentických foraminifer (Obr. 8G,H), pričom báza súvrstvia začína vo vrchnoalbskej intervalovej zóne Rotalipora appennica (Robaszynski, 1998, Fig. 10 – asociácia a), čo indikuje prítomnosť foraminifer *Planomalina buxtorfi* (Gandolfi) (Obr. 12C,D), *Rotalipora ticinensis* (Gandolfi) (Obr. 11E–H, 12A,D) a *Rotalipora appenninica* Renz (Obr. 11B–D, 12A). Už niekoľko desiatok centimetrov nad bázou sa v červených slieňoch vyskytuje fauna s častými druhmi *Rotalipora appenninica* (Renz) a *Rotalipora globotruncanoides* Sigal (Obr. 11I–K), s menším zastúpením *Praeglobotruncana* cf. *stephani* (Gandolfi), *Praeglobotruncana delrioensis* (Plummer), *Muricohedbergella delrioensis* (Carsey), *Muricoedbergella planispira* (Tappan) *Muricohedbergella simplex* (Morrow) (Obr. 11L) a ?*Macroglobigerinelloides* sp. Prvý výskyt druhu *Rotalipora globotruncanoides* indikuje bázu cenomanu s rovnomennou foraminiferovou zónou (Robaszynski, 1998, Fig. 10 - asociácia c).

Stratigrafický hiát na skúmanej lokalite zahŕňa časové obdobie od beriasu do vrchného albu. Na základe analógie z predošlých výskumov možno odhadovať, že vrchnoberiaské až valanžinské horniny boli odstránené eróziou (Aubrecht et al., 2006).