Czorsztyn Ridge was not uniform: new data from the Ukrainian part of the Pieniny Klippen Belt (Eastern Carpathians)

Roman Aubrecht[1,2], Ján Schlögl[1], Michał Krobicki[3] & Andrzej Wierzbowski[4]

[1] Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University, Ilkovičova 6, SK–842 15 Bratislava, Slovakia; roman.aubrecht@uniba.sk, jan.schlogl@uniba.sk
[2] Earth Science Institute, Slovak Academy of Sciences, Dúbravská cesta 9, SK–845 28 Bratislava, Slovakia
[3] AGH University of Science and Technology, Department of Geology, Geophysics and Environmental Protection, Mickiewicza 30, 30-059 Cracow, Poland; krobicki@geol.agh.edu.pl
[4] Institute of Geology, University of Warsaw, Al. Żwirki i Wigury 93, 02-089 Warsaw, Poland; awie@pgi.gov.pl

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Abstract: The Czorsztyn Ridge was the shallowest part of the continental crust ribbon called Oravicum. It originated due to the Jurassic opening of the Ligurian-Penninic-Vahic Ocean. Because of its shallow-water nature, depositional record of the Czorsztyn Succession, which was closest to the ridge top, displays considerable variability. Inventory of lithostratigraphic units and specific developments of this unit lasts since 19th century and is still incomplete. This paper deals with three new localities in the western Ukraine which are different from previously described klippen of this succession: Veliky Kamenets 2, Vilki Dil, and Mala Ugolka. They show some features, which are unique and atypical of the Czorsztyn Succession, and allow us to envisage spatial variability in depositional environments along the Czorsztyn Ridge. The Veliky Kamenets 2 represents a locality with most condensed sedimentary succession ever registered in the Czorsztyn Unit, capturing multiple emergence periods with erosion and karstification, evidenced by numerous sedimentary gaps resulting in very condensed sedimentary record with uneven, bizarre voids, omission surfaces, microstalactitic and meniscus cements. After Bajocian deposition of the crinoidal limestones (Smolegowa and Krupianka limestone formations) there was a karstification period followed by deposition of greenish quartz sandstone with carbonate cement. This sandstone has no analogue with so far known lithostratigraphic units. The Middle Jurassic crinoidal limestones also contain pyroclastic material which manifests one of the earliest volcanic phases in the Pieniny Klippen Belt. The locality probably represents a megabreccia formed by the pre-Albian emersion which is also unique as it was not registered so far at other localities. The Vilki Dil locality is unique by very late onset of marine transgression, where only thin beds of the crinoidal limestone (Smolegowa and Krupianka limestone formations), or locally even the first beds of nodular limestone (Czorsztyn Limestone Formation) rest on terrestric pale sandstones and quartzites. Pale quartz sandstones are typical of the Czorsztyn Succession in the Ukrainian sector of the Pieniny Klippen Belt. They resemble Gresten Beds from the Eastern Alps, but they differ in their heavy-mineral contents. They also differ from other Jurassic sediments of all Oravic units known so far. The sandstones are mostly dominated by ultrastable trinity tourmaline, zircon, and rutile, with the dominance of tourmaline. The Gresten Beds and previously analysed Oravic units are dominated by garnet and the ultrastable trinity is strongly dominated by zircon. This difference may be a reflection of longitudinal variability of the Oravic crustal segment (Czorsztyn Ridge). Siliciclastic admixture is ubiquitous at the examined localities and reaches up to the Berriasian. The eastern localities were likely situated much closer to the source of siliclastics on the emerged portions of the Czorsztyn Ridge than those occurring more westward and that emersion persisted much longer in the eastern part, even after the Bathonian-Callovian sea-level rise. The Mala Ugolka locality is unique by Late Berriasian breccia with cement-coated clasts which represents the first manifestation of post-Tithonian shallowing that preceded the Hauterivian-Aptian emersion of the Czorsztyn Ridge.

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

1. INTRODUCTION

The Pieniny Klippen Belt is a narrow mélange zone located between the West Carpathian internides and externides. The mélange originated due to multiple orogenic phases. It consists of tectonic blocks of Mesozoic sedimentary rocks, mostly Jurassic and Lower Cretaceous limestones, embedded in softer, marly or flyschoid rocks of predominantly Late Cretaceous age. The sediments were detached from their basement, which was later presumably underthrust beneath the Central Western Carpathians. Palaeogeographic reconstruction of this mélange is rather complicated. Most of the mélange components were derived from a palaeogeographic unit called Oravicum (the term introduced by Mahel', 1986); some units originally belonged to the internides, e.g., Manín, Drietoma, Kostelec, and Haligovce units. These non-Oravic units which were ranked by Mahel' (1980) to the so-called peri-Klippen Zone, were incorporated to the Pieniny Klippen Belt during the latest orogenic phases in Cenozoic. The main, Oravic crustal segment was characterized by a central elevation called Czorsztyn Ridge (represented by relatively shallow-marine Czorsztyn Succession) surrounded by deeper basins (represented by deep-marine Kysuca-Branisko/Pieniny, Orava, and Magura successions (Birkenmajer, 1977). The Czorsztyn Succession was the shallowest one of all

Manuscript received: 2017-06-28
Revised version accepted: 2017-11-10

the Pieniny Klippen Belt units and its sedimentary record is spatially and temporally most variable (Aubrecht et al., 1997). In most klippen, the Middle-Jurassic to Lower Cretaceous part of Czorsztyn Succession is preserved. Lower Jurassic sediments were often detached and are preserved only at several localities, e.g., Dolný Mlyn, Beňatina, Novoselitsya, and Priborzhavskoe although the attribution of the deposits from the Beňatina, Novoselitsya, and Priborzhavskoe sections to the Czorsztyn Succession was questioned by some of the authors because of certain differences in the lithostratigraphic content (see opinions in: Rakús, 1995; Krobicki et al., 2003; Schlögl et al., 2004; Wierzbowski et al., 2012[a]). The lithostratigraphic record of the Czorsztyn Succession starts with sandstones with greenish marls intercalations, followed by black to dark-grey clayey limestones to shales with fauna of ammonites, oysters, and spiriferinid brachiopods of Sinemurian age (Dolný Mlyn Formation). It is followed by spotted limestones to marlstones (typical "Fleckenkalk/Fleckenmergel" facies) of Allgäu Formation (Late Sinemurian-Late Pliensbachian). Toarcian to Aalenian is mostly represented by black-shale facies of the Skrzypny Shale Formation, but locally also red varieties may occur (e.g., Hŕbok Formation at Beňatina locality – Schlögl et al., 2004), or by condensed sandy limestones with ferruginous stromatolites and rich ammonite fauna (uppermost Pliensbachian-Aalenian deposits in Priborzhavskoe quarry in Transcarpathian Ukraine – Wierzbowski et al., 2012[a]; Krobicki et al., 2016). The presence of these condensed red varieties typical of the Priborzhavske-Perechin-Novoselitsa-Beňatina zone is treated, however, in different way by some of the authors as indicative of the southern part of the Pieniny Klippen Basin far away from the Czorsztyn Succession (Wierzbowski et al., 2012[a], p. 42). From Bajocian (or latest Aalenian) onward, the

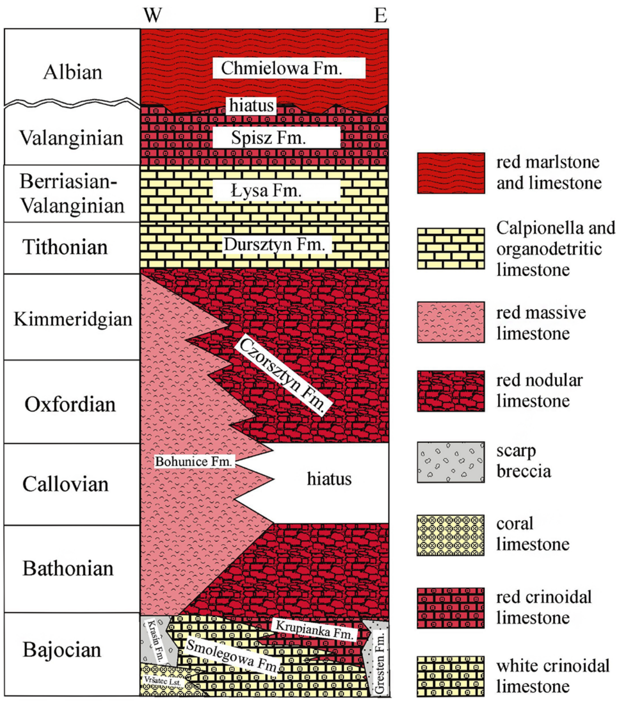

Fig. 1. Bajocian to Albian lithostratigraphic scheme of the Czorsztyn Succession, showing approximate variability trend from west to east.

lithostratigraphic units are much better preserved (Fig. 1), occurring at many places all along the Pieniny Klippen Belt. Bajocian was characterized by rising of the Czorsztyn Ridge (Krobicki & Wierzbowski, 2004, 2014; Krobicki, 2009; Barski et al., 2012; Segit et al., 2015) due to Mid-Jurassic rifting and block tilting. Shallowing of the sedimentary area was indicated by local coral bioherms (Vršatec Limestone) that occur solely in the western part of the Pieniny Klippen Belt (Middle Váh Valley), but at most places it is manifested by presence of crinoidal limestones of white to reddish colours (Smolegowa and Krupianka limestone formations). The crinoidal limestones locally bear signs of synsedimentary tectonics related to rifting, such as cliff breccias (Krasín Breccia – Mišík et al., 1994[a]; Aubrecht, 1997, 2001[a]; Aubrecht & Szulc, 2006) and neptunian dykes (Aubrecht & Túnyi, 2001). Since the latest Bajocian, deepening due to the global sea-level rise occurred in the Oravic sedimentary area. This was manifested in the Czorsztyn Succession by Ammonitico Rosso-type sediments (red nodular limestones – Czorsztyn Limestone Formation), deposition of which lasted until the Early Tithonian. In the Middle Váh Valley but also at some localities in the east, micritic, non-nodular variety of these limestones occur (Bohunice Limestone Formation – Mišík et al., 1994[b]). Lack of nodularity in these limestones was partly caused by the fact, that they represent mud-mound deposits, often with stromatactis structures (Aubrecht et al., 2002; 2009[b]). In Tithonian, the condensed, nodular facies all along the Czorsztyn Ridge gave way to completely non-nodular facies represented by the Dursztyn Limestone Formation, comprising biomicritic Calpionella limestones (Sobótka Limestone Member), ammonite coquinas, or bivalve-brachiopod coquinas (Rogoźnik and Rogoża coquinas). The Lower Cretaceous deposition (Berriasian to Valanginian) is characterized by bioclastic Calpionella-bearing limestones of the Łysa Limestone Formation, overlain by the crinoidal limestones of the Spisz Limestone Formation. In Valanginian, the limestone deposition terminated, followed by a hiatus encompassing the entire Hauterivian, Barremian and almost entire Aptian. The hiatus was caused by a large-scale emersion of most of the Oravic domain, reaching up to the margins of the Kysuca-Pieniny Basin (Aubrecht et al., 2006; Józsa & Aubrecht, 2008). The deposition of red marls (Scaglia Rossa-type of sediment) of the Chmielowa Formation (latest Aptian-Albian) started after hiatus. In Cenomanian, siliceous deposition temporarily occurred in form of the Pomiedznik Formation with radiolarite intercalations. Then, the deposition in form of variegated Globotruncana marls followed by flysch-type deposits of the Sromowce Formation lasted until the very end of Mesozoic, when the Laramian collision of the Oravic domain with Carpathian internides occurred, terminated with synorogenic to early post-orogenic coarse clastics of the Jarmuta Formation.

In the eastern sectors of the Pieniny Klippen Belt (Poland, eastern Slovakia and Transcarpathian Ukraine), lateral variability of the Czorsztyn Succession becomes marked. In addition to the condensed uppermost Pliensbachian-Aalenian deposits in the Priborzhavskoe quarry and better preserved Lower Jurassic parts of the succession, there are also other

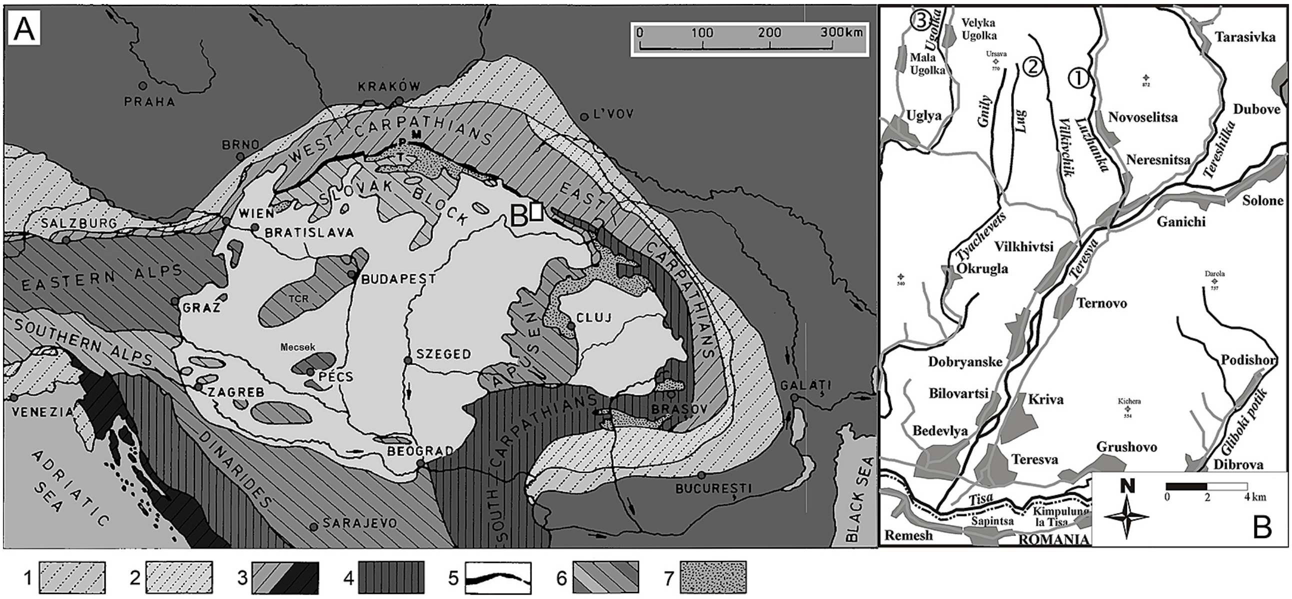

Fig. 2. Position of the examined localities. A – Position of the area in the Western Ukraine (rectangle B) within the Alpine-Carpathian system. Basal map after Birkenmajer (2007) – modified. 1–2 – Neogene Molasse Zone of the Eastern Alps and Carpathian Foredeep; 3 – Alpine and Carpathian Flysch Belt; 4 – Mid-Cretaceous nappes in the Eastern and Southern Carpathians and comparable zones elsewhere; 5 – Pieniny Klippen Belt; 6 – Eastern and Southern Alps, Central Western Carpathians and comparable zones; 7 – Inter-arc post-nappe cover in the Carpathians and the Apuseni Mts. (Upper Cretaceous-Palaeogene); light grey – Neogene volcanics and sedimentary basin filling. B – Position of the examined localities (1 – Veliky Kamenets 2; 2 – Vilki Dil; 3 – Mala Ugolka).

specific features (it should be remembered, however, that some authors do not correlate these deposits with the Czorsztyn Succession – see above). They are for instance earlier, Aalenian local onset of crinoidal limestone deposition (Schlögl et al., 2004), more common indices of Lower Cretaceous basaltic volcanism (Oszczypko et al., 2012), more common presence of detritic Gresten-type arkosic arenites below the crinoidal limestones (Reháková et al., 2011), and common olistolithic origin of the klippen (resting inside Palaeogene coarse-detritic sediments; Nemčok, 1980; Plašienka & Mikuš, 2010; Golonka et al., 2015).

Here we present new data from three localities in the Transcarpathian Ukraine that show these unique features and reveal some other specific features that significantly enlarge depositional variability of the Czorzstyn Ridge during the Jurassic. The data complement the known image of the Czorsztyn Succession and enable us to reconstruct changes in the lithostratigraphic successions and its E–W variability more accurately.

2. STUDIED SITES AND METHODS USED

The examined localities are: Veliky Kamenets 2, Vilki Dil and Mala Ugolka. The sites are located in the northern, mountain area of the Tyachiv District in the Transcarpathian Ukraine (Fig. 2).

The Veliky Kamenets 2 site (N 48°10'43.4'', E 23°44'24.5'') is situated NNW of the Novoselitsa village, about 300 m SE from the Veliky Kamenets locality, which is a marble quarry, several times described in literature (Reháková et al., 2011 with references therein). The Veliky Kamenets 2 represents a pit quarry with poorly exposed, highly condensed strata of the Czorsztyn Succession ranging from Middle Jurassic to Albian.

The Vilki Dil site (N 48°11'3.3'', E 23°43'7.7'') is situated on the western slope of the Vilkivchik Valley, at the local site named Barakishche. The section starts at a local forest road and spreads onto the top of a small ridge. The locality shows the Czorsztyn Succession from Middle Jurassic to Albian. The klippe may represent an olistolith in Palaeogene coarse-clastic rocks, as inferred from neighbouring klippe where a contact between the Czorsztyn Limestone Formation and Palaeogene conglomerates is visible.

The Mala Ugolka site (N 48°12'09.5'', E 23°38'06.9'') represents a pit quarry about 100 m east of the main road in the equally named village, at the western toe of the Mala Teremoksa Hill. The quarry reveals Lower Cretaceous breccias with mudstone to bioclastic matrix. The klippe itself represents a block in Palaeogene conglomerates.

Where possible, lithological sections of the examined sites were measured and drawn. Main lithological units were sampled for microfacies analysis; additional samples were taken from siliciclastic units for heavy mineral analysis. These were crushed, sieved and the heavy fraction was separated in bromoform (density 2.8). Fraction 0.08–0.25 mm was studied in polarizing microscope and ratios of heavy minerals were recorded by ribbon counting. In this paper, only the heavy mineral-ratios are used; detailed heavy mineral analysis and comparison with previously analysed localities in more western sectors of the Pieniny Klippen Belt will be published elsewhere.

3. DETAILED DESCRIPTION OF THE SITES, THEIR LITHOLOGICAL AND MICROFACIES ANALYSIS

3.1. Veliky Kamenets 2

The succession in the pit quarry (Fig. 3A) is difficult to study and the outcrops are quite scattered. The fact that there are some stratigraphically overturned sections but the pre-Albian erosional surface is preserved on the upper (stratigraphically oldest) sides indicates, that the entire locality may represent a megabreccia which originated due to mid-Cretaceous emersion. However, the blocks appear to belong to one, strongly condensed development of the Czorsztyn Succession. Its stratigraphically lower parts are visible mainly at the northern margin of the quarry (Fig. 3B), starting with crinoidal-micritic limestones that stratigraphically rest on pale arkosic sandstones with coalified plant detritus, belonging to the Gresten Beds. This was the only continuous section which was accessible to sampling; rest of the samples was taken from isolated boulders, from which a composite profile was done.

3.1.1. Section at the northern margin of the quarry

The sequence starts with several beds (overall thickness about 140 cm – Fig. 3C) of variably condensed and laminated red to yellowish micrite, to crinoidal packstone, strongly impregnated with black Fe-Mn oxides. Microscopic analysis shows that the bed consists of alternating strongly condensed (predominantly packstones) and less condensed (predominantly wackestones, locally pelmicrites) laminae. Echinoderm particles (including echinoid spines) are most common, forming locally crinoidal packstone laminae. Other common allochems are ostracods (mainly thin-shelled and free of ornamentation, but also some ornamented shells of *Pokornyopsis* sp.– Fig. 3D), benthic foraminifers, such as nodosarids, nubecularids, trocholinids, *Lenticulina* sp., *Spirillina* sp. Sandy quartz admixture is ubiquitous, locally accumulated to sandstone laminae with carbonate cement (Fig. 3E). Except of dominant quartz, rarely also feldspar grains, mica flakes and phosphatic stromatolitic fragments occur in the sandstone. Sandstone fragments occur locally, too. From other allochems, small gastropods, fragments of bivalve shells (including thin-shelled *Bositra*), algae *Globochaete alpina*, ammonite shells (accumulated in some parts), aptychi, foraminifers *Ophthalmidium*, *Dorothia*, *Tetrataxis*, trocholinid foraminifers, so-called "microforaminifers" (separately preserved thin Fe-Mn coatings of the inner part of the foraminiferal tests), skeletons of lithistid sponges, debris of bryozoans and rare fragments of bones are present locally. Towards the stratigraphic top, early planktonic foraminifers *Globuligerina* sp. and calcified radiolarians appear for the first time. Many allochems in the condensed parts are strongly bored and some have initial oolitic coatings (Fig. 4A), or are impregnated by black to brownish Fe-Mn oxides. These impregnations are locally thicker, forming thin hardground crusts. Some black coatings in sandstone laminae have microstalactitic appearance (Fig. 4B), passing locally to meniscus-like cementation, indicating that it might partly originate in vadose environment, probably related to subaerial exposure. From some black veinlets filled with Fe-Mn oxides, dendritic stromatolites grow up, similar to *Frutexites* (Fig. 4C). Some yellowish stromatolites may be of phosphatic origin and contain also serpulid tubes. Stromatolitic and Fe-Mn impregnated parts also locally separate the individual laminae within the sediment. Some portions of the sediment show signs of bioturbation. Presence of cavity-dwelling ostracods *Pokornyopsis* sp. (see Aubrecht & Kozur, 1995; Aubrecht & Schlögl, 2011) in the laminated part about 10 cm above the stratigraphic base indicates that this laminated layer is in fact a somewhat younger neptunian sill filling (subparallel to bedding).

The basal beds are stratigraphically overlain by a 140 cm-thick reddish, indistinctly nodular micritic limestone. It is also strongly impregnated by black Fe-Mn oxides but with different microfacies, dominated by wackestone with planktonic foraminifers *Globuligerina* (Fig. 4D) and calcified radiolarians. Mass occurrence of *Globuligerina* (= *Protoglobigerina*) is indicative of Oxfordian in the Czorsztyn Succession (Wierzbowski et al., 1999). Along with them, ammonite shells and phantoms after dissolved aragonite bivalve shells are common. Calcareous dinocysts (cadosinids) with predominance of *Schizosphaerella minutissima* (Fig. 4E–F) indicate that these deposits are not older than the Late Oxfordian (Reháková, 2000). Aptychi (*Laevaptychus*), echinoderm particles, small gastropods, ostracods, foraminifers *Lenticulina, Spirillina*, thin *Bositra* shells ("filaments"), rhyncholites, and fish teeth are less common. In the upper part of this lithological unit, ossicles of planktonic crinoid *Saccocoma* appear for the first time.

Rest of the outcrop (about 2.5 m) belongs to similar limestones dominated by Saccocoma microfacies. At the base (first 50 cm), there is a wackestone to packstone (formed partly by pressure solution), with mixture of the main microfacies components, forming radiolarian-Saccocoma-Globuligerina microfacies, which indicates Oxfordian/Kimmeridgian transition. Stratigraphically upwards, *Saccocoma* ossicles and radiolarians prevail (Fig. 4G), whereas globuligerinids disappear. Bivalve shell fragments, "microforaminifers", aptychi, ostracods, nodosarid foraminifers, *Lenticulina* sp. rare echinoderm particles, ammonite shells, *Globochaete alpina* and small gastropods occur, too. Calcareous dinoflagellates in the uppermost part are dominated by *Parastomiosphaera malmica* (Fig. 4H–I) and *Colomisphaera pulla* (Fig. 4J) which have their occurrence overlap in the Early Tithonian (Reháková, 2000). The whole upper part of the section can be attributed to the Czorsztyn Limestone Formation.

3.1.2. Isolated block with extremely condensed section

Strong facies variability within the locality is demonstrated by a block (Fig. 5A) found only several tens of meters from the above-mentioned section. The block reveals an extremely condensed section capturing record of about 10 Myr (from Bajocian to Oxfordian) in several tens of centimetres (Fig. 5B). Base of the block represents reddish to greenish stromatolitic hardground crust (Fig. 5C) with several nautilids and ammonites: Nautilidae indet., Phylloceratina indet.,

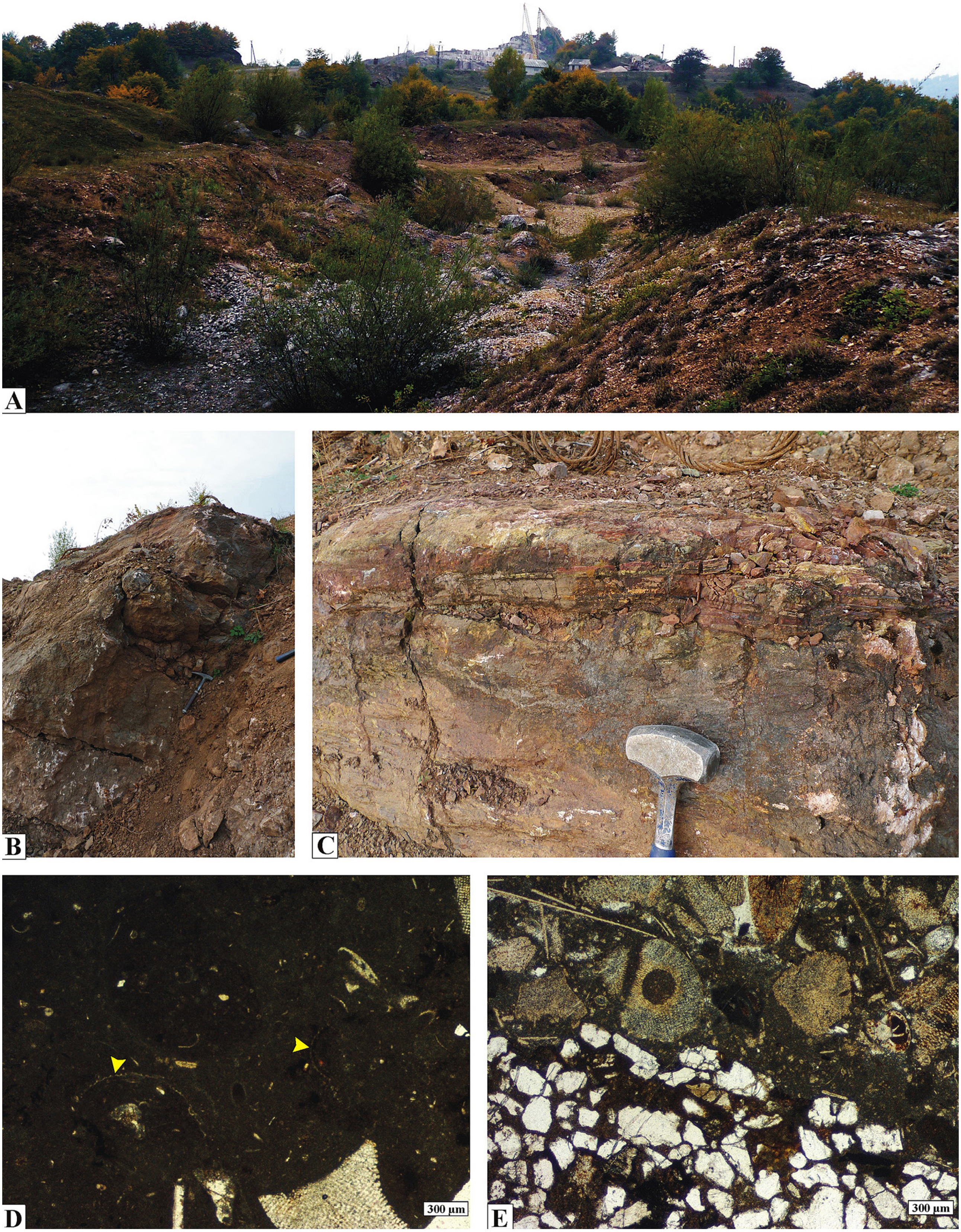

Fig. 3. **Veliky Kamenets 2. A – View on the pit quarry. B – Stratigraphically overturned block section at the northern margin of the pit quarry. C – Stratigraphic base of the previous – crinoidal limestones with laminated neptunian sills. D – Thin shells of ornamented ostracods *Pokornyopsis* sp. (arrows) in the neptunian sill filling. Locality as in B. E – Contact of carbonate-cemented sandstone lamina with crinoidal packstone. Locality as in B.**

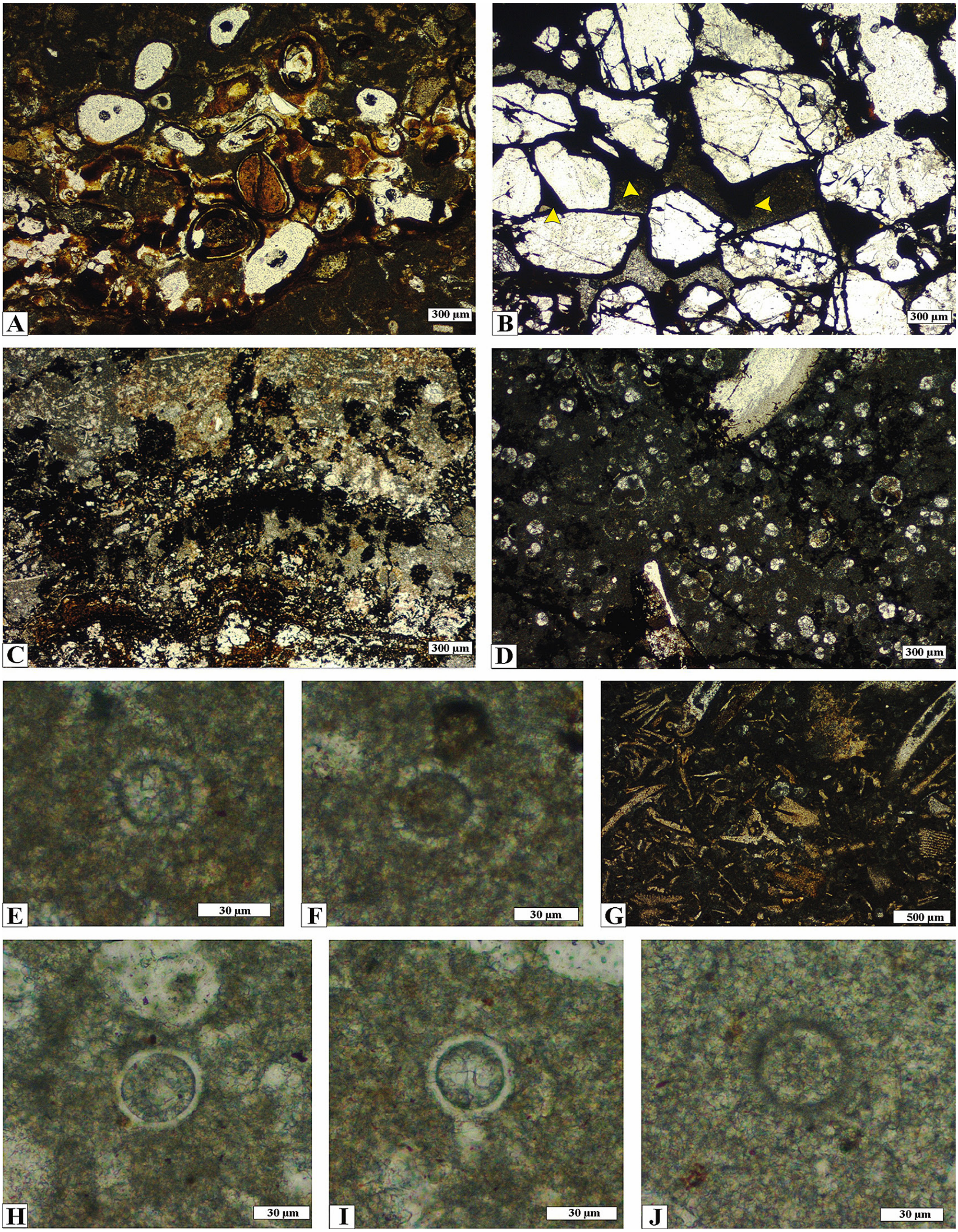

Fig. 4. Veliky Kamenets 2 – northern section. A – Oolitic coatings on allochems in the condensed parts of the crinoidal limestones. B – Sandstone intercalation with initial opaque Fe-Mn coatings displaying asymmetric, microstalactitic-like features (yellow arrows) indicating precipitation in the vadose zone during emersion. C – *Frutexites*-like stromatolites impregnated by opaque Fe-Mn oxides in the crinoidal limestone. D – Wackestone dominated by planktonic foraminifers *Globuligerina* sp. which are indicative of Oxfordian. E–F – Calcareous dinocysts *Schizosphaerella minutissima* from the limestone with Globuligerina microfacies. G – Saccocoma microfacies from the limestone forming the stratigraphically uppermost part of the northern section (containing calcareous dinocysts figured in H–J). H–I – *Parastomiosphaera malmica*. J – *Colomisphaera pulla*.

Nannolytoceras tripartitum, *Lissoceras psilodiscus*, *Oppelia subcostata, Oecotraustes* sp., *Spiroceras* sp., *Pseudogarantiana* sp. juv., and *Garantiana (Hlaviceras)* sp. This assemblage is indicative of Late Bajocian, Niortense to Parkinsoni zones.

Lower part of the block is formed by a pink crinoidal limestone (can be attributed to the Smolegowa Limestone Formation) with voids filled by greenish microbialites. This lithostratigraphic unit is missing in the above mentioned section. The limestone represents bioclastic packstone (Fig. 5D), locally grainstone dominated by echinoderm particles (mostly crinoidal), with some agglutinated foraminifers, such as *Ophthalmidium* sp., sessile nubecularid foraminifers, *Lenticulina* sp., bored fragments of bivalves, rare bryozoans, ostracods, and echinoid spines. The limestone also contains dispersed quartz grains.

The void fillings represent laminated pelmicrites (Fig. 5E), with clusters of opaque Fe-Mn minerals. Rare fauna is represented by ostracods (smooth-shelled but also ornamented *Pokornyopsis* sp. – Fig. 5F, which is a typical cave fauna), thin *Bositra* shells ("filaments"), echinoderm particles and some sponges after which stromatactis-like voids remained. At the contact with the host rock, the voids also contain stromatolites (including *Frutexites*) impregnated by Fe-Mn minerals, sometimes alternating with botryoidal calcite.

Surface of the crinoidal limestone is very uneven and bizarre, with finger-like karren (in longitudinal cross-section) penetrating as deep as 10 cm. Together with the voids mentioned above they were most likely caused by temporary emersion and karstification. Such corrosion structures do not occur at any of the previously described localities of the Czorsztyn Succession, where the deposition of crinoidal limestones is followed by rapid deepening and forming an omission/hardground surface. Therefore we suppose that these bizarre structures did not originate via submarine corrosion.

The uneven surface is covered by a layer of greenish sandstone with angular, well sorted, fine quartz sand grains and carbonate cement, formed by brownish calcite with undulatory extinguishing (Fig. 6A). It is similar to saddle dolomite, but a test with diluted hydrochloric acid showed presence of calcite rather than dolomite. Carbonate locally replaces the entire rock, which indicates its secondary origin. The detritic sandy material is represented mostly by quartz. All quartz types, from monocrystalline, through polycrystalline to strongly pressure-deformed quartz grains with jigsaw-like grain boundaries are present.

The sandstone is overlain by a wackestone to packstone with Bositra-Globuligerina microfacies, which in the Czorsztyn Succession indicates Callovian/Oxfordian transition (Wierzbowski et al., 1999). Along with the main components, small gastropods, juvenile ammonites, echinoderm particles, echinoid spines, foraminifers *Lenticulina*, *Spirillina*, agglutinated foraminifers, originally aragonite bivalve shells, dissolved and filled with micrite are present. The rock contains common nests and seams of dark secondary Fe-Mn minerals, which obviously migrated along thin fractures and stylolites.

The block sequence is terminated by Globuligerina packstone (Fig. 6B), containing also thicker aragonitic bivalve shells replaced by calcite and impregnated by black Fe-Mn minerals, rare echinoderm particles, juvenile ammonites, aptychi (*Lamellaptychus*), rhyncholites, foraminifers *Lenticulina*, and nodosarid foraminifers. Macroscopically, some isolated corals are visible. Sandy quartz grains occur in this rock, too. The rock also contains fragments of stromatolites impregnated by Fe, Mn and probably also P, which coat some allochems but they also form isolated fragments in the rock (Fig. 6B). Towards the top, allochems gradually disappear and rock turns to sterile mudstone.

3.1.3. Three-component block

Another block, at a local road, shows an irregular contact of two sorts of limestone with a volcanic rock (Fig. 7A). One of the components is limestone with dispersed clasts of volcanic glass (Fig. 7B). The limestone is wackestone to mudstone with dispersed allochems, represented mainly by echinoderm particles, common spirillinid foraminifers, less frequent trocholinid foraminifers, nodosarid foraminifers, ammonite shells (with geopetal muddy filling), echinoid spines, bivalves (thick- and thin-shelled), locally small phosphatic clasts, gastropods and rare *Globuligerina*. A cross-section of a complete rhynchonellid brachiopod shell was found, too. Matrix of the sediment is frequently bioturbated. Clasts of volcanic glass have vesicular texture and are almost completely dark under crossed nichols, which means that the glass devitrification still did not reach high stages. On the basis of the host rock (Middle Jurassic), the volcanic clasts represent an earlier volcanic event than that recorded on the neighbouring locality Veliky Kamenets (marble quarry), which is Early Cretaceous in age (Berriasian).

The volcanic rock represents hyaloclastite with vesicular texture (Fig. 7C). The rock is strongly calcified. Drusy calcite also fills voids and veinlets in the volcanic rock. The original vitrific matter is preserved only locally. The volcanic glass underwent almost no devitrification. Small prismatic apatite crystals can be observed in the rock, too.

The volcanic rock is locally covered with dark (black to brown) hardground crust, from which tiny neptunian dykes penetrate the volcanite. Along with Fe-Mn oxides the crust also contains yellowish phosphatic clasts. The hardground and neptunian dykes contain hedbergellid foraminifers (Fig. 7D–F) which are usually indicative of Barremian to Cenomanian. *Ticinella* is missing in the assemblage, indicating that the age can be older than Albian.

3.1.4. Contact of greenish sandstones with crinoidal limestone

In some parts of the locality, transition between sandstone and pale crinoidal limestone was recorded (Fig. 8A). The limestone is formed by a recrystallized crinoidal grainstone, or microsparitic to micritic packstone. The allochems are often corroded. In addition to the crinoidal ossicles, it contains common echinoid spines, some bryozoans, smooth-shelled ostracods, bivalves, agglutinated foraminifers, such as *Ophthalmidium*, nubecularid foraminifers, *Lenticulina*, *Spirillina*, *Tetrataxis*, locally "microforaminifers", serpulid worm tubes, gastropods and calcitized sponge spicules. Sandy quartz admixture is

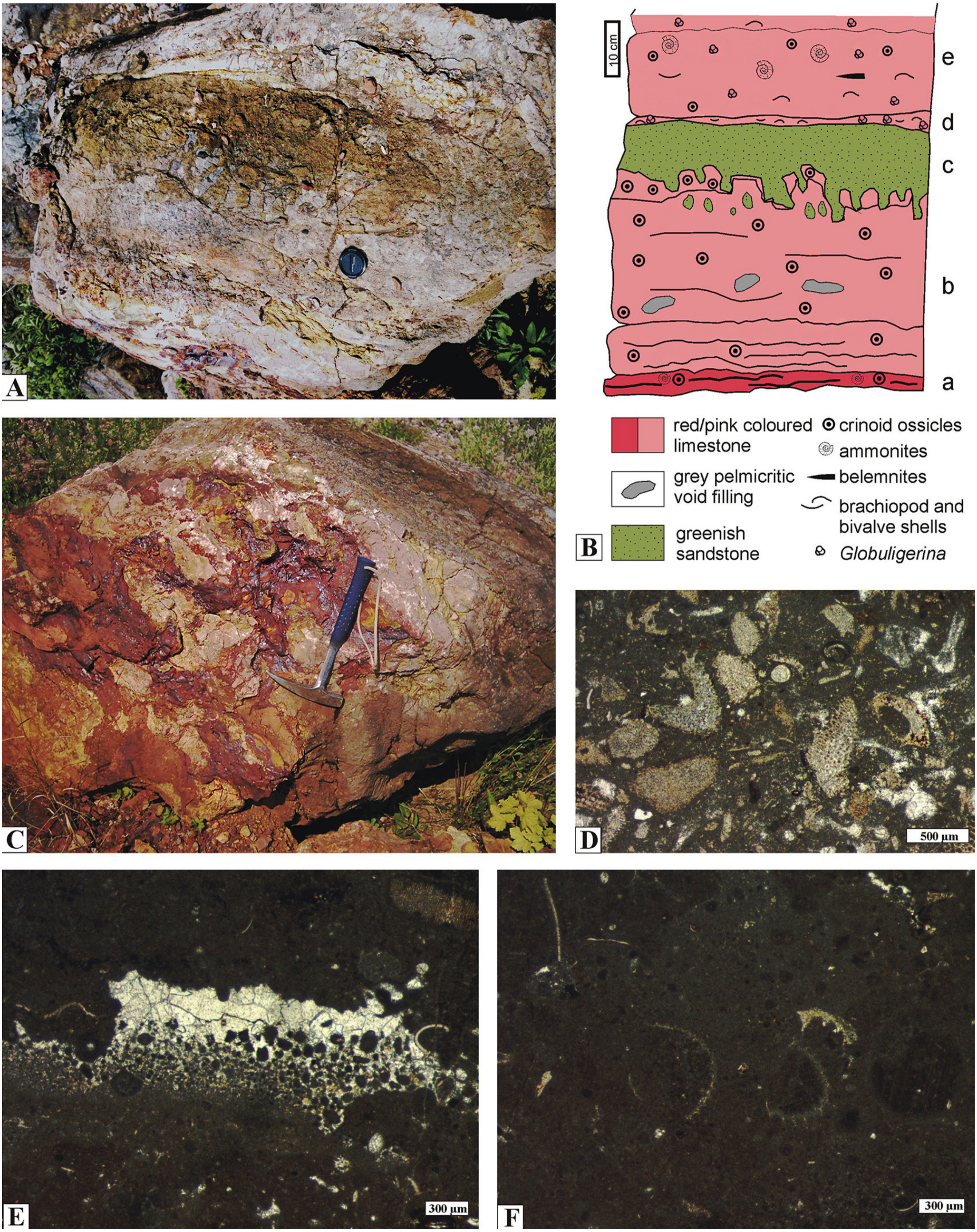

Fig. 5. Veliky Kamenets 2 – block with strongly condensed succession. A – View on the block in the field. B – Schematic sketch of the condensed block: a – condensed hardground layer on the bottom of the block which contained Late Bajocian ammonites, b – pink crinoidal limestone with voids filled by with grey pelmicrite (corresponding with Smolegowa and Krupianka limestone formations - Bajocian), c – greenish sandstone (yet unnamed lithostratigraphic unit) overlaying uneven surface of the crinoidal limestone and filling voids in its upper part, d - wackestone to packstone with Bositra-Globuligerina microfacies, e - Globuligerina packstone with aragonite bivalve shells and juvenile ammonites (d-e correspond with the Oxfordian part of the Bohunice Limestone Formation). C – Red condensed hardground layer on the bottom of the block. D – Crinoidal packstone (b in B). E – Pelmicritic void filling in the crinoidal limestone. F- Cross-sections of the ostracods *Pokornyopsis*, which represented autochthonous cave dwelling fauna in the voids.

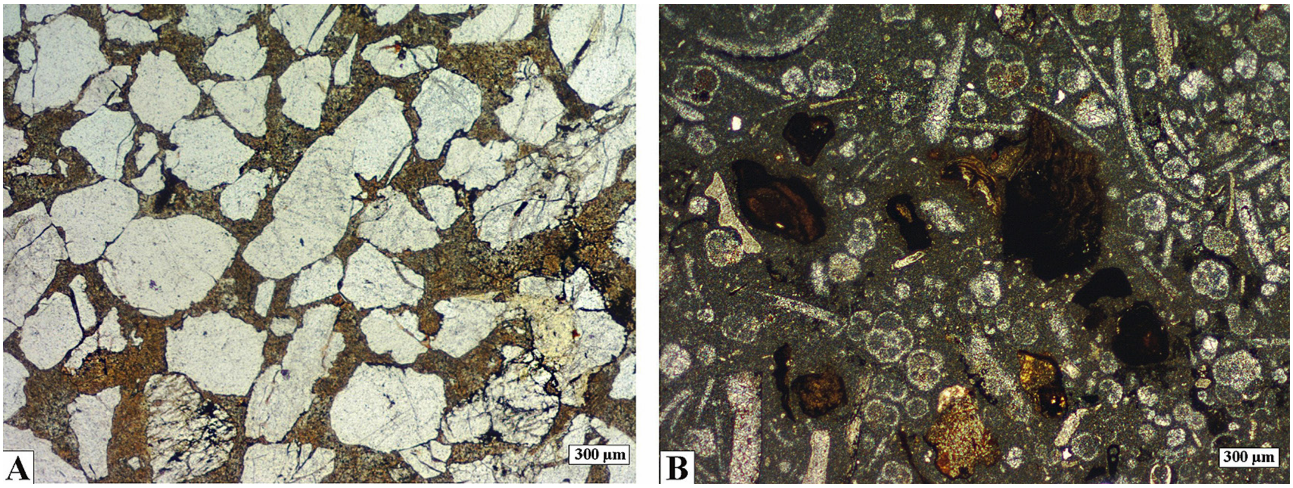

Fig. 6. Veliky Kamenets 2 – block with strongly condensed succession. A – Greenish sandstone filling the corroded uneven surface of the crinoidal limestone. The sandstone is cemented by brownish calcite. B – Globuligerina microfacies from the top of the condensed block. Note the brownish fragments of stromatolites.

common. Some siltstone clasts with brownish matrix were found, too. The limestone also locally contains fragments of calcified volcanic glass and small voids filled with phosphatic *Frutexites*-like stromatolites.

Contact surface between the limestone and sandstone is strongly uneven. The limestone is usually separated from the sandstone by pure blocky calcite, crystal silt laminae, or by radiaxial fibrous calcite growing towards the sandstone. This would indicate that the limestone forms the wall-rock, whereas the sandstone represents a void filling in it. In one instance, dark, Fe-Mn hardground crust was developed between the limestone and sandstone.

The sandstone represents sparite-supported rock with "floating" siliciclastic sand grains. The grains are poorly sorted, dominated by quartz, which mostly possess undulatory extinguishing. Polycrystalline grains are common, too. The quartz grains are often corroded, with calcite penetrating deeply into them. Along with quartz, feldspar grains (e.g., microcline, perthite, kaolinized K-feldspars) and muscovite scales occur less commonly. From heavy minerals, titanite, zircon, rutile, and garnet were registered in thin-sections. The sparite cement is mostly clear, blocky calcite with twinning lamellae. Locally it passes to finer-crystalline and microcrystalline calcite. At least a part of the sparite seems to originate by replacement of sandstone, but clear, inclusions-free appearance contradicts this replacement scenario. In some samples, greenish-brown to black matrix (perhaps phosphatic) occurs within the sandstone, having signs of microbial origin. It locally forms stromatolitic coatings around the sand grains (Fig. 8B) or microbial-like globules inside the matrix.

In one sample, the sandstone contained several circular to oval voids filed with calcite (Fig. 8C). The voids might have originated due to decaying of some organic material, e.g. tree branches, but some signs of dissolution are apparent at the void margins. The dissolution mainly affected sandstone carbonatic matrix, with quartz grains protruding inside the voids. In one void, thin brownish to yellowish (ferric to phosphatic) stromatolitic coating with serpulid worm tubes was observed (Fig. 8D). The initial void filling consists of radiaxial fibrous calcite with inclusions but free of twinning lamellae, followed by a clearer blocky calcite that fills centres of the voids. Locally, sterile micrite and crystal silt occupies the centre. In one of the voids with stromatolitic coating, alternation of radiaxial fibrous calcite and micrite was observed. The remaining sediment contains brachiopod shells full of smooth, thick-shelled ostracods (Fig. 8D), which were most probably cave-dwellers.

3.1.5. Contact of sandstone and nodular limestone

The nodular limestone is obviously younger than the sandstone. Both lithologies are separated by a hardground crust impregnated by black, opaque Fe-Mn oxides (Fig. 9A). The sandstone is similar to that in other samples. Except of quartz and kaolinized K-feldspars, also some mica scales and glauconite grains were found. The sparry cement is mostly blocky; only locally, darker, inclusions-rich fibrous variety was observed. Some carbonate clasts occur, too. Their extinguishing is identical with the surrounding calcite. The clasts locally contain small voids filled with silica.

The hardground crusts are mostly opaque and structureless, but some brownish stromatolites occur, too. The Fe-Mn oxides sometimes deeply penetrate the underlying sandstone. Under the hardground, fibrous calcite crusts were developed locally (Fig. 9B). The limestone, at the base also impregnated by Fe-Mn oxides, represents Saccocoma packstone (Fig. 9C), indicating Kimmeridgian to Early Tithonian age. The succession is different from the block described above, where the sandstone is followed by the Oxfordian limestone with Globuligerina microfacies. This variation in the timing of hiatuses indicates presence of sedimentary gaps and erosion of various intensity and duration.

In another sample, there was also a mineralized hardground crust on the greenish sandstone. The sandstone is relatively well sorted. The grains are mostly angular, formed mainly by quartz (monocrystalline, locally with undulatory extinguishing and

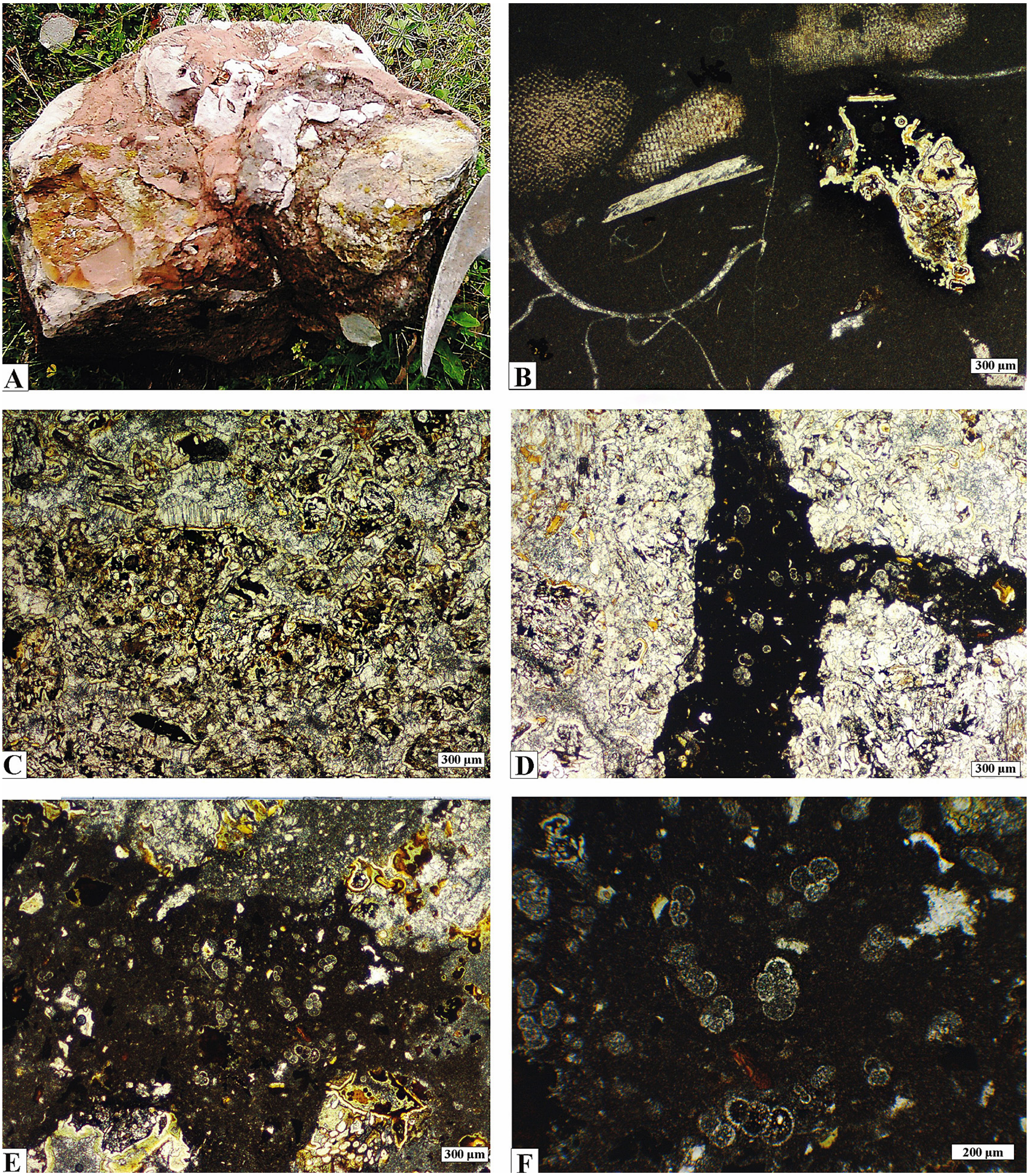

Fig. 7. Veliky Kamenets 2 - block consisting of crinoidal limestone, hyaloclastitic volcanic rock and Albian pelagic marly limestone. A – Field view on the block. B – Crinoidal wackestone with juvenile ammonite and clast of vesicular volcanic glass (right). C – Calcitized volcanic glass with preserved vesicular structure. D – Neptunian microdyke in volcanite, filled with Albian wackestone with hedbergellids. E – Another neptunian microdyke with hedbergellids. F – Detail of the previous.

rarely polycrystalline). Less common are scales of muscovite, chlorite, perthitic feldspars, rarely also kaolinized K-feldspars and carbonate grains (probably dolomite). The sandstone matrix is represented by medium to fine-grained brownish carbonate. It is locally replaced by opaque Fe-Mn oxides that form seams. The hardground crust starts with thin stromatolite (probably phosphatic), followed by well-developed radiaxial fibrous calcite, which is relatively free of inclusions but strongly twinned. The calcite is followed by dark opaque matrix with dispersed allochems, upwards passing to packstone. Among

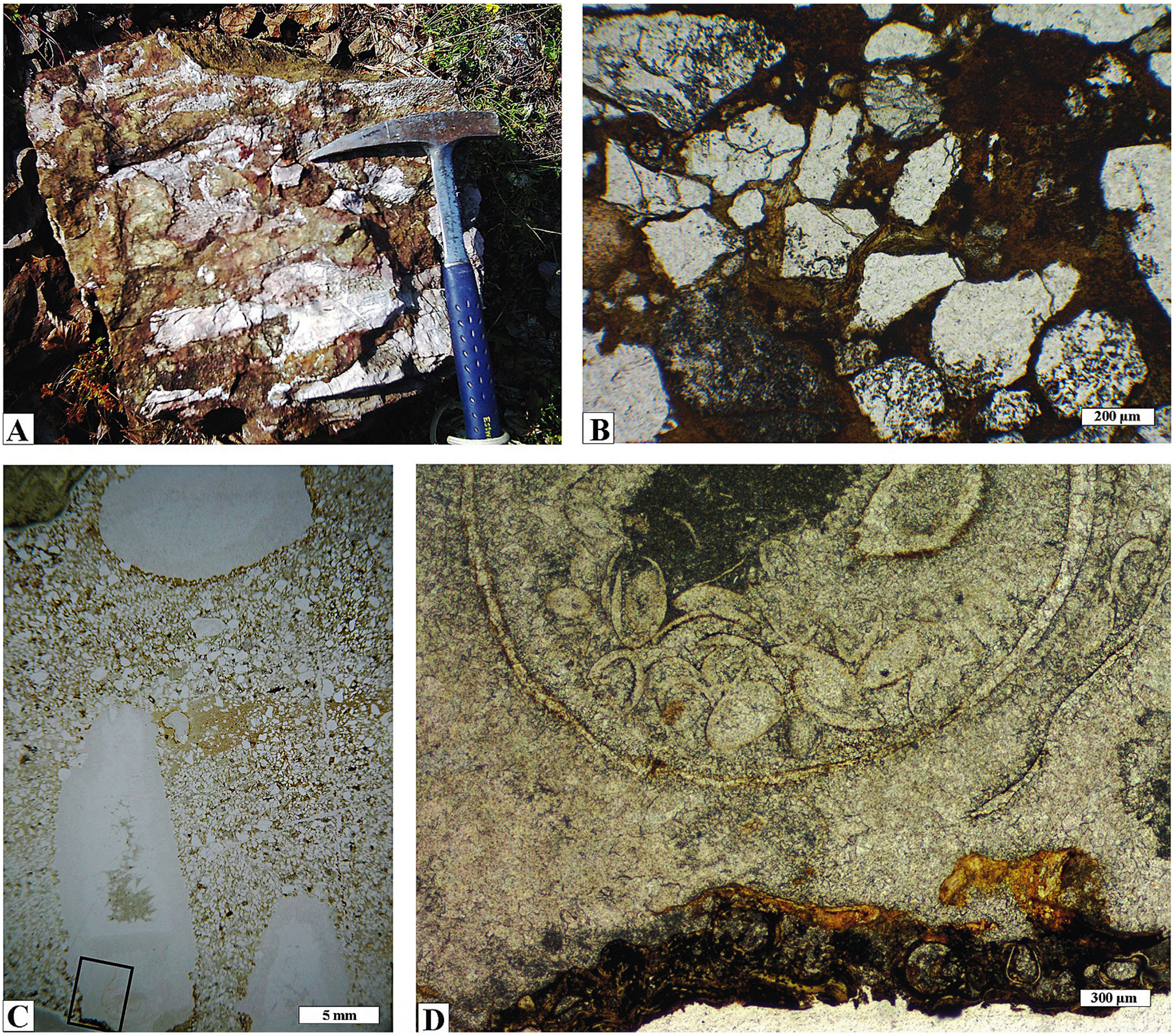

Fig. 8. Veliky Kamenets 2 – contact of greenish sandstones with crinoidal limestone. A – Field view on the block displaying interlayering of pale crinoidal limestones with greenish sandstone. In fact, the sandstone fills bizarre cavities in the limestone. B – Quartz grains in the sandstone coated and cemented by greenish stromatolite, probably of phosphatic origin. C – Ovoidal voids in the sandstone from other block. The voids are filled with radiaxial fibrous calcite and internal sediment. Rectangle marks the position of D. D – Detail from the void filling showing the filling succession from brownish stromatolite at the base to radiaxial fibrous calcite enclosing trapped shells. One shell contains accumulated shells of ostracods which might represent former cave-dwellers.

the allochems that were identified, the most common were "filaments" (*Bositra* shells), also some thicker bivalve shells, crinoid ossicles, calcareous dinocysts *Colomisphaera cieszynica* (Fig. 9D), foraminifers *Lenticulina* sp. and ostracods.

The ammonites collected from the nodular limestone at various places at the Veliky Kamenets 2 are represented by different groups with marked admixture of phylloceratids, already in the lowermost part of the sections directly above the omission surface covered with ferrugineous-manganese crust. The ammonite *Gregoryceras fouquei* (Kilian) found at 0.2 m above the omission surface indicates the presence of the topmost Middle or lower part of the Upper Oxfordian (upper part of the Transversarium Zone, or the Bifurcatus Zone). About 0.3–0.4 m above the surface, the ammonites of the family Ataxioceratidae appear suggesting the uppermost Oxfordian or the Early Kimmeridgian age. This dating by ammonites demonstrates a very slow sedimentation rate.

3.1.6. Pre-Albian erosional surface

Omission surface between Albian marls (Chmielowa Formation) and older lithostratigraphic units is ubiquitous in the Czorsztyn Succession. At the Veliky Kamenets 2, this surface is extensively developed at the whole locality. Unlike at other localities examined so far, the stratigraphically underlying rocks are massively corroded and strongly bored by bivalves and other organisms (Fig. 10A–B). At other localities, karstification features were ubiquitous. At the Veliky Kamenets 2 the corrosion more reminds marine corrosion in the intertidal zone, which is rather atypical for the Czorsztyn Succession, because it indicates the basement rocks spent longer time in the intertidal zone before sinking

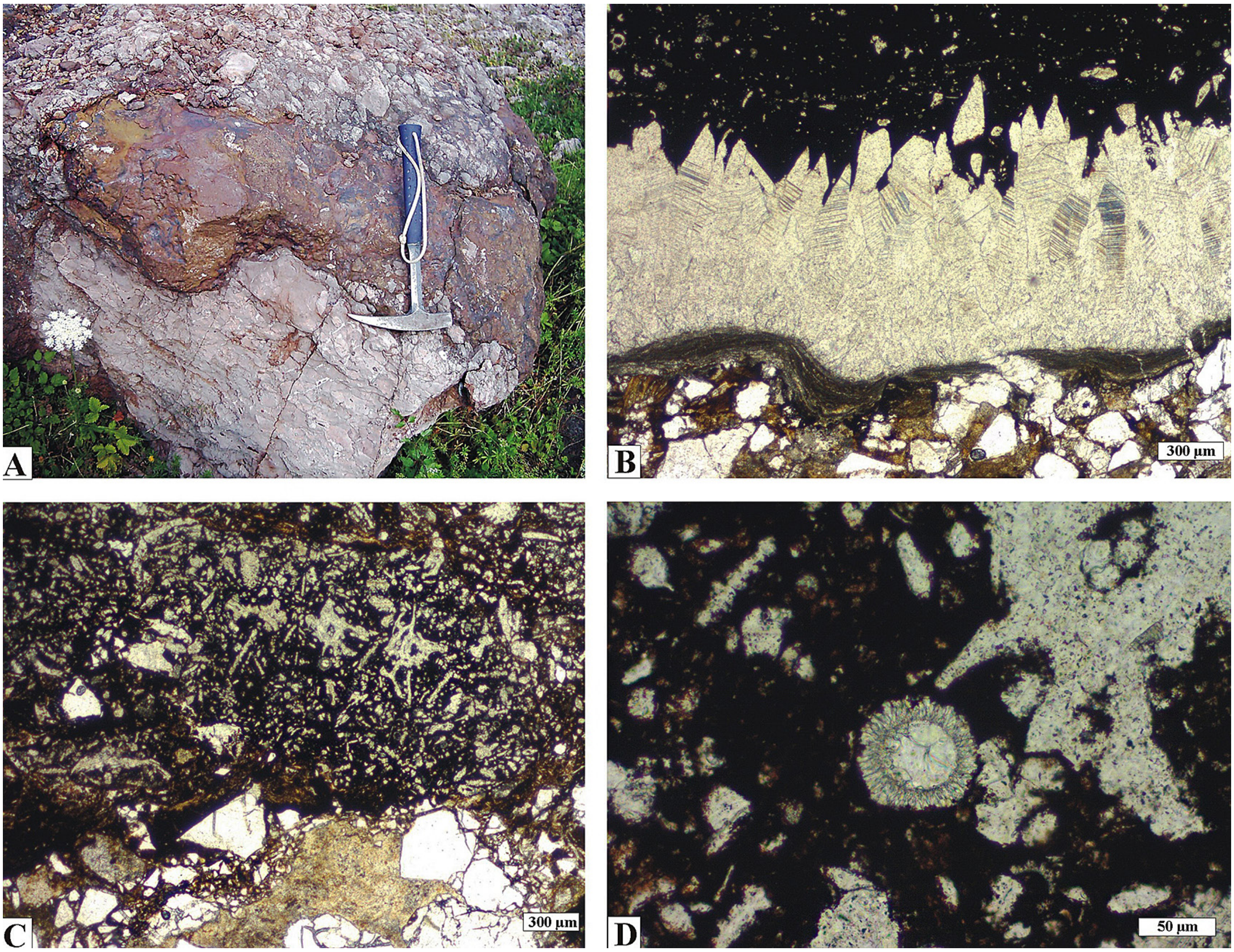

Fig. 9. **Veliky Kamenets 2 – contact of greenish sandstone with nodular limestone. A – Field view on the block showing contact of pale crinoidal limestone (bottom), greenish sandstone coated with Fe-Mn-P impregnated stromatolitic hardground crust (middle) and nodular limestone (Czorsztyn Limestone Formation – top). B – Thin-section showing the greenish sandstone (bottom), coated with greenish stromatolite which is overgrown by with radiaxial fibrous calcite. The final phase is opaque and sterile Fe-Mn hardground crust. C – Contact between the greenish sandstone (bottom) and Saccocoma packstone impregnated with opaque Fe-Mn oxides. D – Detail of the Fe-Mn-impregnated hardground crust with calcareous dinocyst *Colomisphaera cieszynica*.**

below the water level. Due to strong condensation of the Jurassic lithostratigraphic units, the pre-Albian erosion caused that the Chmielowa Formation overlies several underlying units. Strong corrosion, boring and Fe-Mn-P coating of the corroded surface are characteristic (Fig. 10C). Nodular limestones (Czorsztyn Limestone Formation) are corroded so strongly, that their weathered surface resembles breccia (Fig. 10D). Deposits younger than Kimmeridgian - Lower Tithonian Saccocoma limestone were not recorded below the erosion surface.

3.2. Vilki Dil

Section on the Barakishche locality (Fig. 11A–B) represents an almost complete sequence of an atypical Czorsztyn Succession klippe, starting with Bajocian pale sandstone at the base, up to pelagic mid-Cretaceous, variegated marls on the top.

The section starts with coarse-grained white-greyish sandstones to fine-grained conglomerates (Fig. 11C–D), probably of Bajocian age because they gradually pass into the Smolegowa Limestone Formation. Visible part of this unit is about 5 m thick. The rock is dominated by quartz grains which locally attain a size up to 1 cm. The quartz mostly displays undulatory extinguishing, but non-undulatory monocrystalline and polycrystalline grains can be found, too (Fig. 11E). Locally also clasts of recrystallized silicites, prismatic tourmaline grains and rare zircon grains were observed. The rock contains no feldspars, although it macroscopically resembles an arkosic sandstone. Cement of the rock is represented by microquartz (chalcedony), which is still in earlier stages of recrystallization. Opaque pyritic cement is locally present, too. Upwards, the sandstone becomes medium-grained and calcitic cement appears. Some feldspar (microcline) grains appear in this part.

The sandstone gradually passes to yellowish sandy crinoidal limestone (Smolegowa Limestone Formation) which forms the top 2 m of this basal unit. The siliciclastic admixture is similar as in the sandstones below, but the quartz grains are often corroded. Locally, microcline grains, muscovite scales, and rare titanite grains are observable. Skeletal grains appear first

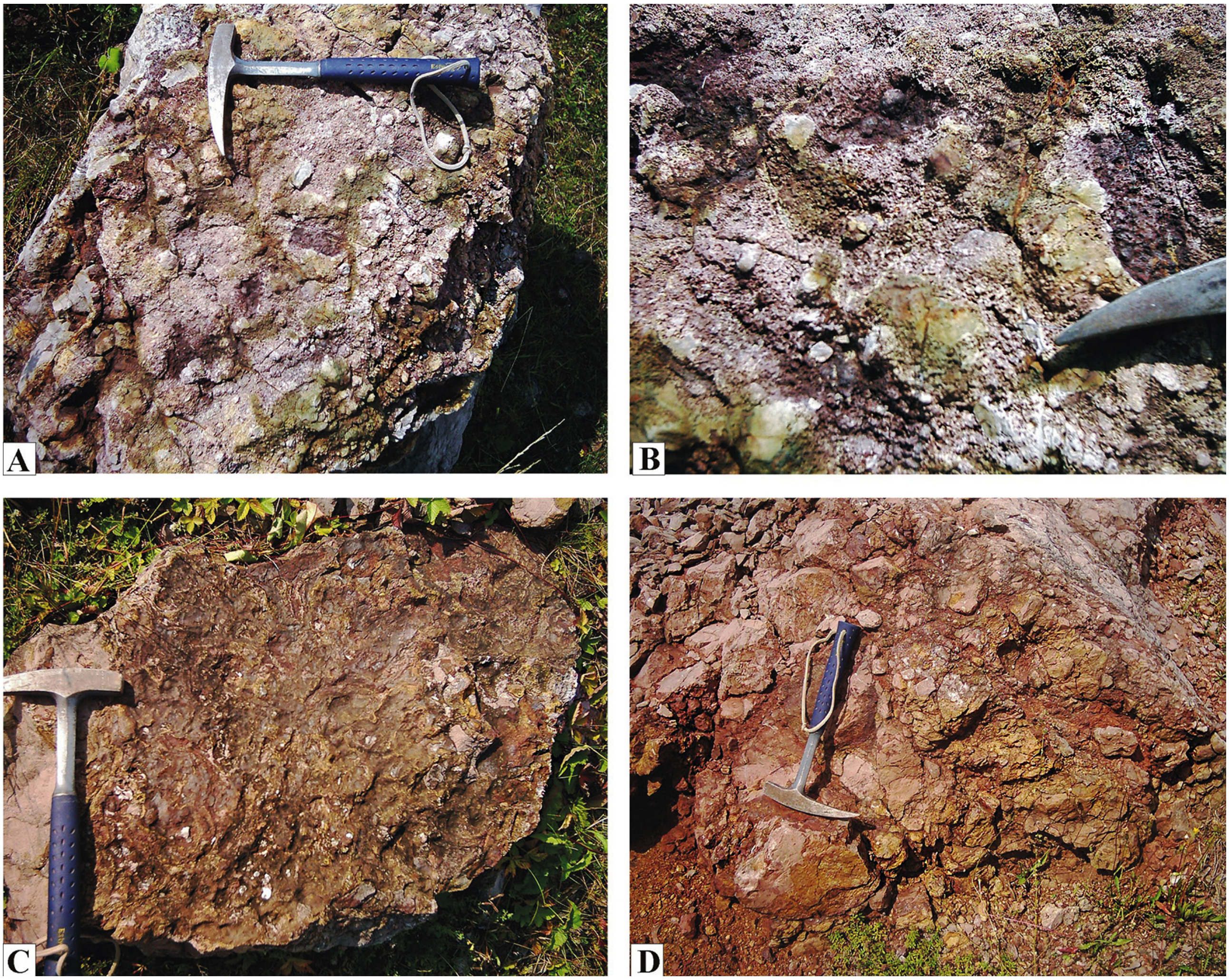

Fig. 10. Veliky Kamenets 2 – pre-Albian erosional surface. A – Corroded and bored pre-Albian surface impregnated by yellowish to reddish, probably ferroan and phosphatic minerals. B – Detail of the previous. C – Fe-P hardground crust coating the pre-Albian erosional surface. D – Strongly corroded and mineralized nodular limestone (Czorsztyn Limestone Formation) reminding breccia.

in separate laminae, free of silicilastic sand. They are mostly represented by bivalve shell fragments (including thin-shelled *Bositra*), less by crinoid ossicles, ostracods, silicisponge spicules (including triaxone forms), foraminifers *Lenticulina* sp., rare belemnite rostra and serpulid tubes. Higher up, sandy biopelmicrite limestone prevails (Fig. 12A), with crinoid ossicles, sessile nubecularid foraminifers, *Bositra* shells, ostreid bivalve shells, trocholinid foraminifers, serpulids and ostracods. Rare ammonoid shells were observed. Opaque, Fe-Mn cements are more common in this part.

The Smolegowa Limestone Formation is followed by an about 7 m-thick red nodular limestone of Ammonitico Rosso facies (Czorsztyn Limestone Formation), but this limestone locally rests directly on the older sandstones. Locally the red micritic limestone with crinoidal laminae fills small fractures in the uppermost part of the crinoidal limestone. The nodular limestone represents packstone with "filaments" (*Bositra* valves), globuligerinids (Fig. 12B), small gastropods, foraminifers *Lenticulina* sp., *Spirillina* sp., less thicker bivalve shells, ostracods, echinoderm particles, nodosarid foraminifers, rare ammonite shells, aptychi, rhyncholites, nubecularids, echinoid spines, fecal pellets, and *Globochaete alpina*. The allochems are locally bored, probably by sponges. The rock contains stromatolites impregnated by ferroan, manganese and phosphatic minerals. The sediment locally displays strong bioturbation. Prevailing globuligerinids are typical of Oxfordian stage in the Czorsztyn Succession (Wierzbowski et al., 1999). Higher up, calcified radiolarians become common and globuligerinids slowly disappear. On the other hand, planktonic crinoids *Saccocoma* predominate in those parts (Fig. 12C), forming even packstones to grainstones, which indicates Kimmeridgian to Early Tithonian age. In these parts, *Globochaete alpina* starts to be frequent and Saccocoma-Globochaete microfacies appears. In higher parts of the formation calcareous dinocysts *Colomisphaera pulla*, *Carpistomiosphaera tithonica* and *Parastomiosphaera malmica* (Fig. 12D) appear, indicating the Malmica Zone (Early Tithonian).

At the boundary with the overlying Calpionella limestone, thin sandstone intercalation occurs. The sandstone is fine-grained, quartz-dominated and well sorted. Feldspars and

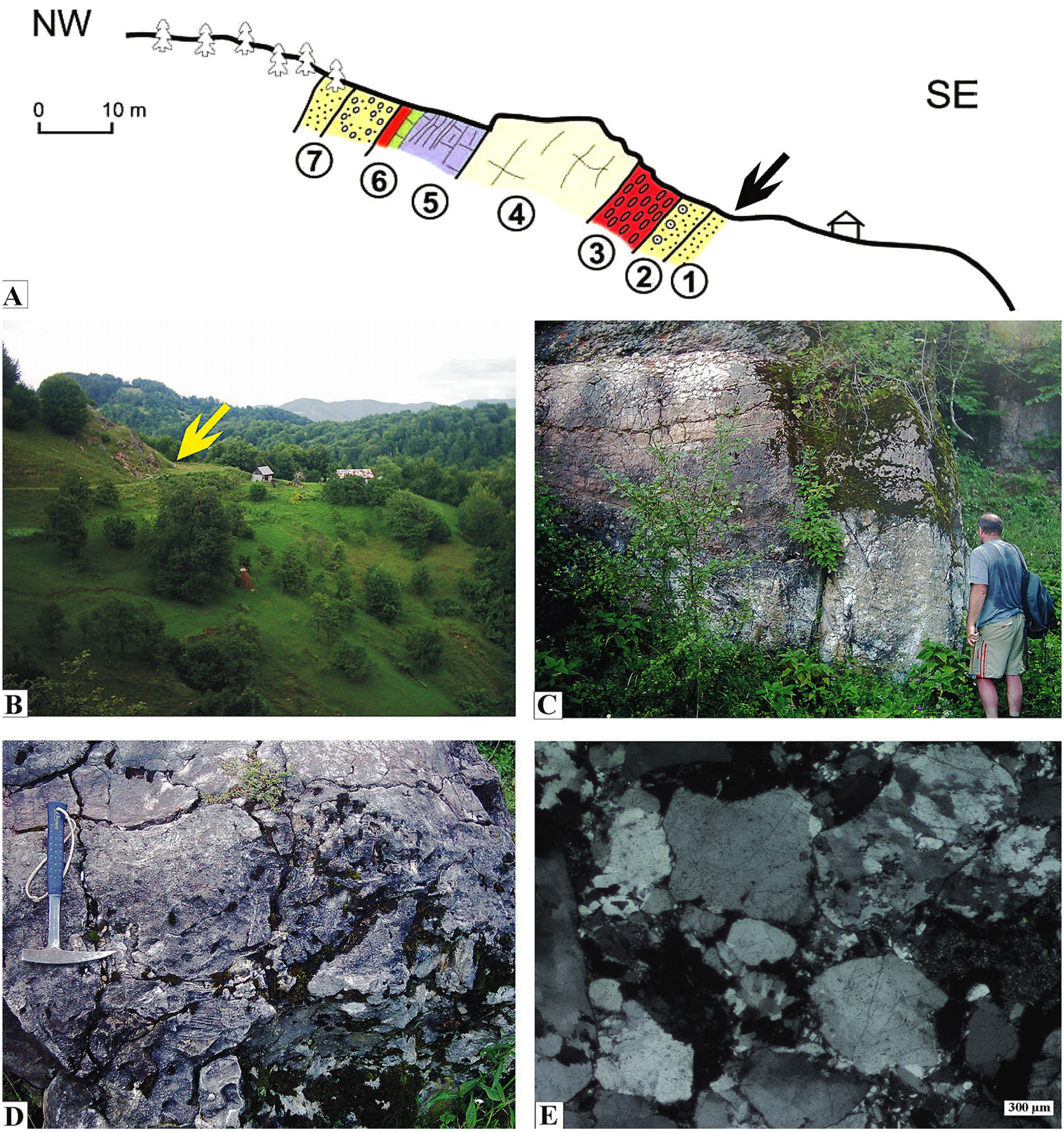

Fig. 11. Vilki Dil. A - General section of the Vilki Dil locality (after Aubrecht et al., 2006 – modified). 1 – White-greyish sandstones (?Bajocian); 2 – Yellow sandy-crinoidal limestones of the Smolegowa Limestone Formation (Bajocian); 3 – Red nodular limestones (Ammonitico Rosso-type) of the Czorsztyn Limestone Formation (Upper Bajocian–Tithonian); 4 – White-yellowish Calpionella limestones of the Dursztyn Limestone Formation (Berriasian); 5 – Violet marly limestones of the ?Chmielowa Formation (Albian); 6 – Variegated marls of the Jaworki Formation (Cenomanian-Turonian); 7 – Yellowish conglomerates and sandstones of the Jarmuta Formation (Palaeogene). Black arrow marks beginning of the section and corresponds to the yellow arrow in B. B – Field view on the Vilki Dil section. Base of the section is marked by yellow arrow. C – Base of the section showing pale sandstones to fine-grained conglomerates. In the upper part of the wall, crinoidal limestones (Smolegowa Limestone Fm.) appear. D – Detail of the pale sandstones at the base of the Vilki Dil section. Note the small quartz pebbles. E – Microphoto (crossed nichols) of the pale sandstone, showing monocrystalline to polycrystalline quartz grains.

carbonate grains also occur. No skeletal remnants were observed in this rock.

White-yellowish Calpionella limestones of the Dursztyn Limestone Formation (Berriasian) are 17 m thick. They consist of calpionellid packstones to wackestones (Fig. 12E) dominated by *Calpionella elliptica* (Fig. 12F) and less frequently by *Calpionella alpina* which are indicative of Berriasian. Other microfauna, which is relatively rare, comprises agglutinated foraminifers *Ammobaculites* sp., then foraminifers *Lenticulina* sp., *Spirillina* sp., *Marssonella* sp., nodosarid foraminifers, tiny echinoderm particles, juvenile ammonites, aptychi, *Bositra* shells, gastropods, calcified radiolarians, and ostracods. Sediment frequently displays signs of bioturbation.

The contact with the overlying violet marly limestones (Chmielowa Formation) is sharp. The surface of topmost Calpionella limestone bed is corroded and irregular, with traces of borings (?bivalve-type), covered by P-Fe-Mn crusts (Fig. 13A–B). The thickness of violet marly limestones does

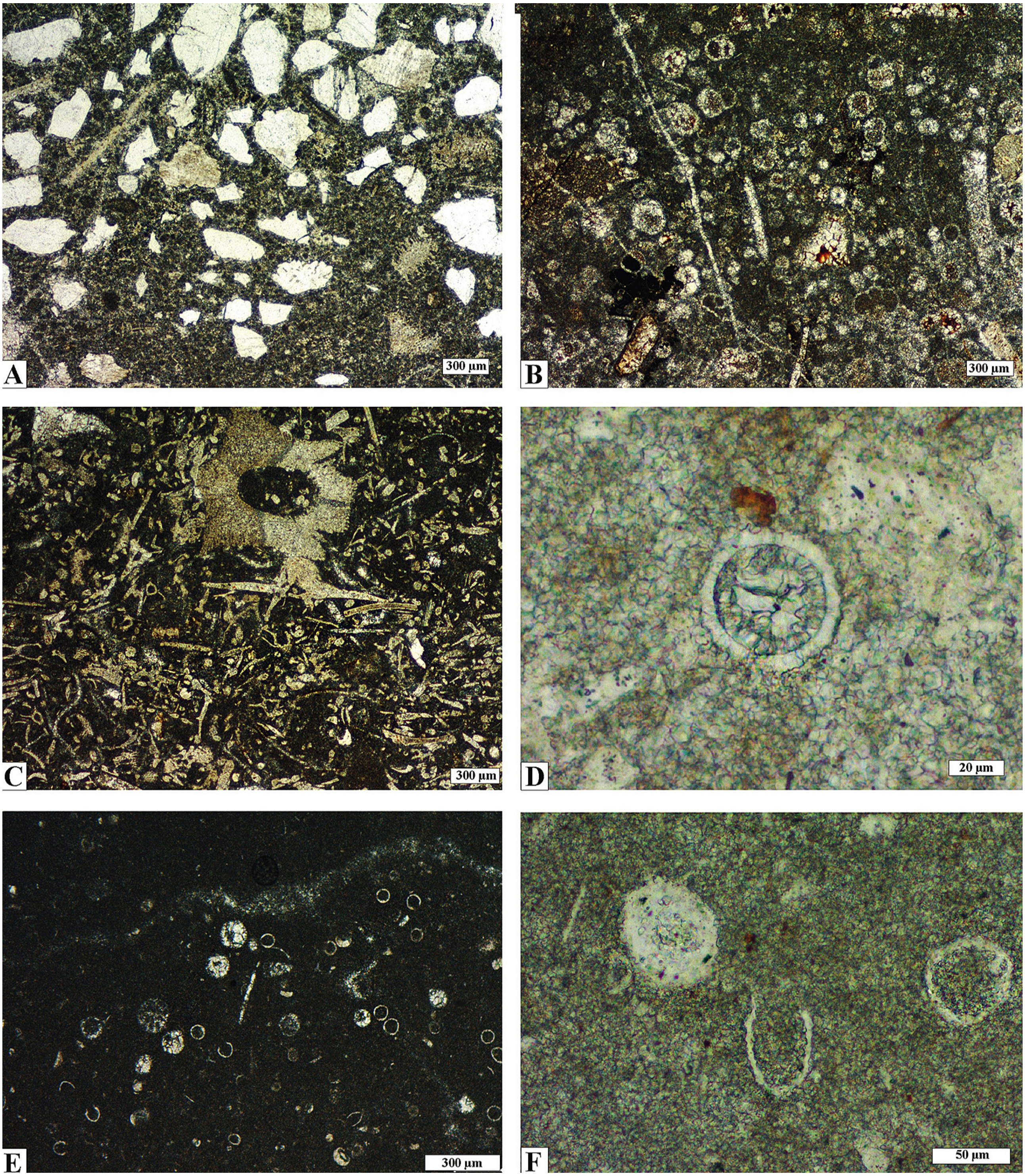

Fig. 12. **Vilki Dil. A – Microphoto of sandy crinoidal limestone with micropeloidal matrix. B – Globuligerina microfacies in the nodular limestone (Czorsztyn Limestone Formation). The microfacies is indicative of Oxfordian. C – Saccocoma microfacies in the nodular limestone indicates Kimmeridgian to Early Tithonian age. D -** ***Parastomiosphaera malmica*** **indicating the Malmica Zone (Early Tithonian). E – Microfacies consisting of** ***Calpionella alpina*** **and calcified radiolarians. Dursztyn Formation, Berriasian. F –** ***Calpionella elliptica*** **from the Dursztyn Limestone Formation,, Berriasian.**

not exceed 2–2.5 m and they are overlain by green, spotty marls (Pomiedznik Formation?). The rock is dominated by radiolarian-hedbergelid microfacies. Radiolarians are mostly calcified. From foraminifers, hedbergellids (Fig. 13C–D) but also *Rotalipora ticinensis* (Fig. 13E) are present, indicating Late Albian-Cenomanian age.

3.3. Mala Ugolka

Brecciated limestones crop out in the abandoned quarry (Fig. 14A), with clasts commonly coated by various cements and stromatolites (Fig. 14B–E). The cements are frequently broken, forming new clasts in the breccia (Fig. 14C–D) and thus demonstrate repeated brecciation events.

The clasts consist of crinoidal biopelsparite, with tiny peloids probably of microbial origin (Fig. 15A). Along with crinoidal ossicles, the limestone contains sessile nubecularid foraminifers, "microforaminifers", foraminifers *Lenticulina* sp., *Dorothia* sp., nodosarid foraminifers, fragments of bivalves and brachiopods, bryozoans, serpulid tubes and gastropods. Sandy quartz grains are common. The allochems are frequently bored, with borings filled by opaque, Fe-Mn minerals. The limestone locally contains stromatactis-like cavities, filled with radiaxial fibrous calcite (RFC) and sterile laminated micrite. RFC penetrates deeply to the limestone, enclosing numerous "floating" allochems (Fig. 15B). The cavities may be of various origin, but most likely they represent cavities after decayed silicisponges (Aubrecht et al., 2002; Aubrecht & Szulc, 2006).

The cement coatings on the clasts are formed by radiaxial fibrous calcite (RFC). It is mostly free of twinning lamellae, full of opaque inclusions, zoned, locally interrupted by micritic laminae (Fig. 15C), thin stromatolitic laminae, or opaque laminae sometimes with crystal silt. The RFC coating is locally terminated by stromatolitic laminae, which separate it from the matrix. The RFC crystal terminations locally display signs of etching and corrosion (Fig. 15D).

Matrix of the breccia is red to brownish, nearly sterile micrite (mudstone), passing locally to wackestone with uneven distribution of allochems, containing rare crinoidal ossicles, calcareous dinoflagellates *Cadosina fusca* (Fig. 15E), ostracods, calpionellids *Calpionella alpina* (Fig. 15F), *Remaniella borzai* (Fig. 15G) and *Tintinopsella carpathica* (Fig. 15H), foraminifers *Spirillina* sp., *Lenticulina* sp., calcified silicisponge spicules, locally clasts of pelmicrite and calcarenite. Calpionellids and calcareous dinoflagellates indicate Late Berriasian age of the breccia.

4. HEAVY MINERAL CONTENT IN SANDSTONES

Lower to Middle Jurassic light-grey sandstones from the Veliky Kamenets locality (Reháková et al., 2011), Vilki Dil, and Vilkivchik Valley (locality not treated in this paper), as well as the Middle to Upper Jurassic greenish sandstone from the Veliky Kamenets 2 were analysed for heavy mineral content (Tab. 1,

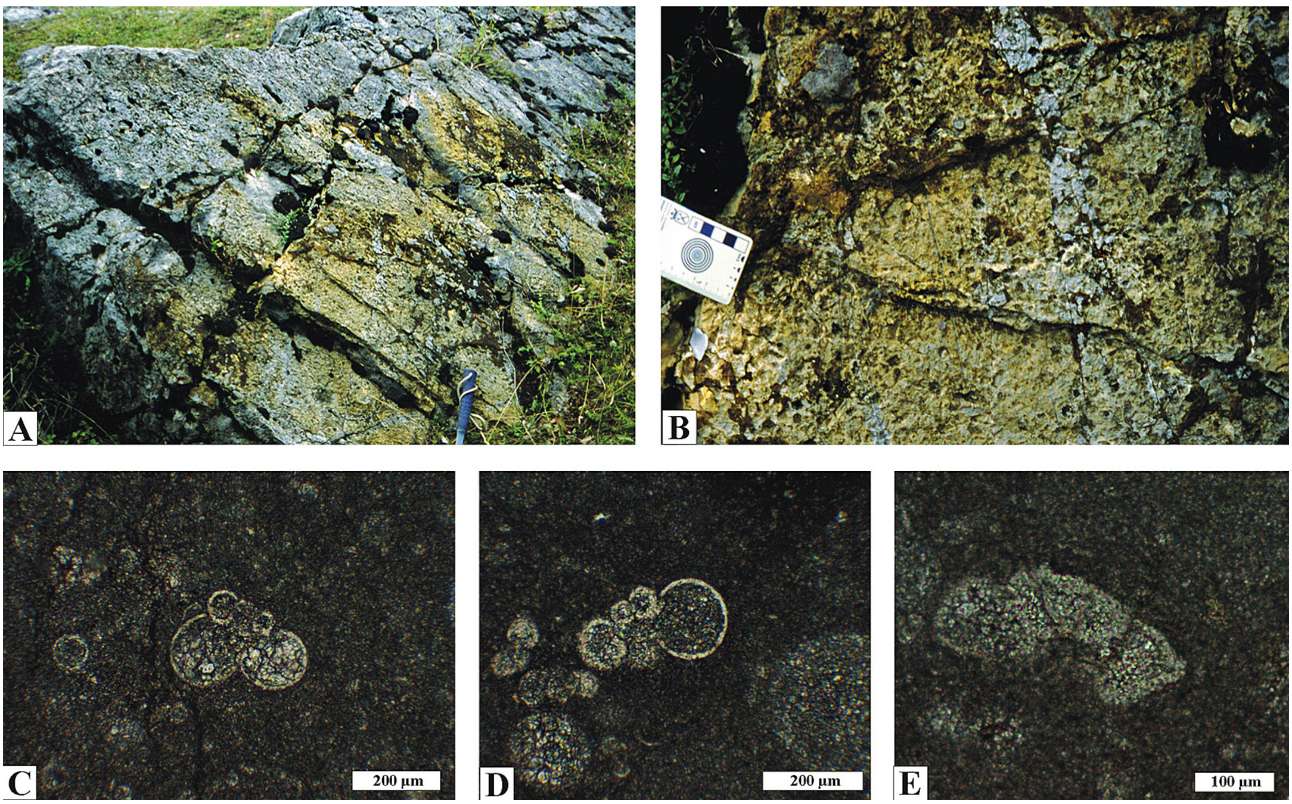

Fig. 13. Vilki Dil – Onset of the Albian marls. A – Top of the Dursztyn Formation, bored and covered by yellowish phosphatic stromatolites. B – Detail of the previous. C-D – *Hedbergella* sp. from the Chmielowa Formation. E – *Rotalipora ticinensis* from the Chmielowa Formation, indicating Late Albian-Cenomanian age.

Fig. 14. Mala Ugolka. A - Field view panorama showing the pit quarry outcrop. B – Breccia with weathered limestone clasts coated by radiaxial fibrous calcite crusts. C – Broken part of the breccia showing broken and resedimented radiaxial fibrous calcite crusts. D – Slab from the previous. E – Slab showing breccia with crinoiodal limestone clasts coated by grey stromatolite crusts.

Fig. 16). The heavy mineral spectra are dominated by ultrastable minerals, as tourmaline, zircon, and rutile, with lesser amount of garnet and apatite and with local presence of titanite, amphibole, staurolite, epidote, and very rare Cr-spinels. High ZTR index (proportion of the ultrastable trinity zircon-tourmaline-rutile) ranging from 73 to more than 90%, is noteworthy. In the next chapter, these heavy mineral assemblages are compared with the data published earlier from the Pieniny Klippen Belt.

5. DISCUSSION

We show that the three localities in western Ukraine share similarities with more western segments of the Pieniny Klippen Belt but also possess several consistent differences. The similarities are: 1) Identical stratigraphic succession involving Bajocian crinoidal limestones (Smolegowa and Krupianka limestone formations), followed by Ammonitico Rosso facies

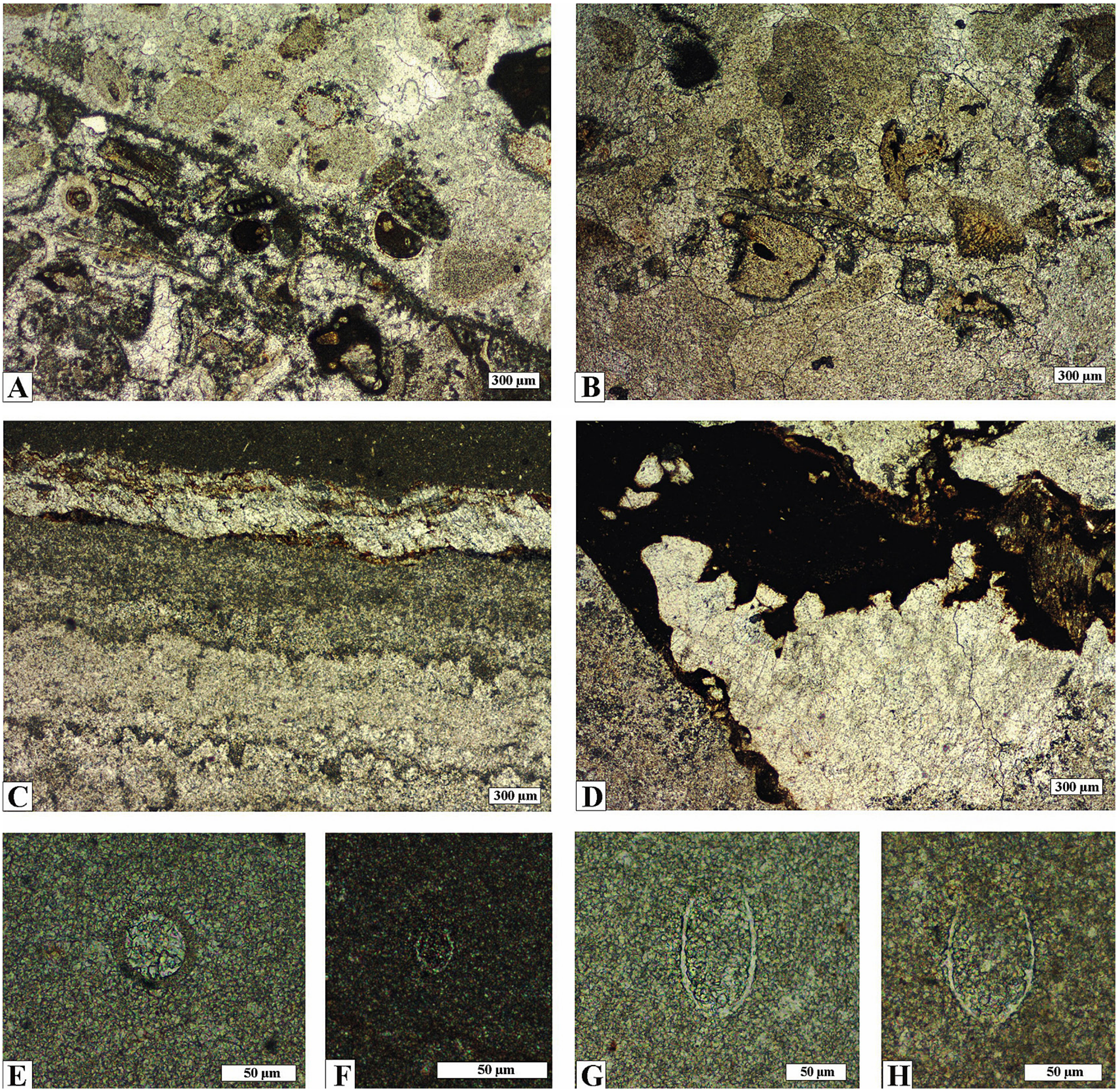

Fig. 15. Mala Ugolka – microphotos of the breccia. A – Crinoidal grainstone to micropelsparite. Clast in the breccia. B – Radiaxial fibrous calcite deeply penetrating to crinoidal limestone from stromatactis-like cavity. The calcite surrounds several "floating" allochems. C – Radiaxial fibrous calcite interrupted by several thin micritic coatings. D – Radiaxial fibrous calcite with corroded crystal tips coated by opaque Fe-Mn oxides. E-H – Microfossils from the breccia matrix. E – ***Cadosina fusca*****. F –** ***Calpionella alpina*****. G –** ***Remaniella borzai.*** **H –** ***Tintinopsella carpathica*****.**

(Czorsztyn Limestone Formation), after the sea-level rise in Bathonian–Callovian, lasting as far as Tithonian, and biodetritic pelagic limestones of the Dursztyn Limestone Formation. The succession displays the same stratigraphic gap in form of erosion surface and hardgrounds encompassing Hauterivian to Aptian time span, followed by Albian and younger pelagic marls of the Chmielowa and Pomiedznik formations. The differences are: 1) strong condensation of some developments of the Czorsztyn Succession and its analogues, 2) detritic sandy formations reaching stratigraphically much higher stratigraphic levels (Berriasian) and having atypical heavy-mineral assemblages, with high ZTR index (dominated by tourmaline) and low content of garnet, 3) manifestations of Middle Jurassic to Lower Cretaceous volcanic activity, 4) resedimentation events as early as Berriasian, and 5) presence of breccia to megabreccia with strongly bored clasts at the base of the pre-Albian omission surface. Below we discuss these atypical features in detail, grouped in three subchapters according to their topics.

5.1. Sedimentary gaps, resedimentation events and strong condensation of some developments

The succession at the Veliky Kamenets 2 appears to be the most extremely condensed unit of all known developments of the Czorsztyn Succession and its analogues. The largest klippen, e.g., Vršatec Klippen in the western sector of the Pieniny Klippen Belt (Mišík, 1979) attain tens to hundreds meters in thickness of the limestone part (Middle Jurassic to Lower Cretaceous). Extremely attenuated developments occur rarely (e.g., Stankowa Skała – Zydorowicz & Wierzbowski, 1986; Sidorczuk, 2005; Sidorczuk & Nejbert, 2008). Some developments display local extreme condensation in some parts of the

Tab. 1. Percentual ratios of translucent heavy minerals in the detritic formations of the selected Czorsztyn Succession localities in the western Ukraine. Explanations: Gr – garnet, Zr – zircon, Ru – rutile, Tu – tourmaline, Ap – apatite, Am – amphibole, Ti – titanite, St – staurolite, Sp – spinel, Ep – epidote.

	N-latitude	E-longitude	Gr	Zr	Ru	Tu	Ap	Am	Ti	St	Sp	Ep	ZTR index
Veliky Kamenets	48°10′48.1″	23°44′7.3″	6.6	14.5	10.5	65.8	1.3	0.0	0.0	1.3	0.0	0.0	90.8
Veliky Kamenets II	48°10′43.4″	23°44′24.5″	23.8	15.2	16.7	41.4	0.0	0.5	1.9	0.0	0.0	0.5	73.3
Vilki Dil – Barakishche	48°11′3.3″	23°43′7.7″	0.0	26.3	11.6	37.9	15.8	2.1	0.0	2.1	0.0	4.2	75.8
Vilkivchik valley – quarry	48°10′26.1″	23°43′44.3″	10.4	21.1	33.1	27.3	0.0	0.0	4.2	0.3	1.0	2.6	81.5

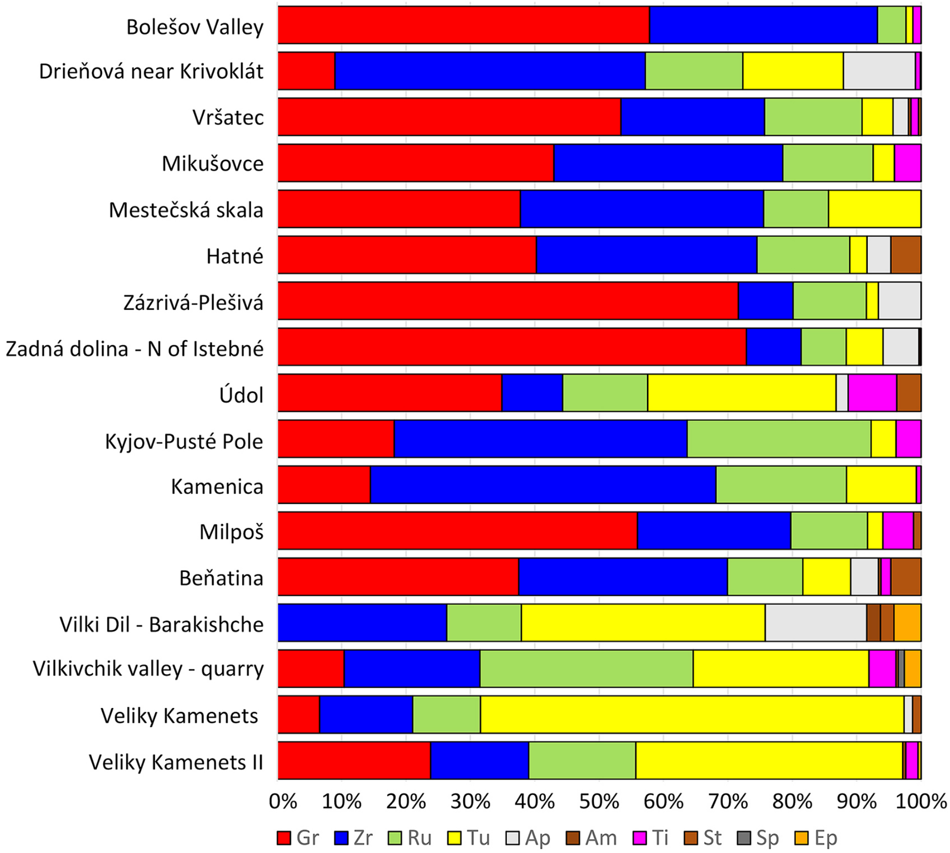

Fig. 16. Percentual ratios diagram of the heavy mineral contents from the Middle Jurassic clastic sediments in the examined samples from the western Ukraine (four samples at the bottom), compared with previously analysed localities in Slovakia (data from Aubrecht, 1993). The localities are arranged according to their position in the Pieniny Klippen Belt from west to east. Note the decreasing trend in garnet content and increasing percentage of tourmaline in this direction. Explanations – see Tab. 1.

lithostratigraphic column (mainly in the Czorsztyn and Bohunice limestone formations), passing to uncondensed sections in the range of several tens of meters, e.g., in the aforementioned Vršatec Klippen (Schlögl et al., 2008). This underlines the strong variability in the Jurassic deposits of the Czorsztyn Succession even in relatively short distances. However, the strong condensation of the Bajocian crinoidal limestones (either primary or secondary) visible at the Veliky Kamenets 2 and Vilki Dil has not been reported to date.

Condensed horizons, omission surfaces and hardgrounds are common in the Czorsztyn Succession (see e.g. Birkenmajer, 1958; Rojkovič et al., 2003; Mišík & Aubrecht, 2004), but only the pre-Albian gap was proved to represent surface related to emersion, erosion, and karstification (Aubrecht et al., 2006). Earlier, mostly Jurassic sedimentary gaps were considered to have originated due to submarine erosion and/or non-deposition (Birkenmajer, 1958; Mišík, 1994). However, bizarre surface and common void fillings at the Veliky Kamenets 2 locality indicates that several emersion events were present there, connected with dissolution and karstification. They are often followed by completely different type of sediment, e.g., greenish sandstone, which is not known from other localities in the Pieniny Klippen Belt. It is difficult to prove any presence of terrestric filling but the nature of voids indicates that they did not originate via submarine dissolution. Absence of any marine microfossils in the greenish sandstone indicates that it may represent a terrestric sediment. Some opaque Fe-Mn cements in the sandstone displaying meniscus and microstalactitic features point to possible precipitation in vadose zone and support the possible terrestric origin of the sediment. The meniscus cement is not necessarily indicative of vadose environment, as similar structures of microbial origin were reported from subtidal environment, too (Hillgärtner et al., 2001), but microstalactitic structures (oriented in one direction) could not originate in this way. Microbially-induced structures originated in fully submerged environment would not display gravity-influenced growth. Berriasian resedimentation event inferred from the breccias at the Mala Ugolka locality coincides with Neo-Cimmerian uplift that was registered in the Czorsztyn Ridge by changes in brachiopod fauna to more shallow-marine one (Krobicki, 1994, 1996). The Walentowa Breccia, a member of the Łysa Limestone Formation, as proved by Wierzbowski & Remane, 1992; see also Wierzbowski, 1994) is of the Late Berriasian age. The microfauna in the interstitial voids of breccia at the Mala Ugolka does not allow higher age interpretation than the Late Berriasian, which corresponds well with the age of the Walentowa Breccia Mb. However, the breccia at the Mala Ugolka displays features that are atypical for Walentowa Breccia, such as isopachous crusts of RFC (obviously marine) and clasts of Bajocian crinoidal limestones. These features are typical for much older Krasín Breccia which reflected Bajocian synsedimentary tectonics (Aubrecht, 1997, 2001[a]; Aubrecht & Szulc, 2006). Clasts of the crinoidal limestones point to deeper erosion that could be inferred from the Walentowa Breccia, as the latter contains almost exclusively clasts of Calpionella limestones and the Saccocoma limestones. Multiphase brecciation and signs of etching on previously precipitated RFC crusts indicates that the initial brecciation might have commenced earlier, perhaps already in Tithonian. An extreme case, that the shallowing may have caused emersion and resedimentation of the Bajocian Krasín Breccia cannot be excluded, too.

5.2. Detritic sandy formations

In the Oravic klippen in more western sectors of the Pieniny Klippen Belt, sandy admixture is common in the Jurassic limestones, but purely arenitic formations are rare and are exclusively of the Early Jurassic age (Andrusov, 1931; Aubrecht, 2001[b]; Schlögl et al., 2004; Józsa & Aubrecht, 2006). Moreover, the sandy admixture disappears with Bathonian–Callovian deepening and reappears only in thin layer on the pre-Albian palaeokarst surface (Aubrecht et al., 2009[a]). In the western Ukrainian part of the Pieniny Klippen Belt, the sandy admixture is ubiquitous all through the Jurassic and Cretaceous, with purely arenitic formations reaching Upper Jurassic. Most of the arenitic formations occur in form of pale-grey to white arkosic-like sandstones to quartzites. Greenish sandstone revealed at the Veliky Kamenets 2 locality is an exception that has never been observed before. The white sandstone resembles arenites of the Gresten Formation in the Eastern Alps (Trauth, 1909) in their appearance and in their content of coalified plant remnants. Absence of marine fauna allows to presume of the terrestric origin of these arenites. As such, it is difficult to estimate their age span. At the Veliky Kamenets locality, Vilkivchik Valley, and Vilki Dil, the pale sandstones are overlain by Bajocian crinoidal limestones which determines the highest possible age of the detritic sediment. The greenish sandstone at the Veliky Kamenets 2 is in contact with limestones containing Globuligerina microfacies, which means their age span may reach Oxfordian. The sandy admixture is still dispersed in younger limestones as far as Lower Cretaceous. This is different from more western occurrences of the Czorsztyn Unit (and Oravic units as a whole), where the main siliciclastic sandy input has ceased after the Bathonian-Callovian deepening and drowning. Obviously, eastern part of the Czorsztyn Ridge was relatively higher and the sediments at the examined localities were deposited closer to the emerged land.

Concerning the heavy mineral content, the greenish sandstone from the Veliky Kamenets 2 is the only from the examined samples, which is partly similar to other analysed Oravic Jurassic sediments as it has higher content of garnet. However, strong dominance of the ultrastable trinity zircon-tourmaline-rutile in the remaining samples, as well as dominance of tourmaline among the ultrastable heavy minerals in all samples described in this paper is atypical for Oravic units analysed previously (Aubrecht, 1993, 2001[b]). Similarly, it is atypical for all the arenites from the units that are considered to be palaeogeographically linked to the Oravicum, such as the Gresten Unit in the Eastern Alps (Faupl, 1975), Gresten and other detritic formations on the Bohemian Massif margin (Štelcl et al., 1972, 1977; Nehyba & Opletal, 2016, 2017), or the Polish Platform adjacent to the Tethys (Méres et al., 2012). On the other hand, this heavy-mineral assemblage is typical for the units of the Central Western Carpathians (Aubrecht, 2001[b]). To explain such a difference, more detailed provenance analysis of heavy mineral spectra is necessary, which is by now beyond the scope of this paper. However, provided that the Oravic crustal segment was surrounded from all sides by deeper basins, the clastic admixture might be derived only from the emerged Czorsztyn Ridge. Changes in the heavy mineral spectra points to lateral variability in its composition. Similar lateral change was indicated also for the Silesian Cordillera (Wieser, 1985), which was most likely derived from the same sector of the stable Europe by the Jurassic rifting (Aubrecht et al., 2009[a]).

5.3. Middle Jurassic to Early Cretaceous volcanic activity

Direct manifestations of the Middle Jurassic to Lower Cretaceous volcanism in the Oravic units are concentrated invariably in the eastern sectors of the Pieniny Klippen Belt, i.e. in Ukraine and Romania (Mišík, 1992). Westward, only distal pyroclastic falls were registered (e.g. in the Orava territory – Mišík et al., 1991), or isolated clasts of volcanics were found in the Upper Jurassic limestones (Mišík & Sýkora, 1993; Schlögl - unpub. data). Fragments of volcanic glass in the limestones at the Veliky Kamenets 2 belong to one of the oldest phases of volcanism, which were registered in the Oravic units. The host rocks represent crinoidal limestones, passing to micritic organodetritic limestones with rare *Globuligerina*. As there is still not mass occurrence of this foraminifera, the limestones are most likely older than Oxfordian. Sedimentation of crinoidal limestones is mostly concentrated to Bajocian. The age of the volcanic activity reflected by the sediments at the Veliky Kamenets 2 can be then placed to the time span from Bajocian to Callovian. The volcanic fragments can be older, or coeval with the limestone. However, as the volcanic glass fragments are heavily calcified, it is substantiated to presume, that they do not represent older detritus, but their alteration was caused by the surrounding limestone environment immediately falling to the sea bottom. Due to the lack of primary volcanic structures it is difficult to determine whether the glass belongs to acidic, or basaltic volcanics, but the latter possibility seems more likely. In the Czorsztyn Succession and its analogues, volcanism of this age has never been indicated. In the neighbouring Niedzica Succession in the Pieniny Klippen Belt of southern Poland the presence of the pyroclastic material in the Bathonian-Early Callovian deposits was earlier recognized (Wierzbowski et al., 2012[a]). Close in age are also cinerites mentioned by Bombiţă & Savu (1986) and Bombiţă & Pop (1990) from Poiana Botizii in Romania. However, the unit from which these rocks were described has uncertain tectonic and palaeogeographic position and it is not clear if it belongs to the Pieniny Klippen Belt.

6. CONCLUSIONS

1. Three occurrences of the Czorsztyn Succession and its equivalents were studied in the Ukrainian part of the Pieniny Klippen Belt: Veliky Kamenets 2, Vilki Dil, and Mala Ugolka. They bear some features which are unique and atypical for the Czorsztyn Succession localities occurring in Slovakia and Poland.

2. Veliky Kamenets 2 represents locality with most condensed sedimentary succession that was ever registered in the Czorsztyn Unit. There were several emergence periods with erosion and karstification. After Bajocian deposition of the crinoidal limestones (Smolegowa and Krupianka limestone formations), there was a karstification period followed by deposition of greenish sandstone with carbonate cement which has no analogue with so far known lithostratigraphic units. Because the formation of the crinoidal limestones was strictly related with the uplifting of the Czorsztyn Ridge, the origin of the discussed special deposits were possibly strictly related with the coeval tectonic activity. It seems thus highly probable that their formation was confined to the formation of the synsedimentary faults. This may explain the limited spatial distribution of the unusual features recognized in the deposits studied. The crinoidal limestone also contains pyroclastic material which is a manifestation of one of the earliest volcanic phases in the Pieniny Klippen Belt. The locality itself probably represents a megabreccia formed by the pre-Albian emersion which is also unique. Vast majority of the localities lack any basal breccia.

3. Vilki Dil locality is unique by very late, Bajocian onset of marine transgression, where only thin beds of the crinoidal limestone (Smolegowa and Krupianka limestone formations), or the first beds of nodular limestone (Czorsztyn Limestone Formation) overlie terrestric pale sandstones and quartzites. Pale, arkosic-like sandstones are typical of the Czorsztyn Succession in the area where the examined localities are situated. They remind the Gresten Beds from the Eastern Alps. However, they differ in their heavy-mineral contents not only from the Gresten Beds, but also from other Jurassic sediments of all Oravic units known so far. The sandstones are mostly dominated by ultrastable trinity tourmaline, zircon, and rutile, where tourmaline prevails. The Gresten Beds and so far analysed Oravic units are dominated by garnet and the ultrastable trinity is strongly dominated by zircon. This difference may be a reflection of lateral variability of the Oravic crustal segment (Czorsztyn Ridge). Siliciclastic admixture is ubiquitous at the examined localities as high as Lower Cretaceous. This indicates that the localities were situated much closer to emerged Czorsztyn Ridge than those occurring more westward and that emersion persisted much longer, even after Bathonian-Callovian sea-level rise.

4. Mala Ugolka locality is unique by Upper Berriasian breccia (age analogue of the Walentowa Breccia Member) with cement-coated clasts, which represents the first manifestation of post-Tithonian shallowing that preceded the Hauterivian–Aptian emersion of the Czorsztyn Ridge.

Acknowledgements: The authors acknowledge the financial support from the projects APVV-0212-12 and APVV 14-0118, VEGA 2/0028/17 and VEGA 2/0136/15. Valuable comments, corrections, and suggestions of the reviewers Dr. Adam Tomašových (SAS, Bratislava) and Dr. Renata Jach (JU, Cracow) are highly appreciated. Help of D. Reháková with determination of calcareous dinocysts and calpionellids is also warmly acknowledged. Š. Józsa helped us with evaluation of Cretaceous planktonic foraminifers.

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