Cretaceous Research 140 (2022) 105323

Contents lists available at ScienceDirect

Cretaceous Research

journal homepage: www.elsevier.com/locate/CretRes

Mid-Cretaceous turnover in the Oravic segment of the Pieniny Klippen Belt (Western and Eastern Carpathians): New data and synthesis

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A R T I C L E I N F O

Article history:
Received 14 March 2022
Received in revised form
6 July 2022
Accepted in revised form 23 July 2022
Available online 17 August 2022

Keywords:
Cretaceous
Western Carpathians
Oravicum
Paleokarst
Redeposition
Subcrustal erosion

A B S T R A C T

The Oravicum provides a crustal ribbon, whose deposits recently form a major part of the Pieniny Klippen Belt being a mélange zone between the Carpathian internides and externides. The Hauterivian–Albian turnover completely changed its character. The paper brings synthesis of old and new data that reveals processes which had taken place at that time.

The Hauterivian–Albian uplift and tilting resulted in shallowing, emersion and karstification of the elevated part of the Oravicum for about 20 Ma. It caused slumping and redeposition in the basinal part. An Urgonian-type platform occurred on the basin margin.

Subsequent Albian collapse caused the drowning of the Oravicum to neritic/bathyal depths with deposition of oceanic red beds, black shales, and flysch deposits.

The new data elucidate some phenomena: 1) Karstification is evident despite that isotopes show no evidence of purely fresh-water speleothems. 2) A newly found block of Urgonian-type limestone with basal breccia is a rare example of the presence of Oravic material in the exotic flysches. 3) Slumping of sediments in the deeper parts of the Oravicum might lead to local unroofing of the older, Aalenian black shales with subsequent deposition of Cretaceous black and red shales on them, thereby explaining the frequent tectonic mixing of these two types of lithostratigraphic units.

The final synthesis indicates that the Oravicum lost at least a part of its basement during the Albian when it was likely in contact with the Carpathian internides. Subcrustal erosion by a subducting mid-oceanic ridge beneath the Carpathian plate is the most plausible explanation.

1. Introduction

The end of the Early Cretaceous was a period of large changes all over the Globe and especially in the Tethyan realm. In the Tethys, the large-scale eustatic and ecological changes (Haq, 2014; Wagreich et al. (eds.), 2020 and the articles therein) are combined with tectonic events related to the closure of various oceanic branches (e.g., Neotethyan, Alpine Atlantic, etc., see Stampfli and Borel, 2002; Stampfli et al., 2002; Csontos and Vörös, 2004; Schmid et al., 2008; Handy et al., 2010; Gawlick and Missoni, 2019), crustal shortening and forming of accretionary wedges. At that time, carbonate sedimentation ceased and was replaced by siliciclastic deposition in most of the sedimentary basins. One of these was the Pieniny Basin, or Pieniny Klippen Belt Basin (Birkenmajer and Gasiński, 1992), which covers the Oravic terrain. Its deposits recently form the main part of the Pieniny Klippen Belt in the Western and Eastern Carpathians.

The Pieniny Klippen Belt (PKB) is a long complex zone situated along the boundary between the West Carpathian internides and externides. It is a mélange zone, formed by rocks of the sedimentary cover of a former terrain called the Oravicum and partly also by rocks belonging to the units derived from the Central Western Carpathians. The Pieniny Klippen Belt sedimentary units exhibit variable lithology and a complex internal structure, since they had undergone a long-term polyphase tectonic history which produced the present 'block in matrix' structure. Blocks (or klippen) of harder Middle Jurassic to Lower Cretaceous limestones are embedded in softer shales, marls, and flysch formations, mostly of the Late Cretaceous age. The original paleogeographical reconstruction of

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https://doi.org/10.1016/j.cretres.2022.105323
0195-6671/

the Pieniny Klippen Belt and especially the Oravic units is difficult. The recent model of the Oravic terrain (Fig. 1) is more or less the same as that of Birkenmajer (1977), with some corrections and complementation by Wierzbowski et al. (2004) and Plašienka and Mikuš (2010). It consisted of units deposited in deep-marine (Kysuca–Pieniny Unit and Grajcarek/Šariš Unit) to shallow-marine (Czorsztyn Unit) environments. In the centre, there was the Czorsztyn Ridge that was periodically emerged and submerged during its history.

The Oravic basement was presumably formed by a continental crust, however, only fragments of its sedimentary cover are preserved until now. Siliciclastic material in the cover's deposits is the only witness of its composition (Aubrecht, 1993; 2001a). The presence of pyrope-almandine garnets indicate that this crustal segment might have been derived from the Moldanubian zone of the Bohemian Massif, which is rich in granulites and eclogites containing the same types of garnets (Aubrecht and Méres, 2000; Aubrecht et al., 2009). An alternative theory that the Czorsztyn ridge represented a mid-oceanic ridge (Krobicki et al., 2003) is very speculative and unsubstantiated.

Since the Middle Jurassic to the Early Cretaceous the Oravic block underwent several extensional tectonic phases, that were manifested mainly in the shallowest Czorsztyn sedimentary zone. A Bajocian rifting phase led to the differentiation of previously unified sedimentary area to the Czorsztyn Ridge and the Kysuca–Pieniny Basin. This phase was accompanied by formation of cliff breccia to megabreccia bodies in the Czorsztyn Unit (Krasín Breccia – Mišík et al., 1994a; Aubrecht, 1997, 2001b; Aubrecht and Szulc, 2006). Further extension in the Czorsztyn Zone is manifested by neptunian dykes filled with Bathonian to Oxfordian red mudstones (Birkenmajer, 1958; Mišík, 1979; Aubrecht and Túnyi, 2001). In the period of the Berriasian–Valanginian, there were some events of resedimentation (Walentowa Breccia and its equivalents) that were recorded in both the shallowest, Czorsztyn Zone (Birkenmajer, 1977; Krobicki et al., 2010), and the deepest, Kysuca–Pieniny Zone (Józsa and Reháková, 2017).

The present paper deals with a special, key period when the Oravic tectonic block lost at least part of its presumed crustal basement. It likely began in the Hauterivian and ended approximately in the Cenomanian, when the bathymetry of all the Oravic units drastically changed. Since that time, in all the units, only hemipelagic to pelagic sedimentation have taken place, and the previous contrasting bathymetric differences that had existed since the Middle Jurassic were more or less eliminated. The Czorsztyn sedimentary area possibly became even slightly deeper, as indicated by the Albian, Cenomanian, and Turonian cherts and radiolarites that do not occur in the Kysuca Unit, which was previously a deeper one (for an overview, see Sýkora et al., 1997).

2. Geological setting – what do we know so far?

The study is based on a synthesis of existing data that were previously published, in combination with new data obtained later. The position of the localities bringing new data (see Section 4) is marked in Fig. 2; for the rest, see the corresponding cited references. The present contribution is mainly focused on the sedimentary record of the main contrasting units – Czorsztyn Unit and Kysuca–Pieniny Unit (Fig. 3). There is a little data from the "transitional units", which had presumably emerged as the Czorsztyn Zone (Aubrecht et al., 2006).

2.1. Czorsztyn Unit

A lack of Lower Cretaceous deposits in the Czorsztyn Unit had been reported earlier by researchers (Birkenmajer, 1958; Andrusov et al., 1959), who noticed that the limestone succession of the klippen in all places was invariably truncated and abruptly replaced by Albian red marls (Couches Rouges, Scaglia Rossa facies). This was interpreted as the result of a tectonic phase (Pieniny Phase – Andrusov, 1938; Mišík, 1994) linked to the unconformity of the limestones and red marls. The same unconformity was interpreted later as erosional, which had either been caused by an emersion

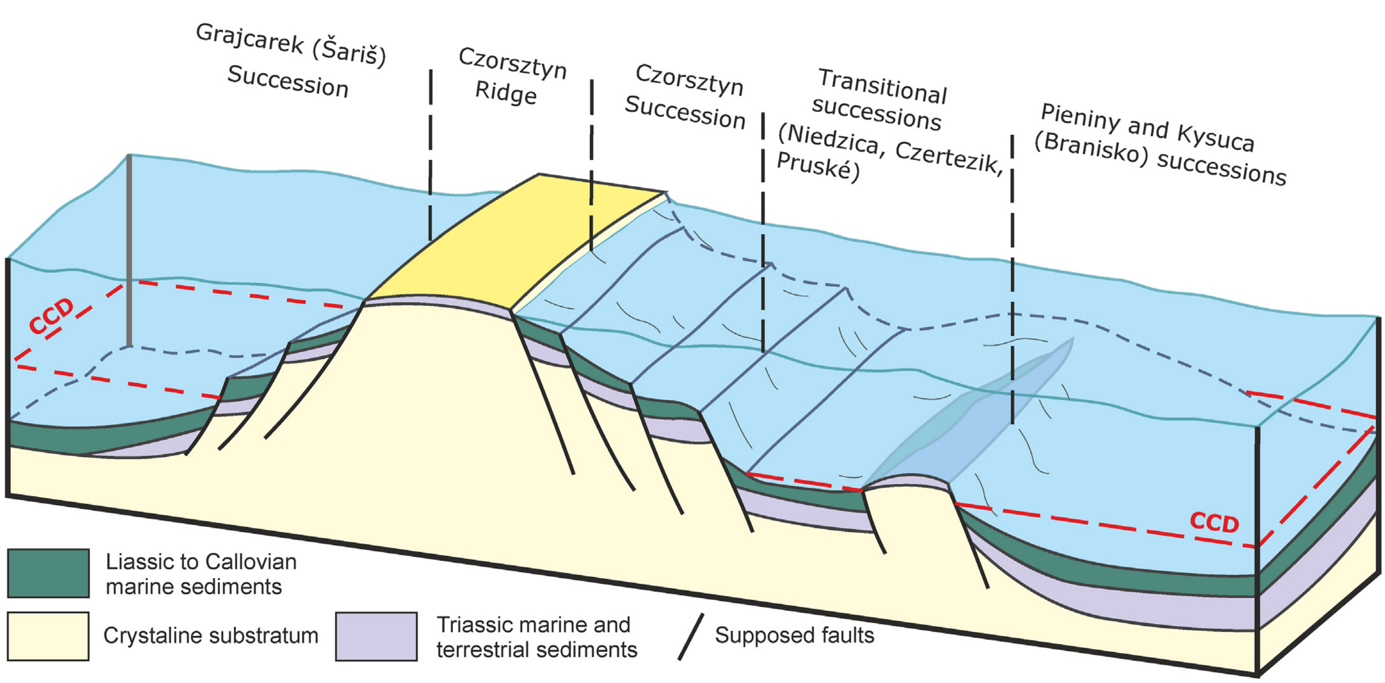

Fig. 1. Paleogeographic block-diagram sketch showing position of the Oravic units. After Birkenmajer (1977), with modification of Krobicki and Wierzbowski (2004) and Plašienka and Mikuš (2010).

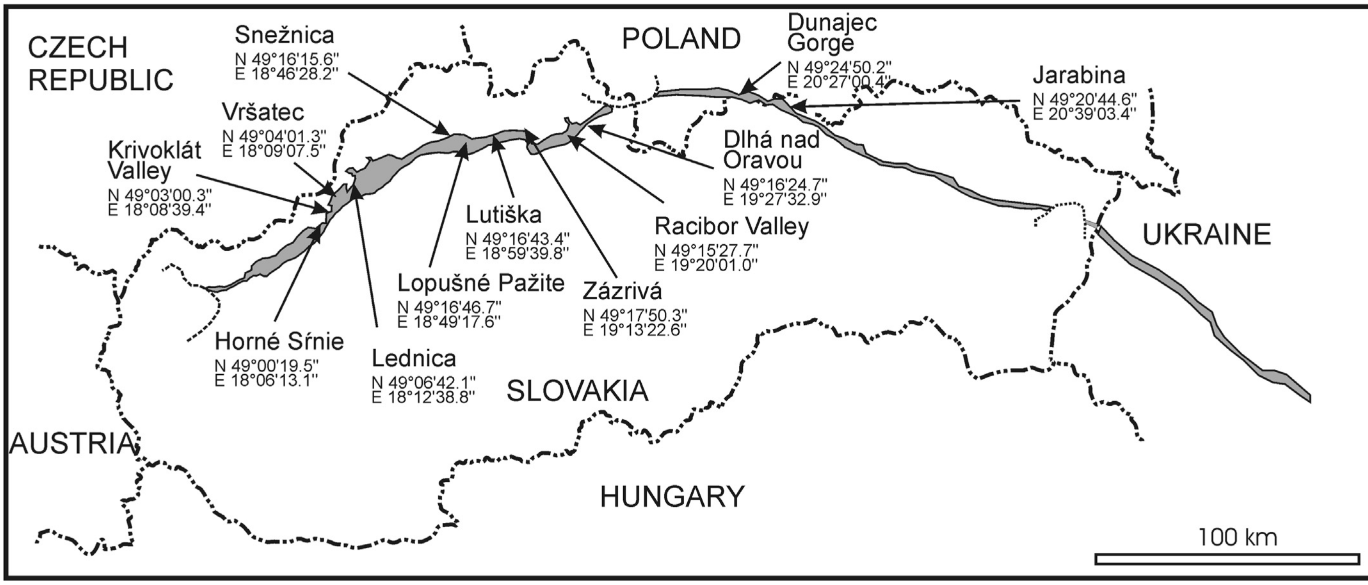

Fig. 2. Position of the localities which provided new data examined in this paper with respect to the course of the Pieniny Klippen Belt.

(Manín Emersion Phase, see Andrusov, 1959) or a submarine non-deposition and erosion (Birkenmajer, 1958, 1975). The emersion was supported by Mišík (1994). The solution of this problem is not easy, since there is a striking contrast in bathymetry of the underlying limestones and overlying marls. The Lower Cretaceous deposits of the klippen mostly consist of organodetritic limestones with crinoids (Łysa Limestone Formation) and crinoidal limestones (Spisz Limestone Formation). According to Birkenmajer (1977), the first one is of Berriasian to Valanginian age, whereas the latter is of the Hauterivian age. Nevertheless, current stratigraphic data show that all the Spisz Limestone Formation should be dated to the Valanginian (Wierzbowski, 1994). The Spisz crinoidal limestone represents the last sedimentary record before the onset of the red marls and points to a considerable shallowing of the depositional environment. In addition, its age indicates that there is a sedimentary gap encompassing the entire Hauterivian, Barremian and Aptian. After this gap, a sudden onset of Albian red marls is visible in most places, without any transition typical for normal transgression, e.g., basal breccias or conglomerates. Therefore, the question of emersion, or submarine erosion, has persisted for a long time. In recent decades, new data has appeared that helped to elucidate this problem (Aubrecht et al., 2006, 2017; Jamrichová et al., 2012). They have revealed that the stratigraphic gap was caused by erosion and karstification due to large-scale emersion of the entire Czorsztyn Ridge. The emersion affected the “transitional units” as well, and reached as far as the margin of the Kysuca Basin. At several sites (Horné Sŕnie, Vršatec, Lednica and Zázrivá), the rocks below the base of the red marls display a distinct karstic karren surface (Fig. 4A, B). The surface is commonly bored by bivalves (Fig. 4C). At these sites, it was also revealed that the karstification had taken place in two phases (Fig. 4C). After the first phase, a short-time submersion of the ridge occurred during the late Aptian/early Albian, leading to the deposition of organodetritic mudstones with dispersed crinoids, phosphatic-ferroan stromatolites and oncolites, accumulations of belemnites, fish teeth, and siliciclastic admixture, with heavy fraction dominated by Cr-spinels derived from newly-emerging ophiolitic sources (Aubrecht et al., 2009). At the base of paleokarst, silcrete remnants were found at two sites – Kamenica and Dolný Mlyn (Mišík, 1996). The erosion and karstification reached various stratigraphic levels of the underlying limestones, from the Berriasian (Łysa Limestone Formation) as deep as the Bajocian Smolegowa Limestone Formation (crinoidal limestones). In some places (Vršatec, Horné Sŕnie and Veliky Kamenets 2), the basement rocks were penetrated by neptunian dykes with Albian filling (Mišík, 1979; Aubrecht et al., 2006, 2017). The vast majority of the localities displays no distinct karst features, and there is a simple contact between the underlying limestones and the overlying red marls. Basal breccias were found at a few sites only, e.g., Dolný Mlyn (Aubrecht et al., 2006) and Veliky Kamenets 2 (Fig. 4D, see also Aubrecht et al., 2017). The Albian age was also attributed to Wapiennik Breccia Member of the Czorsztyn Succession (Arabas et al., 2011), which was originally dated to the Callovian–Oxfordian by Birkenmajer (1977).

2.2. *Kysuca–Pieniny Unit*

The Kysuca–Pieniny Unit consists of deep-marine sedimentary successions that mostly seemed to be unaffected by the examined Hauterivian to Cenomanian events, except for the general cessation of the Maiolica-type facies after the Hauterivian–Barremian and the onset of shaly and marly sedimentation in the Aptian (previously called *Globigerina*-radiolarian beds). These deposits were later formally defined as the Kapuśnica Formation by Birkenmajer (1977). Herein, we shall keep the more detailed subdivision by Haško and Samuel (1977) to the Koňhora, Tissalo, Lalinok, and Kysuca formations (Fig. 3, 5A). However, a special development of this unit, which is known as the Nižná Unit (originally defined as a subunit by Scheibner, 1967), displays sedimentary features that are related to these events. The Barremian–Aptian time is represented here by an Urgonian-type of limestone (Fig. 5B–C) called Nižná Limestone (Scheibner, 1967), which was initially mistakenly mapped as Middle Jurassic, crinoidal limestone (Andrusov, 1931). Nižná Limestone displays various facies from a shallow, marine, rudist-coral-sponge reef (Fig. 5D) as far as distal calciturbidites embedded in the black shales overlain by the Tissalo and Lalinok formations (Fig. 5E, Józsa and Aubrecht, 2008). The shallow-marine facies commonly rest unconformably on older strata (Fig. 5F) and are often underlain by a breccia consisting of clasts to larger blocks of Maiolica-type limestones, their cherts, and radiolarites (Fig. 6).

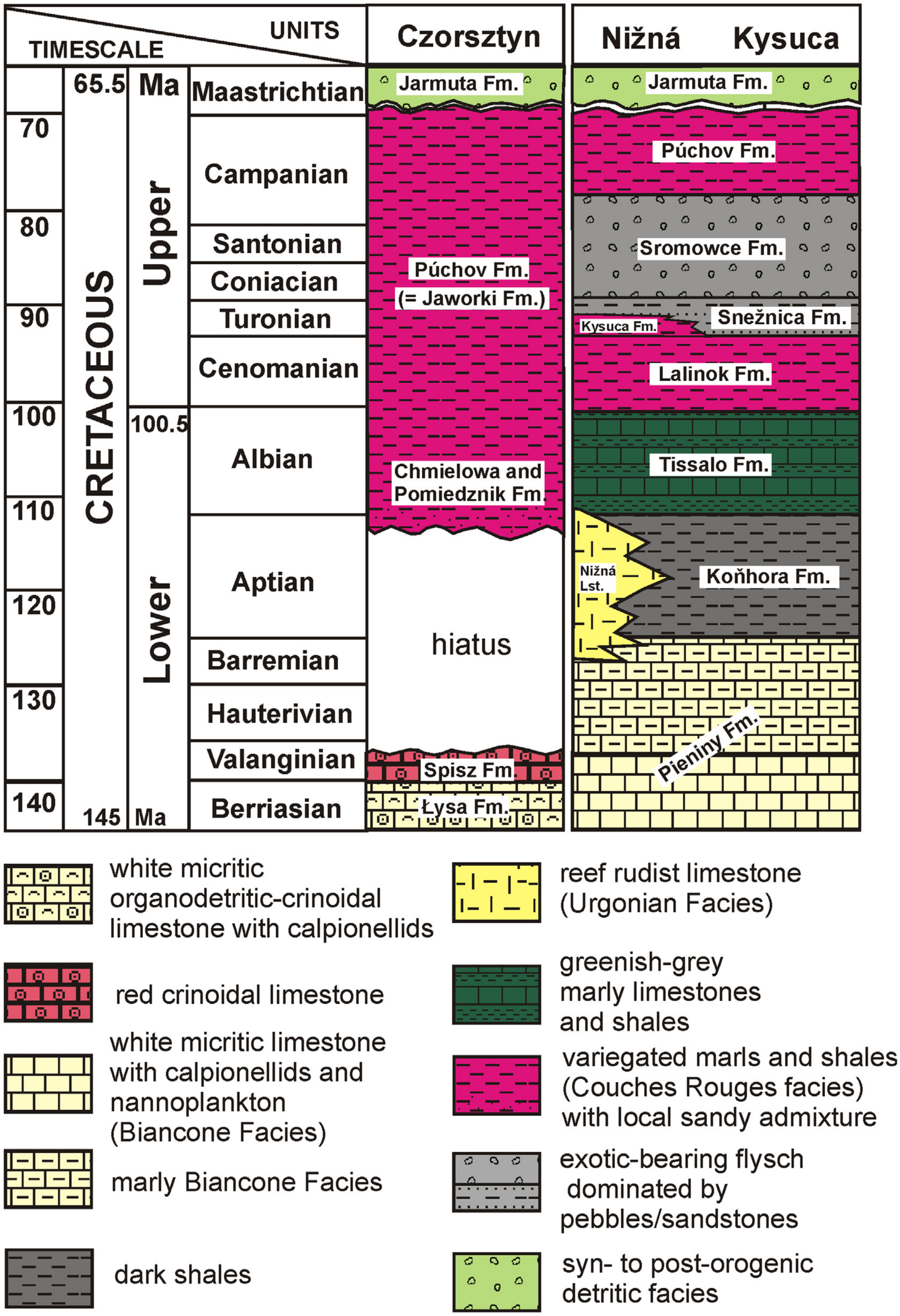

Fig. 3. Schematic lithostratigraphic columns of the contrasting Oravic units (Czorsztyn and Kysuca/Nižná). The scheme is composed on the basis of the following literature: Scheibner (1967), Birkenmajer (1977), Haško and Samuel (1977), Aubrecht et al. (2006) and Józsa and Aubrecht (2008).

This breccia was first mentioned by Scheibner (1967) and later studied in detail by Józsa and Aubrecht (2008) and consequently named Tvrdošín Breccia. It is usually just a few meters thick; however, at Dlhá nad Oravou, its thickness reaches tens of meters (Fig. 6C–D). The Urgonian-type limestone indicates that the Barremian–Aptian emersion affected the entire Oravic realm as far as the margin of the Kysuca Basin. The Tvrdošín Breccia points to the initial tilting and erosion of this margin. The first shallowing in the

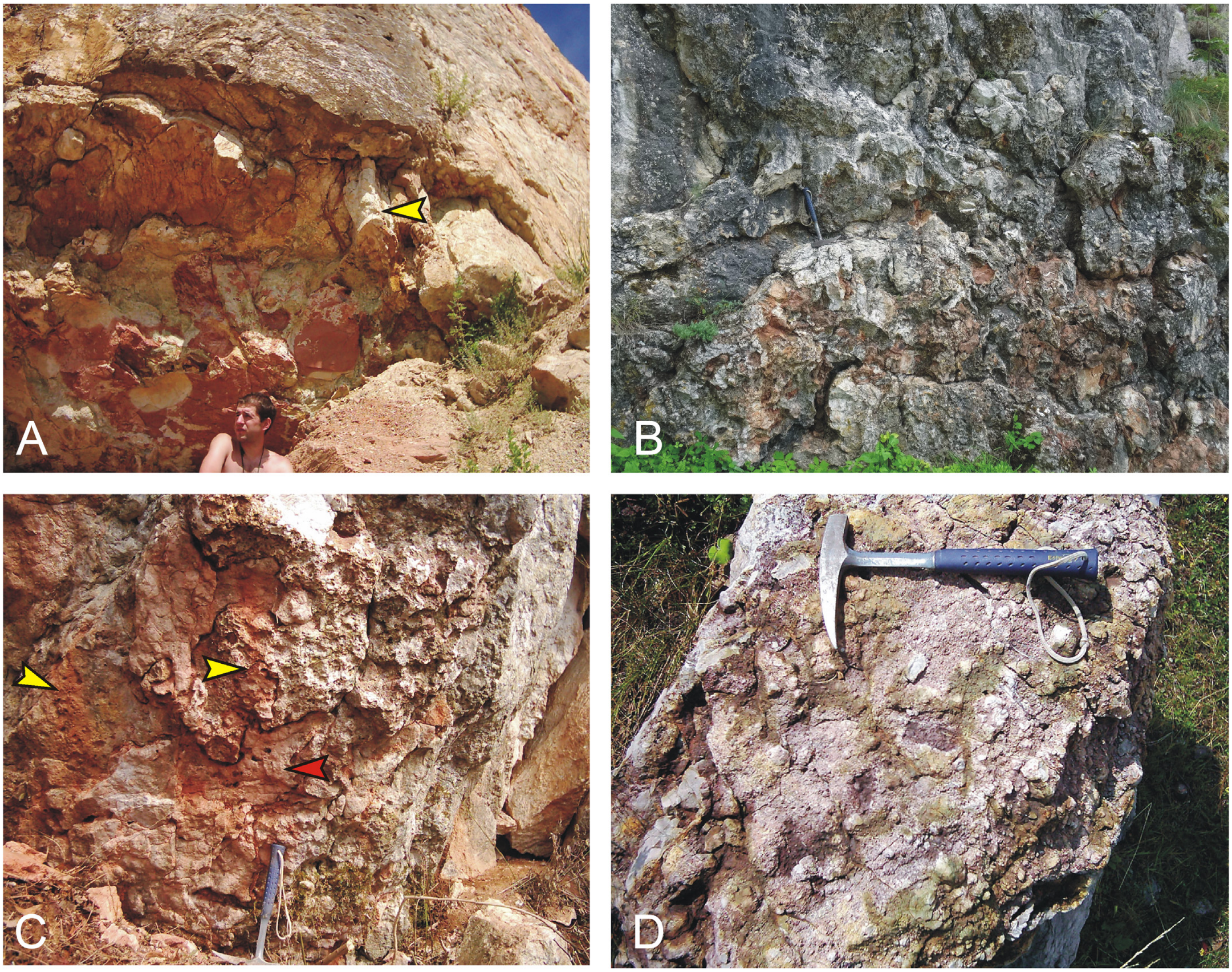

Fig. 4. Selected outcrop photos illustrating the Cretaceous paleokarstic phenomena in the Czorsztyn Unit. (A) Well-developed paleokarst (overturned) incised as deep as the Bajocian crinoidal limestones. Karren with rain grooves (yellow arrow) are well visible. Horné Sŕnie – state in the year 2005, presently destroyed by quarrying. Person as a scale. (B) Karren surface on the subvertically inclined paleokarst surface. Lednica castle cliff. (C) Paleokarst surface at Lednica showing two phases of karstification. The uneven surface created by the first phase has been submerged again and bored by bivalves (bored parts marked by yellow arrows). Then it was covered by organodetritic wackestone of the latest Aptian (red arrow), which has been also karstified during next emersion. (D) Corroded and bored pre-Albian breccia impregnated by yellowish to reddish, (ferroan and phosphatic) minerals. Veliky Kamenets 2 (for A–C – see Aubrecht et al., 2006; for D – see Aubrecht et al., 2017). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

Kysuca Unit was expressed a bit earlier by crinoidal detritus in the Maiolica-type limestones defined as Horná Lysá Limestone (Mišík et al., 1994b, 1996). The detritus may correspond to that of the Spisz Limestone in the Czorsztyn Unit. The first manifestations of tilting in this unit were locally evidenced in Hauterivian Maiolica-type *Nannoconus* limestones, which show signs of slump deformation, disintegration, and forming of calciturbidites (Fig. 7, Aubrecht, 1994; see also Mišík and Rojkovič, 2002).

3. Material and methods

The aforementioned data were recently complemented by new field and laboratory data from localities known so far, but also from newly discovered ones. Synthesis of these data shed new light on the processes that occurred in the Hauterivian–Cenomanian time in the Oravic realm. The new research is based on sedimentological, tectonic, isotope, and micropaleontological methods.

Tilting of the Oravic crustal segment was studied using field measurements of the paleokarst features versus previous bedding in the Czorsztyn Unit. The orientations of protruding karstic bulges and rain grooves on them, as well as the last bedding planes of the underlying strata were mainly measured. These measurements were performed at the localities of Zázrivá, Lednica, and Vršatec. The exact field measurements were supplemented by the data derived from photos of inaccessible places (Vršatec, Dunajec Gorge) or localities that were destroyed by quarrying (Horné Sŕnie). The measurements were plotted and evaluated by Stereonet software, version 11.1.3 (Allmendinger et al., 2013).

Calcite filling (radiaxial fibrous calcite and blocky calcite) of the pre-Albian veinlets, as well as some stromatolitic coatings predating the calcite filling of the Czorsztyn Unit from the localities: Horné Sŕnie, Lednica, and Jarabina (studied petrographically by Aubrecht et al., 2006) were analyzed for stable carbon and oxygen isotope composition in order to reveal their marine or

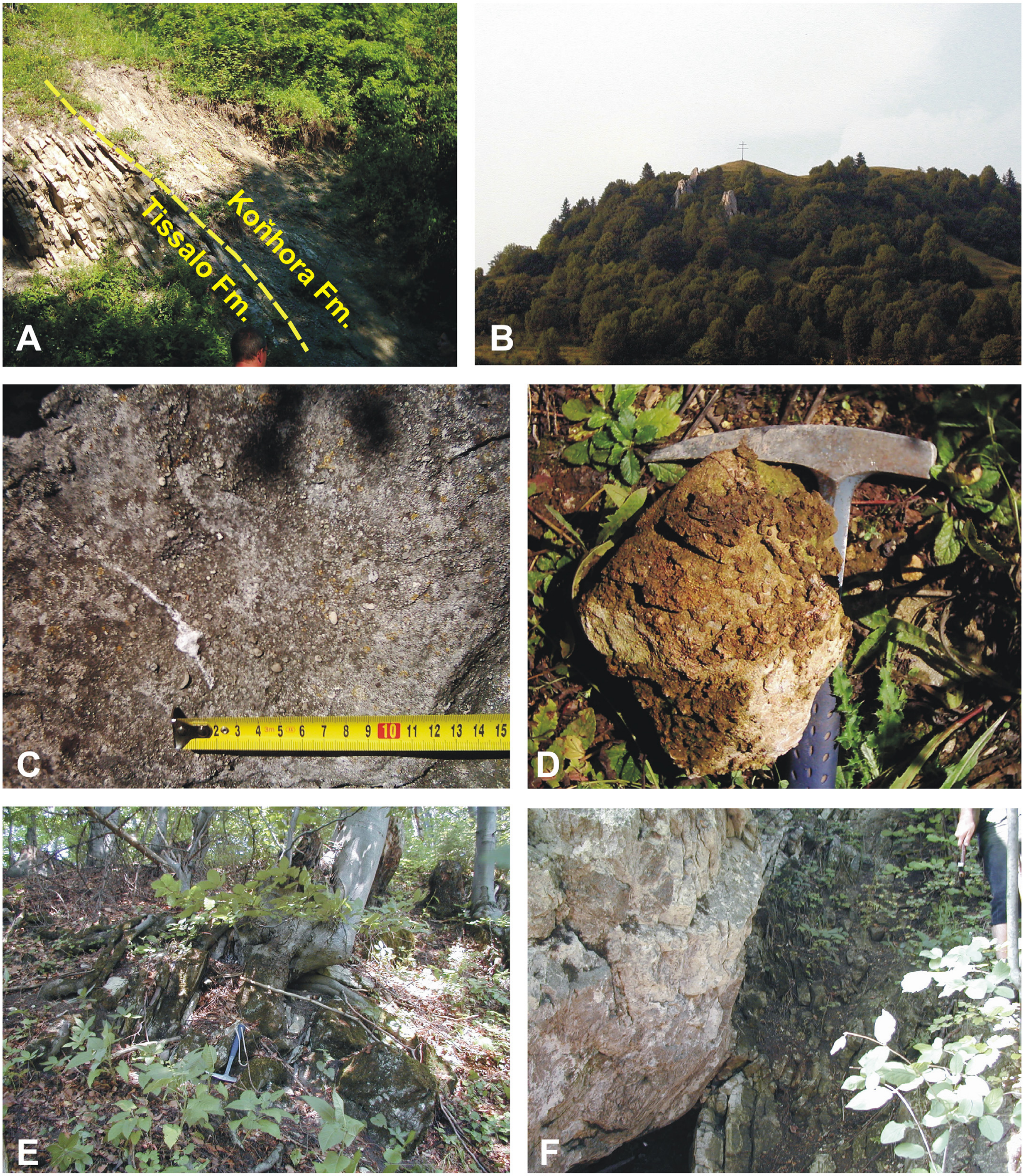

Fig. 5. (A) Contact of overturned bed of the Koňhora Formation (black shales – Aptian) with Tissalo Formation (greenish-gray marly limestones – Albian). Type section of the Kysuca Unit between Vranie and Rudina. (B) Ostražica Hill above the town of Nižná. The cliffs are formed by Urgonian-type of limestone (Nižná Limestone) that replaces the Koňhora Formation in the Nižná Unit. (C) Organodetritic Nižná Limestone. Skalka above Dlhá nad Oravou. (D) Coral boundstone in the Nižná Limestone with positively weathered silicified corals. Skalka Section. (E) Red to gray marlstones and limestones (Tissalo and Lalinok Formations), overlying the distal calciturbidites of the Nižná Limestone. Artificially trenched section at Vysoký Grúň. (F) Nižná Limestone (pale, left) conformably overlying greenish Jurassic Czajakowa Radiolarite Formation (dark, right). Rest of the Jurassic and Lower Cretaceous sediments is missing. Ostražica section. For details see Józsa and Aubrecht (2008). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

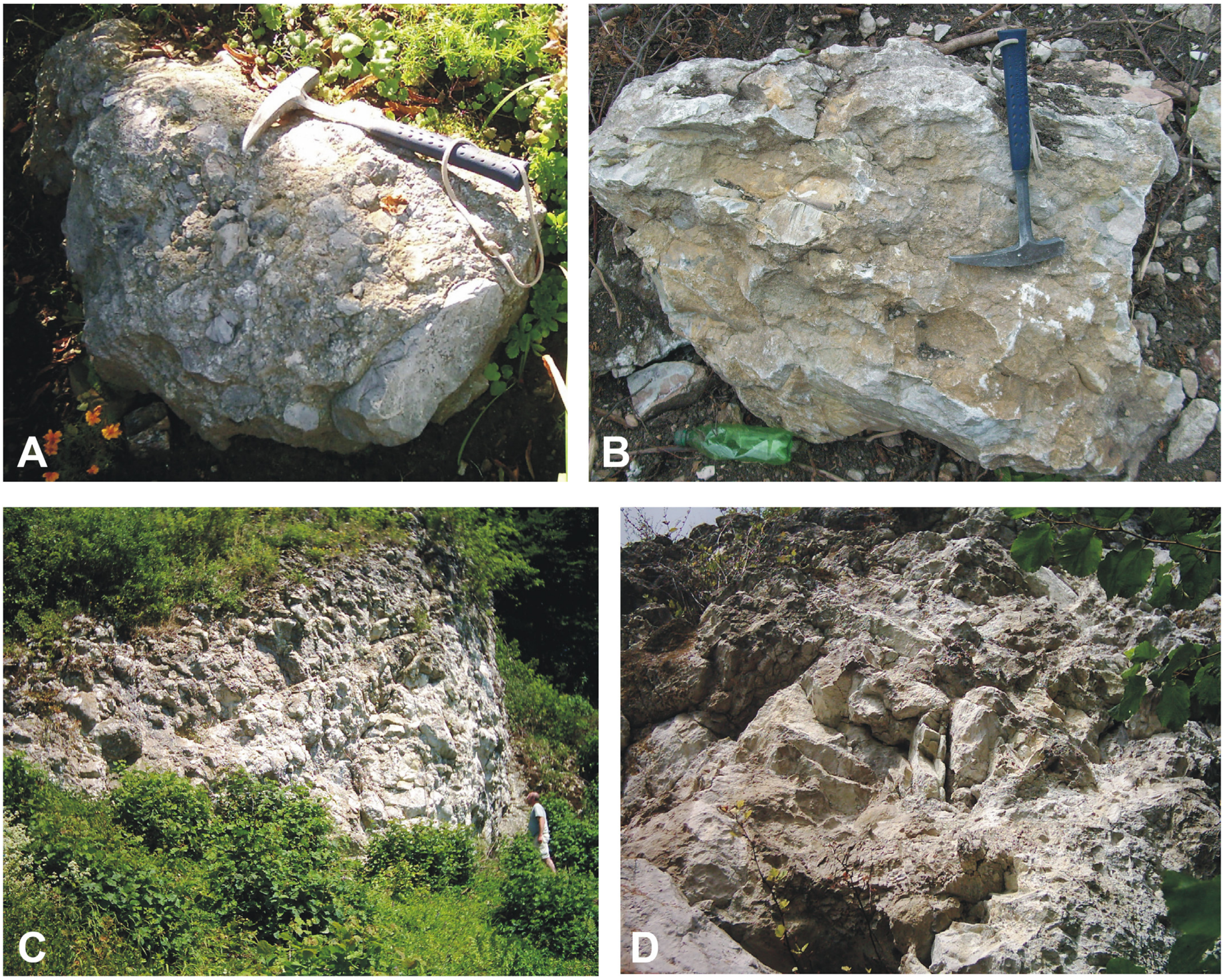

Fig. 6. (A) Tvrdošín Breccia Member at the base of the Nižná Limestone with clasts of Middle Jurassic to Lower Cretaceous limestones and silicites. Zemianska dedina section. (B) Another example of the breccia. Krásna Hôrka section. (C) The largest outcrop of the coarse-grained Tvrdošín Breccia. It consists of chaotically arranged clasts of decimetre size. Skalka section. Person as a scale. (D) Closer view on the breccia at Skalka section. For details see Józsa and Aubrecht (2008) and Starek et al. (2010).

freshwater origin. About 10 mg of powdered sample was analyzed using the method of McCrea (1950). The samples were reacted overnight in sealed vessels at 25 °C with 100% orthophosphoric acid. The isotope composition of the extracted CO_2 was analyzed by means of a Finnigan Mat Delta Plus mass spectrometer at the Institute of Geological Sciences and Institute of Paleobiology, Polish Academy of Sciences in Warsaw. The oxygen and carbon isotope results are reported in δ notation in per mil relative to the V-PDB standard by assigning a $\delta^{13}C$ value of +1.95‰ and a $\delta^{18}O$ value of −2.20‰ to NBS19. The precision of the results (2σ), which was measured on repeated analyses of a laboratory reference, was close to ±0.10‰ and ±0.05‰ for $\delta^{18}O$ and $\delta^{13}C$ values, respectively.

Involvement of slumping in detailed folding of the Maiolica limestones at some Kysuca–Pieniny localities has been studied previously by structural measurements and petrographic analysis. A new occurrence of the Tvrdošín Breccia in the Krivoklát Valley (a tributary of the Middle Váh Valley) has been studied by means of microfacies analysis both, on clasts and on the Urgonian matrix. The same methods were used in a study of the newly-found, upper Albian matrix-supported breccia from the Racibor Valley in Orava territory.

Cenomanian breccia with black-shale matrix was studied two ways: by microfacies analysis and by micropaleontological study of extracted foraminifers. The samples from the breccia matrix (about 1 kg of dry bulk sediment) were treated with detergents and washed repeatedly with water. The residues were sieved at 70, 125, 200, and 500 μm mesh sieves. Microfossils were picked from the 125 μm fraction, transferred into a cardboard microslide, and counted under a Leica S8APO binocular microscope. The microfossils for the SEM study were mounted on an aluminum stub and gold coated. The same specimens were photographed from different views to better illustrate the morphology of the analyzed species. The images were taken using a Quanta FEG 250 at the Slovak Academy of Sciences in Bratislava. All the samples, thin-sections, and microslides with picked foraminifera are housed in collections at the Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University in Bratislava.

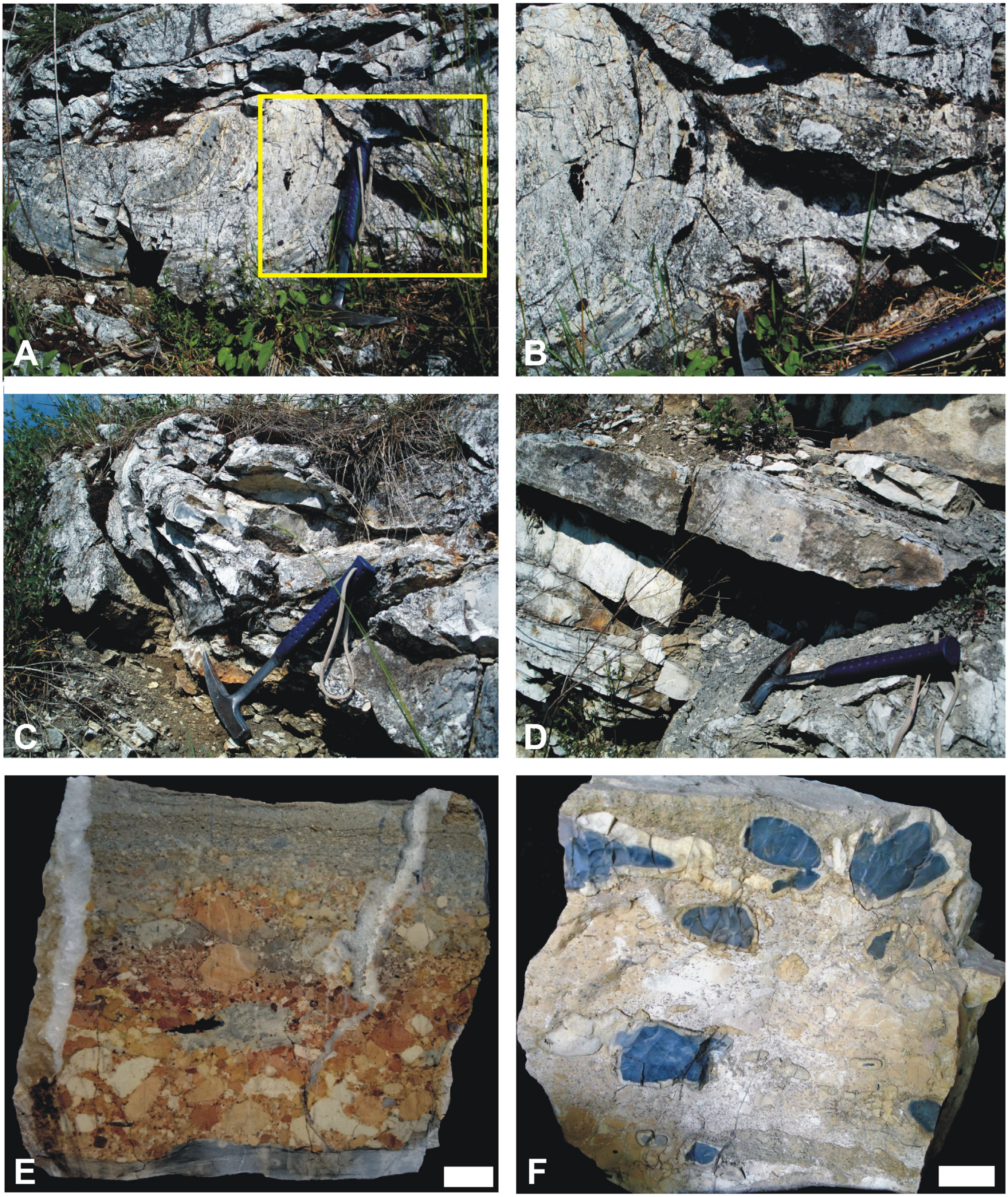

Fig. 7. Hauterivian slump folds and breccias at Istebné section (see Aubrecht, 1994). The field photos reflect the state from 2009. Recently the outcrop is densely covered with bushes and other vegetation. (A) North-facing hinge of a slump fold in the Pieniny Limestone (Maiolica-type), with deformed cherts copying the beds. The section is overturned. The rectangle marks the area focused in Fig. 7B. (B) Closer viev on the contact between the slump fold and slump breccia (above the hammer). (C) Another example of a slump fold hinge oriented in opposite direction than the previous one. (D) Fine-grained turbiditic breccia bed (above the hammer). (E) Slab of the grade-bedded turbiditic breccia from Fig. 7D. The basal dark layer consists of a marlstone with nannoconids. Scale bar = 1 cm. (F) An example of coarse-grained slump breccia consisting mostly of clasts of the Pieniny Limestone and its cherts. Scale bar = 3 cm.

4. Results

4.1. Tilting of the Czorsztyn sedimentary area

In their previous publication Aubrecht et al. (2006) reported a lack of tilting in the examined sites. However, they performed no structural measurements to prove this statement. It is not easy to reconstruct primary orientation of structures in the Pieniny Klippen Belt, because in this block-in-matrix mélange, this can be done only using paleomagnetic correction (see e.g., Aubrecht and Túnyi, 2001). Nevertheless, to measure an eventual mid-Cretaceous tilting of the Oravic crustal segment, it is not necessary to achieve absolute orientation values; a relation to the basement bedding and orientation of the paleokarst features provide sufficient information. Paleokarst is mostly preserved if protected against erosion by tectonic overturning of a klippe. We performed measurements at three localities, where the paleokarstic features are best preserved. Unfortunately, the fourth, best locality, Horné Sŕnie, was destroyed by quarrying. The remaining localities Zázrivá, Vršatec, and Lednica enabled only a few measurements which were not statistically representative. However, even without exact measurements in the field, a closer look on the orientation of paleokarstic features clearly shows that the basement surface had been inclined prior to erosion (Fig. 8A–B). The karst commonly involves loafy promontories that are usually rounded on the top (Aubrecht et al., 2006 – fig. 10A-B); however, most of them are truncated, perhaps by the next erosion phase. At the locality of Zázrivá, these truncated surfaces clearly deviate from the original bedding (Fig. 8B), which also points to the tilting. There are common rain grooves on the paleokarst promontories, whose orientation systematically deviates from a vertical one to about 20° (Figs. 8–9, Table 1) after applying the tilt-correction (turning to the last bedding plane). Since the grooves were carved on the bulge walls, which are not always normal to the bedding planes, this systematic deviation has relatively lower evidence value. However, stronger deviation of one bulge axis (Fig. 8A), including even stronger deviation of the rain grooves measured at Vršatec (Fig. 8C), points to quite steep angles of tilting (39° and 49° respectively – see Fig. 9, Table 1).

4.2. Isotopic record of the pre-Albian calcite veinlets in the Czorsztyn Unit

Calcite veinlets cutting the karstified limestone but not penetrating the covering upper Aptian and younger deposits were analyzed. A bizarre veinlet with initial stromatolitic coatings and the subsequent polyphase, isopachous radiaxial fibrous calcite (RFC) filling (Fig. 10A), was analyzed from the Horné Sŕnie locality (Fig. 10A). The veinlets from Lednica and Jarabina were more or less straight (Fig. 10B) and consisted of one-phase unzoned blocky calcite.

The obtained isotope results can be divided into two groups (Fig. 11, Table 2): The first one is characterized by high $\delta^{13}C$ values (between +1.9 and +3.2‰ VPDB) and high $\delta^{18}O$ values (−0.9 to 0.1‰ VPDB). It consists of samples from Horné Sŕnie and samples from Jarabina closeby. A second one encompasses relatively high $\delta^{13}C$ values (between +1.6 and +2.1‰ VPDB) and low $\delta^{18}O$ values (−5.8 to −4.1‰ VPDB) measured from the Lednica veinlets. The isotope composition of the first group is typical of low-latitude marine bulk-carbonate rocks (cf. Yin et al., 1995; Nelson and Smith, 1996). The results of the second group can be interpreted as distinctive of altered marine calcites, which were affected by low-fluid/rock ratio burial diagenesis at elevated temperatures of 30–39 °C or, alternatively, late diagenetic freshwater alteration. Both processes may have affected $\delta^{18}O$ values, without significant alteration of the carbon isotope composition of the rocks (cf. Banner and Hanson, 1990). It is, however, worth noting that incomplete equilibration between soil CO_2 and percolating water in a semi-closed system can be responsible for elevated $\delta^{13}C$ values of some speleothems (McDermott et al., 2006). Elevated $\delta^{18}O$ and $\delta^{13}C$ values of carbonates deposited in karst conditions may also occur in specific conditions under partial evaporation during dryer periods or progressive ^{18}O and ^{13}C enrichments of local karst water reservoir, e.g., at the site of calcite precipitation, due to Rayleigh-distillation process (cf. McDermott et al., 2006; Mickler et al., 2006). In both cases, the presence of typical fresh-water karst deposits cannot be confirmed based on stable isotope data.

4.3. Possible slump origin of detailed folding of Maiolica-type limestones in the Kysuca–Pieniny Unit

After recognition of slumps in Hauterivian Maiolica-type limestones (see Section 2), a possible slump origin was recognized at various localities of this type of limestone (Pieniny Limestone Formation).

Slump folds have been characterized as contortions of individual beds or packets of beds embedded within virtually undisturbed strata of approximately the same age, which originated by gravity-induced horizontal movement of a coherent slump mass (e.g., Helwig, 1970). In spite of their macroscopically ductile appearance, the slump folds are usually devoid of detectable internal deformation, such as the axial-plane cleavage or pressure solution seams. They represent typical soft-sediment deformation structures of semi-consolidated deposits. Slump folds are commonly tight to isoclinal, often occurring as rootless fold hinges detached from their parental strata. If slumping occurs on a steep slope, slumping is very rapid; or if the slump body continues for longer distances, the deformed strata may lose the coherence and eventually create mass-transport bodies, such as intraformational olistostromes or breccias (e.g., Farrell, 1984; Festa et al., 2010, 2012).

In marine conditions, slumping most commonly affects the deep-water clastic "flysch" deposits characterized by rapid sediment accumulation and high-energy synsedimentary tectonic processes. In the Western Carpathians, slumping structures in flysch formations were thoroughly described and interpreted for the first time for instance by Książkiewicz (1958) and Marschalko (1963). However, the soft-sediment deformation processes, such as creeping, boudinage, and slumping or sliding were reported, though rarely, also from the well-bedded eupelagic strata like radiolarites or Maiolica-type and similar limestones (Röhlich, 2010; Ortner and Kilian, 2016). In this section, we describe some examples of slumping structures from the Lower Cretaceous limestone formations that were related to the synsedimentary tectonic movements in the Oravic units associated with renewed elevation of the Czorsztyn Ridge.

Slump fold structures were observed in the eupelagic Maiolica-type Pieniny Limestone Formation (Birkenmajer, 1977) in several places (Fig. 12). As commonly observed at numerous localities in the world, slump folds exhibit a ductile appearance similar to folds developed in metamorphic conditions (Woodcock, 1976; Beckers and Debacker, 2005; Waldron and Gagnon, 2011; Alsop and Marco, 2014; Ortner and Kilian, 2016). Fold systems are predominantly represented by the class 2 folds of Ramsay (1967) with similar geometry (Fig. 12A,E,F). They are tight to isoclinal, inclined or recumbent, sometimes with refolded axial planes (Fig. 12A). Fold asymmetry is commonly interpreted as an indication of the paleoslope orientation (Marschalko, 1963; Woodcock, 1976, 1979; Bradley and Hanson, 1998), but non-cylindrical fold hinges can be curved and in extreme cases of long-distance slumps., or at the lateral ramps of slump cells, fold axes might have become reoriented parallel to the movement direction (e.g., Lajoie, 1972; Farrell

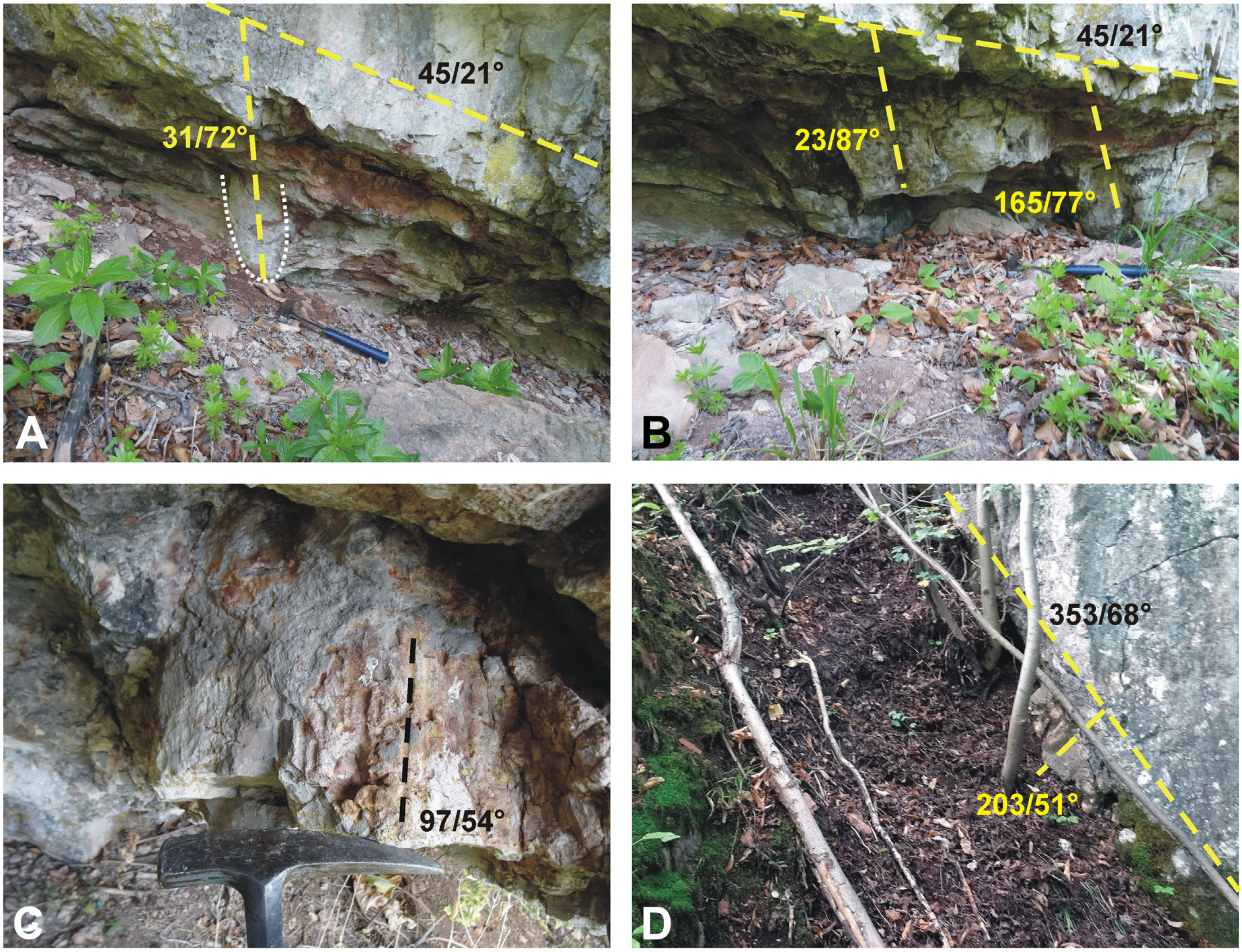

Fig. 8. Representative measurements of the paleokarst features orientation. (A) Loafy promontory (lined by white dots) with axis that considerable deviates from being perpendicular to the bedding plane (45/21°). Zázrivá. (B) Rain grooves orientation on two truncated bulges. Note that the truncation surfaces also deviate from the bedding plane. Zázrivá. (C) Rain grooves measured on a truncated paleokarstic bulge at Vršatec (97/54°). Although the bedding plane is not visible on the picture, this orientation strongly deviates from being normal to the bedding plane (285/77°). (D) One of the two rain-grooves measured at Lednica locality.

and Eaton, 1987; Alsop and Marco, 2013, 2014). One such possible example of two laterally-adjacent slump sheets is presented in Fig. 12B.

In contrast to slump folds, the superimposed tectonic folds exhibit a morphology typical for the brittle deformation field of fully lithified, well-bedded sedimentary formations – concentric parallel folds (class 1b of Ramsay, 1967), or angular chevron-type folds and kink bands (folds Ft in Fig. 12A, C, E). Unlike the passive slump folds, the late tectonic folds formed by the buckling of sub-horizontally lying multilayers, which are upright, mostly symmetric, sometimes showing a weak axial-plane solution cleavage. In the Pieniny Formation, folds produced by layer-parallel shortening of consolidated strata are far more common than slump folds, although virtually non-deformed successions with homoclinally dipping beds still prevail.

However, as pointed out by Farrell (1984) and Farrell and Eaton (1987), the superimposed upright fold tracks might have been related also to the terminal phases of the slumping process, generated by additional shortening at the slump toe. This situation cannot be excluded in the area of the Dunajec Gorge in the Pieniny Mts., where distinguishing of individual fold generations is almost impossible on the weathered and inaccessible vertical rock cliff walls that cut disharmonically folded strata in various directions (e.g., Fig. 12D). Nevertheless, where differentiation is possible, the tectonic folds were clearly formed after a considerable post-slumping time span and affected the whole sedimentary successions, not only the slump bodies.

4.4. A new occurrence of the Tvrdošín Breccia found outside the Orava territory

The Tvrdošín Breccia that originated due to the emersion of the Oravic area at the margin of the Kysuca Basin during the period of the Hauterivian to Aptian had only been known from the Orava territory in northern Slovakia. It was first described by Mišík (1990) from the Krivoklát Valley in the western (Púchov) sector of the Pieniny Klippen Belt. According to their description, Józsa and Aubrecht (2008) expressed their presumption that it may belong to the Tvrdošín Breccia. However, unlike the occurrences in the Orava territory, where it is in situ, the latter is found in an isolated block within the Coniacian–Santonian exotic conglomerates on a slope on the southern side of the Krivoklát Valley (N 49°03′00.3″,

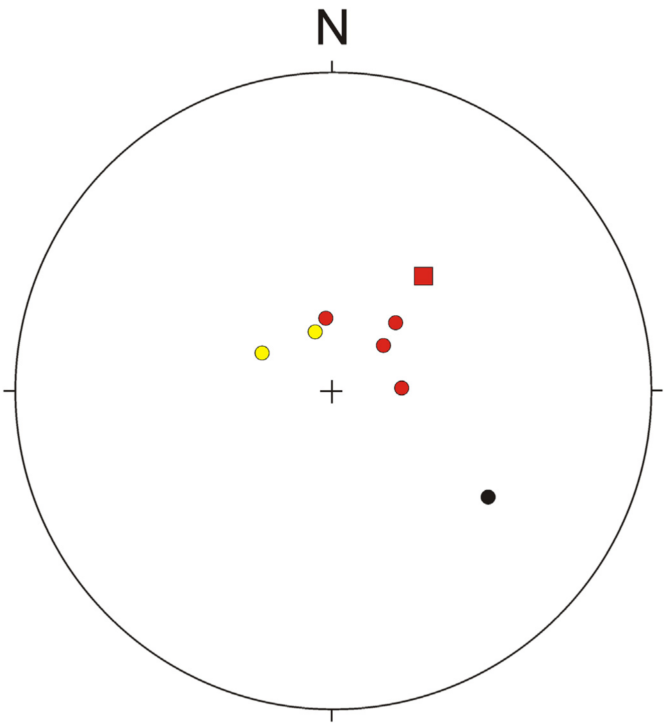

Fig. 9. Tilt-corrected lineations measured in the examined paleokarst sites. The dip azimuths are not relevant, just the dip angles. Red circles – rain grooves at Zázrivá locality. Red square – axis of the bulge figured in Fig. 8A. Yellow circles – rain grooves at Lednica, black circle – rain groove at Vršatec. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

E18°08′39.4″, Fig. 13A) about 500 m beyond the town limits of the village of Krivoklát (Mišík and Sýkora, 1981; Marschalko, 1986). The conglomerates most likely belong to the Kysuca–Pieniny Unit. The breccia is matrix-supported, with dispersed clasts of cm to dm size (Fig. 13B–D).

Most of the clasts are represented by radiolarian-“filamentous” (cross-sections of thin-shelled bivalves) wackestones. They are often laminated, with prevailing spherical radiolarians. The rocks are often silicified, forming cherts. Less common are clasts with hedbergellids, which are only slightly older than the matrix. In some parts, clasts of fine-grained organodetritic limestones are common. They consist of sponge spicules, hedbergellid foraminifers, agglutinated benthic foraminifers, calcified radiolarians, “filaments”, ostracods, and echinoderm particles. Clasts with calpionellids are less common.

The Urgonian-type matrix predominantly consists of poorly-sorted packstone to grainstone, formed mainly by echinoderm particles, bivalve fragments (including those of oysters), fragments of corals, bryozoans, sponge skeletons, agglutinated foraminifers, coralline algae (locally with authigenic quartz inside), serpulid tubes, brachiopods, gastropods, echinoid spines, and microbialitic intraclasts. The allochems are commonly bored and micritized and/or encrusted by nubecularid foraminifers or stromatolites on the surface. Some aragonitic allochems were dissolved and replaced by calcite, with micritized rim preserved. Quartz sand grains are relatively rare.

The organodetritic limestones contained some long-ranging, larger benthic foraminifera spanning from the Hauterivian, yet mostly occurring in Barremian – Aptian or possibly lower Albian deposits (Table 3). The identified species included *Vercorsella scarsellai* (De Castro), *Quinqueloculina* sp., *Novalesia producta* (Magniez), *Cornuspira* sp., *Melathrokerion* cf. *valserinensis* Brönnimann and Conrad (Fig. 14). Frequent indeterminable fragments of larger orbitolinoid foraminifera are present in most of the samples (Fig. 14G).

Planktonic foraminifera detected in some finer-grained parts yielded larger, many-chambered *Globigerinelloides* spp. (Fig. 14H). These taxa are typical for the middle Aptian (Gargasian) (Longoria, 1974; Caron, 1985; Sliter, 1989; Verga and Premoli Silva, 2003; Moullade et al., 2005). The planktonic foraminifera are dispersed in a fine, organodetritic matrix. An equivalent microfacies is reported from the Orava sector of the Pieniny Klippen Belt as a fine-grained variety of the Nižná Limestone Fm. (Józsa and Aubrecht, 2008). The age and character of the breccia is identical with occurrences in the Orava territory. However, the position of the examined block in the exotic conglomerates is quite atypical and indicates interesting paleogeographic constraints (see the discussion).

4.5. *Newly recognized signs of Albian–Cenomanian resedimentation in the Oravic units*

At two sites in the Orava segment of the Pieniny Klippen Belt, Albian–Cenomanian breccias were found. They do not appear in any published lithostratigraphic schemes of the Oravic units to date, which generally presume relatively calm sedimentation with only rare occurrences of arenites (Birkenmajer, 1987).

The first occurrence is an isolated block found approximately on the northern side of the Racibor Valley about 600 m from its mouth to the Orava River (N 49°15′27.7″, E 19°20′01.0″). Its precise location is unknown and all the attempts to find the source rock in situ have been so far unsuccessful. However, the sample is of high importance for reconstruction of the mid-Cretaceous evolution of the Oravic units. The sample is a matrix-supported breccia with angular to subangular clasts of several cm in size (Fig. 15A,B). The most numerous clasts are

Table 1
Structural geological data of the pre-Albian karst phenomena in the Czorsztyn Unit (Zázrivá, Vršatec and Lednica localities).

	Primary data in °		Tilt-corrected data		Deviation
	Dip azimuth	Dip	Dip azimuth	Dip	
Zázrivá					
Last bedding of the basement (S0)	45	21	0	0	
Rain groove 1 (see Fig. 8B)	23	87	42	66	24
Rain groove 2	286	74	357	71	19
Rain groove 3 (see Fig. 8B)	165	77	84	72	18
Rain groove 4	177	84	51	74	16
Axis of karst promontory (see Fig. 8A)	31	72	38	51	39
Vršatec					
Last bedding of the basement (S0)	285	77	0	0	
Rain groove (see Fig. 8C)	97	54	291	41	49
Lednica					
Last bedding of the basement (S0)	353	68	0	0	
Rain groove 1 (see Fig. 8D)	203	51	301	70	20
Rain groove 2	180	50	347	74	16

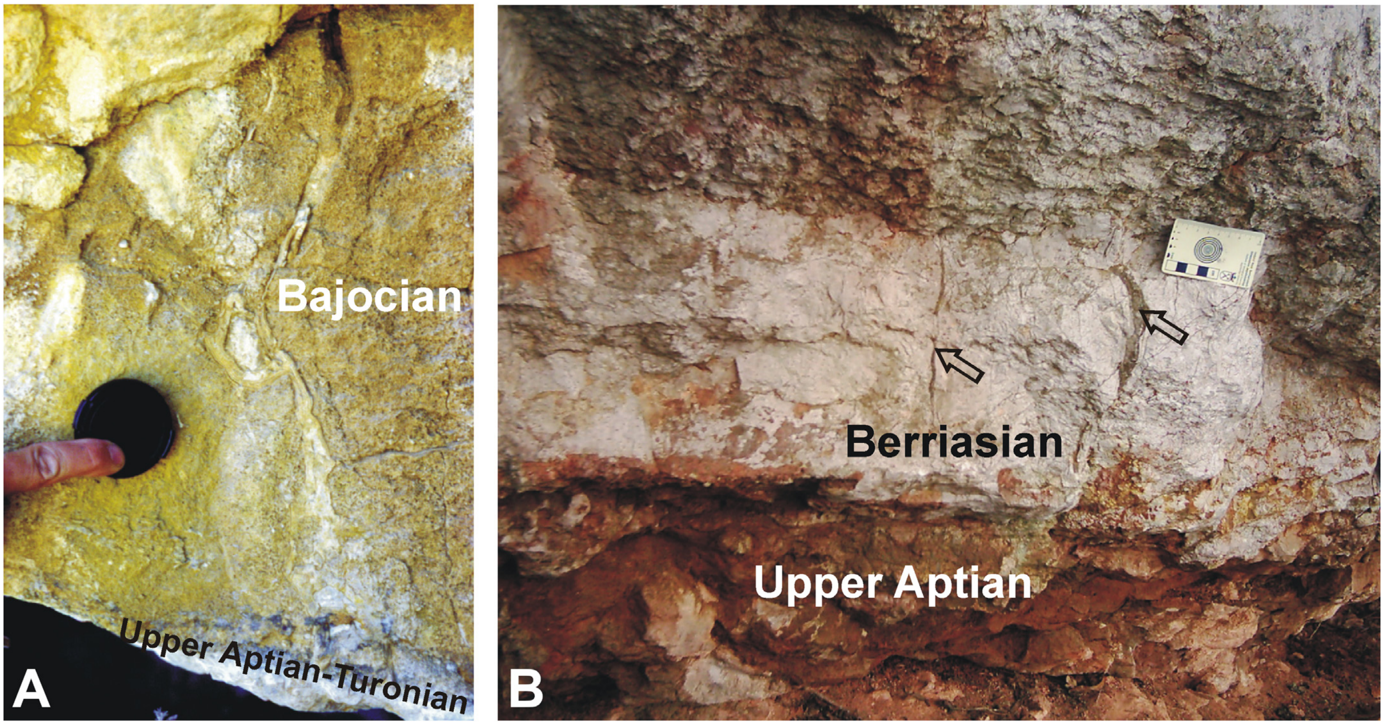

Fig. 10. (A) Bizarre veinlet filled with radiaxial fibrous calcite analyzed for the isotopes; the veinlet starts at the paleokarst surface and penetrates the Bajocian crinoidal limestone. Its irregular shape indicates dissolution origin. Horné Sŕnie. (B) Berriasian limestone cut by blocky calcite veinlets (arrows) that do not continue to Upper Aptian limestone. Lednica.

of organodetritic limestones (wackestones) with calpionellids *Calpionella alpina*, *Crassicollaria intermedia* and *Crassicillaria parvula*, indicating Tithonian–Berriasian age. Along with calpionellids, the limestones contain calcified radiolarians (locally even calpionellid-radiolarian microfacies occur – Fig. 15C), then fragments of bivalves, aptychi (including *Laevaptychus*), foraminifers *Lenticulina* sp., crinoid ossicles, echinoid spines, gastropods and ostracods. The limestone contains a very fine, silty quartz admixture. Some clasts with *Saccoccoma*-crinoidal microfacies (Kimmeridgian-lower Tithonian - Fig. 15C), *Globuligerina* microfacies (likely Oxfordian - Fig. 15D) and cadosinid microfacies (with *Cadosina fusca*) occur as well.

The breccia matrix is mudstone to wackestone, with a mixture of many reworked allochems, such as *Saccoccoma* ossicles, aptychi, and even calpionellids. The reworking is locally so perfect that they are seemingly a part of the matrix. Only a slightly different micritic filling of the allochems reveals their reworking (Fig. 15E). The youngest allochems are single-keeled, planktonic foraminifers belonging to the Rotaliporinae gen. et spec. indet. and globular chambered planktonic foraminifera (Fig. 15E–F). The occurrence of single-keeled representatives of the Rotaliporinae is indicative of the late Albian–Cenomanian age. In the matrix, voids rimmed with short-bladed fibrous calcite occur. They might have originated via desiccation and shrinkage of some colloid filling (Fig. 15G).

The second occurrence was found at a road along the railway between Dlhá nad Oravou and Krivá in the territory of Orava about 430 m south of the mouth of the Dlžniansky Cickov creek (N 49°16′24.7″, E 19°27′32.9″). It is a clast-supported breccia, with a black-shale matrix (Fig. 16A,B).

The clasts, although displaying some macroscopical variability (gray micritic, sometimes grainy, locally spotted limestones and silicites) consist of a limited set of microfacies. The most common is wackestone to packstone microfacies of frequent smaller globular chambered trochospiral morphotypes of planktonic foraminifera, radiolarians, and sponge spicules (Fig. 16C). Locally, the foraminifers prevailed (Fig. 16D). Such an assemblage of planktonic foraminifera resembles the assemblages with *Microhedbergella* and *Ticinella* reported from the early Albian (Huber and Leckie, 2011). The rock also contains agglutinated benthic foraminifers, the foraminifers *Lenticulina* sp., and fragments of thin-shelled bivalves. The prevailing few-chambered planktonic foraminifers (hedbergellids) and a lack of keeled foraminifers infers that the majority of the clasts were derived from rocks not younger than the early Albian. The primary source of the clasts is thus just a lower part of the Tissalo Formation, which was also termed earlier as "*Globigerina*-radiolarian" beds (Birkenmajer, 1957; Scheibner, 1958).

The shaly breccia matrix contains similar microfacies, however, free of radiolarians (Fig. 16B). The breccia matrix is particularly rich in planktonic foraminifera of moderate preservation (Fig. 17, Table 3). The extracted assemblage contained Cenomanian species, such as *Rotalipora* cf. *montsalvensis* (Mornod), *Thalmanninella reicheli* (Rat), *T. globotruncanoides* (Sigal), *T.* cf. *greenhornensis* (Morrow), *Praeglobotruncana gibba* (Klaus) and *P.* cf. *inermis* Hasegawa. The accompanying assemblage consists of *Thalmanninella brotzeni* Sigal, *Parathalmanninella* cf. *appenninica* (Renz), *Praeglobotruncana stephani* (Gandolfi), *P. delrioensis* (Gandolfi) and smaller globular chambered taxa, such as *Muricohedbergella* spp. and *Macroglobigerinelloides* sp. Ranges of all the identified species overlap in the Cenomanian, while the youngest identified species is indicative of the middle Cenomanian R. reicheli taxon range Biozone (Robazsynski and Caron, 1995; Caron and Spezzaferri, 2006; González-Donoso et al., 2007; Coccioni and Premoli Silva, 2015).

5. Interpretations and discussion

The previous chapters summarize all the important data which enable the reconstruction of events that happened in the course of the Hauterivian to Cenomanian in the Oravic domain (see Fig. 18). Herein, we will present these events in the light of new data and provide interpretation of their causes and triggering mechanisms that controlled the entire process.

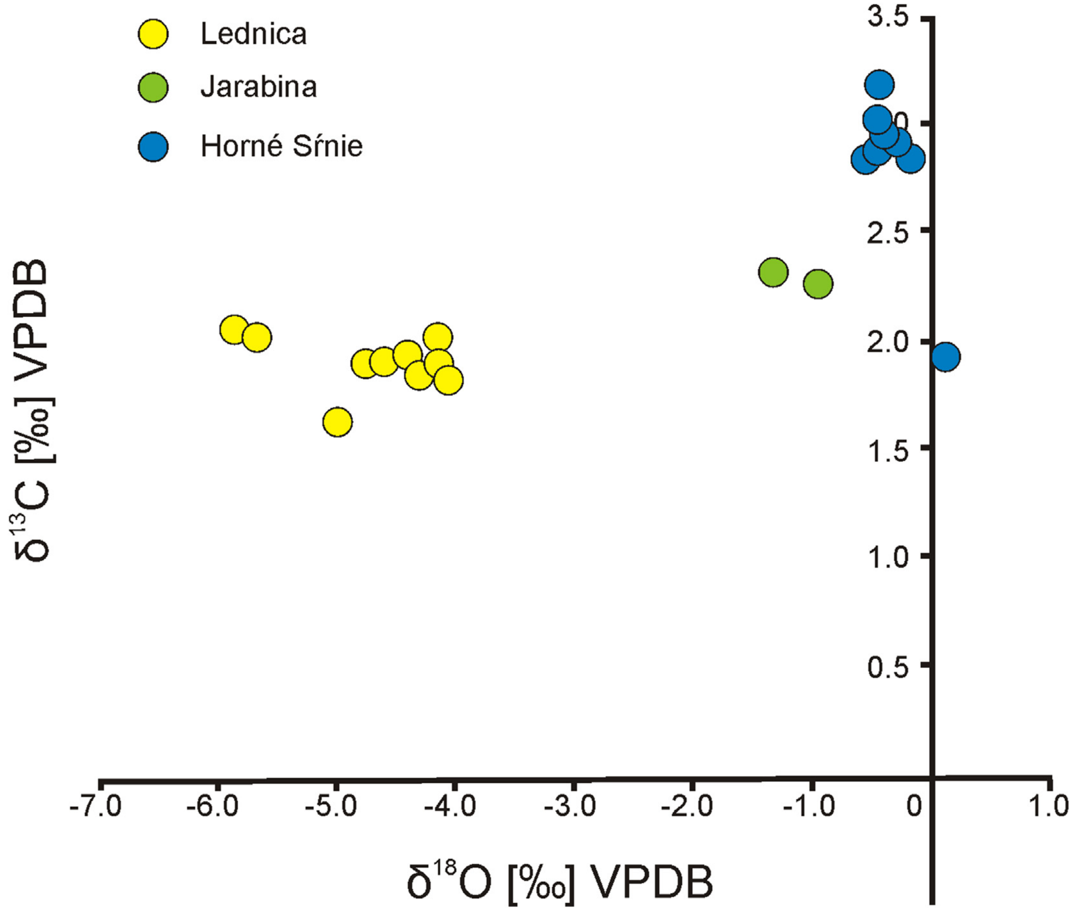

Fig. 11. Crossplot of the carbon and oxygen isotope values ($\delta^{18}O$ vs. $\delta^{13}C$) of the pre-Albian veinlets from the Czorsztyn Unit.

Table 2
Oxygen and carbon isotope data of individual components of the pre-Albian calcite veinlets from the Czorsztyn Unit (Horné Sŕnie, Jarabinand Lednica localities).

Sample	Description	$\delta^{13}C$ ‰ PDB	$\delta^{18}O$ ‰ PDB
Horné Sŕnie-a1	Calcite veinlet in the crinoidal limestone	2.86	−0.19
Horné Sŕnie-a3	The same veinlet – second phase – RFC	2.90	−0.43
Horné Sŕnie-a4	Initial stromatolitic veinlet filling	2.85	−0.52
Horné Sŕnie-a5	The same veinlet – second phase – RFC	2.91	−0.28
Horné Sŕnie-a6	Small neptunian dyke – pale mudstone	1.92	0.11
Horné Sŕnie-a7	RFC veinlet filling	3.17	−0.46
Horné Sŕnie-a8	RFC veinlet filling	2.98	−0.41
Horné Sŕnie-a9	RFC veinlet filling	3.03	−0.46
Jarabina 1	Pre-Albian blocky calcite veinlet	2.31	−1.32
Jarabina 2	Pre-Albian blocky calcite veinlet	2.28	−0.94
Lednica 1	Pre-Albian blocky calcite veinlet	1.91	−4.72
Lednica 2	Pre-Albian blocky calcite veinlet	1.83	−4.06
Lednica 3	Pre-Albian blocky calcite veinlet	1.63	−5.00
Lednica 4	Veinlet cutting the Late Aptian limestone	2.07	−5.83
Lednica 5	Pre-Albian blocky calcite veinlet	2.03	−5.69
Lednica 6	Pre-Albian blocky calcite veinlet	1.94	−4.40
Lednica 7	Pre-Albian blocky calcite veinlet	1.89	−4.14
Lednica 8	Pre-Albian blocky calcite veinlet	1.87	−4.29
Lednica 9	Pre-Albian blocky calcite veinlet	2.01	−4.14
Lednica 10	Pre-Albian blocky calcite veinlet	1.92	−4.59

5.1. What does the new data indicate from the paleokarst developed on the emerged parts?

5.1.1. Structural measurements in the paleokarst

The latest structural measurements on the paleokarstic features showed that the emersion of the Czorsztyn Ridge was connected with, or even caused by basement tilting. The measurements, no matter how statistically representative, show a relatively consistent deviation of most of the rain grooves of about 20° from normal to the last bedding planes. However, some data, which considerably deviate from this value being much steeper, indicate that the tilting was not uniform all over the ridge. This result is logical as even a minimum tilting of about 20° would have caused elevation of more than 100 m per 1 km of distance. Taking into consideration that in

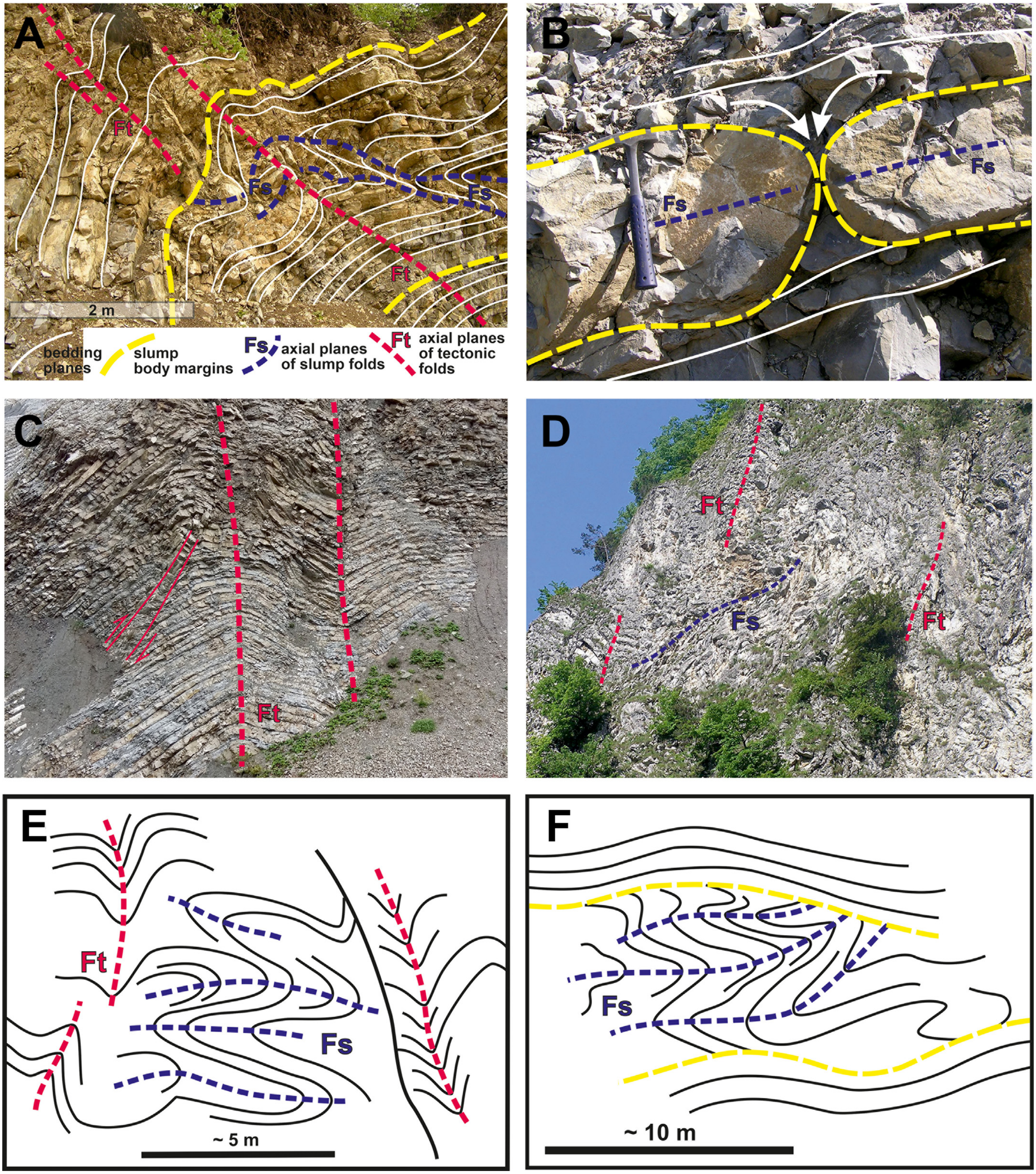

Fig. 12. Examples of slump structures developed in the Lower Cretaceous Pieniny Formation. (A) Slump body embedded in well-bedded strata affected only by the late tectonic folds. Note refolded axial planes of slump folds in the middle part of the picture and similar-type tight folds to the right. Pieniny Unit, quarry Lopušné Pažite in the Kysuca region. (B) Two opposite-facing slump fold hinges in a layer of allodapic limestone with fold axes likely parallel to the slump direction. The triangular void below the interfacing slumps was filled with a limy mud expelled from the overlying bed (white arrows). Pieniny Unit?, Lutiška saddle in the Kysuce region. (C) The most common appearance of the little disturbed Pieniny Formation affected only by the post-lithification upright parallel or chevron buckle folds and kink bands. Quarry Snežnica, Kysuce region. (D) Complicated fold trails on the steep cliff walls caused by interference of slump and superimposed tectonic folds. The Dunajec River Gorge, Pieniny Mountains. (E, F) Line drawings of slump and tectonic folds which can be partly followed from a distance on not accessible steep cliffs in the Dunajec Gorge, lower part of the Lesnica side valley. Note the isolated slump body with eroded upper surface in (F).

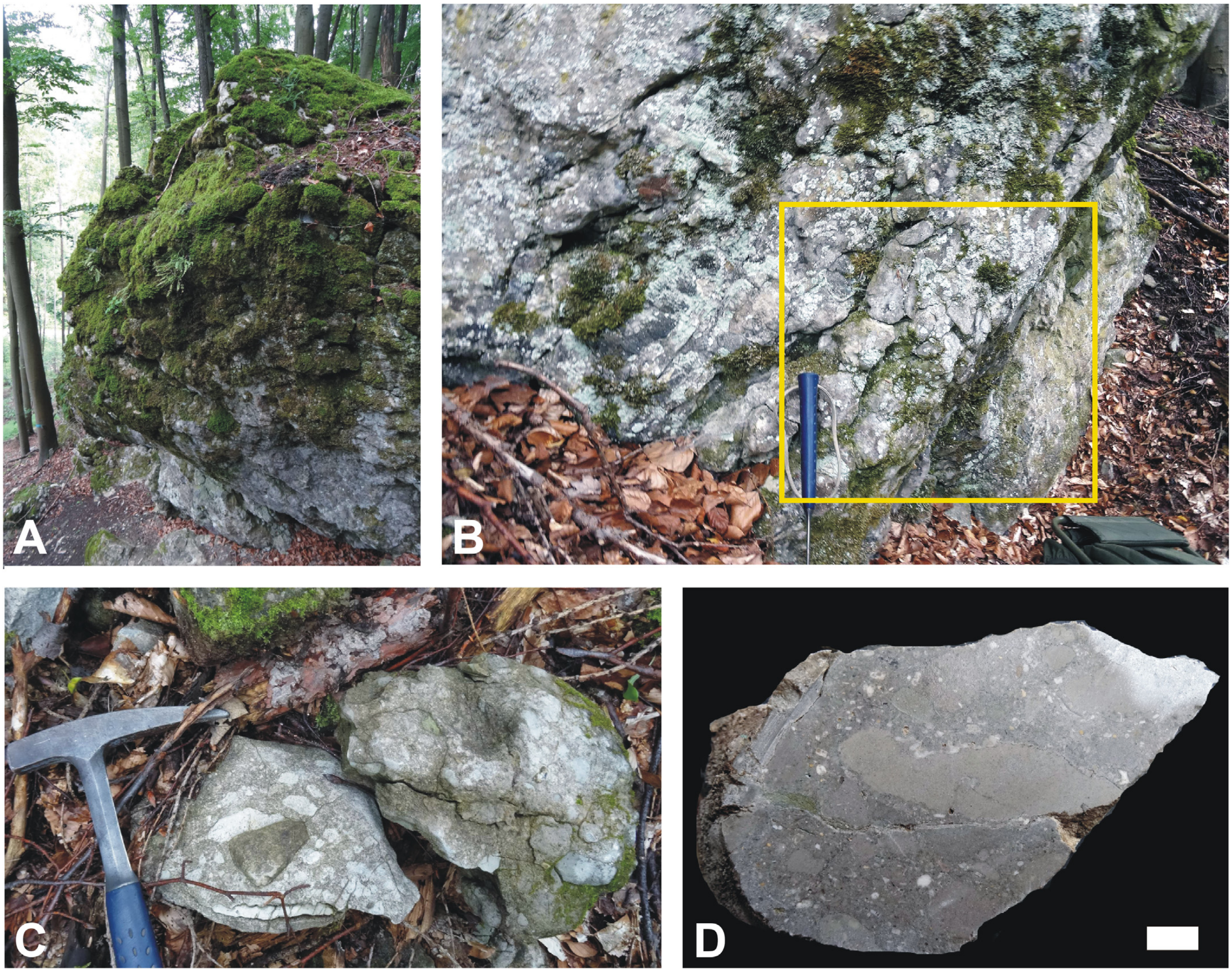

Fig. 13. (A) Block (olistolite) of the Tvrdošín Breccia in the Albian exotic conglomerates in the Krivoklát Valley. (B–C) Breccia consists of limestone and silicite clasts. The yellow rectangle in b marks the sampling place of the breccia. (D) Slab documenting matrix supported structure of the breccia. The matrix is represented by Urgonian-type limestone. Scale bar = 1 cm. Sample KrD1. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

the Vršatec Klippen, which belong to the largest klippen of the Czorsztyn Unit, the true thickness of the Bajocian to Valanginian limestones is only about 500 m, the whole-block tilting would cause exposure of the entire sedimentary succession as deep as the crystalline basement. This scenario would lead to much more severe erosion and much deeper karstification than recorded. In these circumstances the most condensed parts of the Czorsztyn Unit deposits, which are locally only a few meters thick (see e.g., Aubrecht et al., 2017), would not be preserved at all. Therefore, the tilting of smaller blocks might have occurred, instead of affecting the entire crustal segment as a single monolith. On the other hand, this block-by-block tilting had to be spread all over the Oravic segment, as evidenced by the simultaneous slump structures and resedimentation on the opposite side at the Kysuca Basin margin. It most likely took place via reactivation of older faults from the previous extensional phases (Fig. 18).

5.1.2. Oxygen and carbon isotope data

Oxygen and carbon isotope analyses of the pre-Albian calcite veinlets below the karstic surface, indicate that they are not of a clear fresh-water origin. The deposits may be related to submarine cementation of open karst crevasses or, which is less likely, to specific precipitation conditions occurring in a vadose environment. The submarine formation of the veinlets may be supported by the lack of any features of vadose-zone cementation, such as asymmetric cement growth, microstalactites, etc. The veinlets from the Horné Sŕnie locality show bizarre shape that obviously originate from dissolution, yet they are filled with obviously marine radiaxial fibrous calcite. Since the Early Cretaceous erosion at this locality is the deepest in the Czorsztyn Unit, it is uncertain whether these veinlets originated during the studied phase of emersion, or they represent relics of the previous emersion (e.g., during the Bajocian, see Aubrecht, 1997; Aubrecht and Szulc, 2006). The veinlets from Jarabin and Lednica are straight and filled with blocky calcite. However, their isotopic pattern is different. The oxygen and carbon isotope compositions of cements from the Jarabina locality are similar to marine carbonates, whereas oxygen isotope composition of the samples from Lednica is shifted towards more negative $\delta^{18}O$ values. This might have been caused either by thermal overprint or, alternatively, by freshwater influx. The negtive oxygen

Table 3
Distribution of foraminiferal species from the Tvrdošín Breccia (Krivoklát Valley) and from the breccia between Dlhá nad Oravou and Krivá. 2-22. Samples from thin sections. M. Washed sample of the breccia matrix. A.f. Agglutinated foraminifera. C.b.f. Calcareous benthic foraminifera. L. m.-ch. – larger many-chambered.

Foraminifera		Samples																
		Krivoklát Valley										Krivá – D.n. Oravou						
		2	3	9a	9b	10	11	16b	17	19	21	11b	14	15	16	17b	22	M
Benthic foraminifera	*N. producta*	x				x												
	V. scarsellai		x															
	N. cf. *bronnimanni*				x													
	M. cf. *valserinensis*								x									
	orbitolinoids	x	x	x	x	x	x	x	x	x								
	smaller a.f	x	x	x		x	x	x	x	x	x	x	x				x	
	Cornuspira sp						x											
	Quinqueloculina sp						x	x	x									
	smaller c.b.f						x	x										
Planktonic foraminifera	*Globigerinelloides* sp. (larger)			x														x
	Macroglobigerinelloides sp											x	x	x	x	x	x	
	Microhedbergella/Ticinella spp																	x
	Muricohedbergella spp.																	x
	P. delrioensis																	x
	p. stephani																	x
	P. gibba																	x
	P. cf. inermis																	x
	Pa. appenninica																	x
	Th. globotruncanoides																	x
	Th. reicheli																	x
	Th. brotzeni																	x
	Th. cf. greenhornensis																	x
	R. montsalvensis																	x

isotope shifts of karst deposits should, however, be normally accompanied by low δ^{13}C values owing to organic carbon input from the pedogenic processes. Nevertheless, no comparative Mesozoic and older speleothem isotope data are available so far, so the possibility of original fresh-water cementation of Lednica samples remains an open question.

5.2. What does the resedimentation indicate in the submerged parts of the Oravicum?

5.2.1. Slumps in the Maiolica-type limestones

Resedimentation at the marginal parts of the Kysuca–Pieniny Basin most likely resulted from the same tilting which affected the Czorsztyn and "transitional" units of the Oravicum. Slumping process in the Maiolica-type limestones had probably started earlier than Hauterivian, as indicated by common slump structures embedded between undeformed beds. Slump folds and other soft-sediment deformation structures usually develop in tectonically active regions like trench depressions and growing accretionary wedges in contractional, or tilted halfgrabens in extensional regimes. Nevertheless, they may occur in any setting within sedimentary basins, where the bottom topography and uneven sediment accumulation and compaction associated with an increase in pore pressure of trapped fluids generates gravitational instabilities that are potentially balanced by downslope movements. The movements typically influence the youngest, unstable, well-bedded strata that are detached from underlying, partly lithified sediments. The seismic shocks are likely, although not necessarily the main triggering agents (Helwig, 1970; Owen et al., 2011; Alsop and Marco, 2013).

Intraformational soft-sediment slump fold structures in the investigated pelagic limestones of the Pieniny Formation were obviously formed long before the compression-related tectonic movements that are dated by the first pre-to syn-orogenic flysch-type clastics of the Cenomanian–Turonian Snežnica Formation (Fig. 3). On the other hand, they seem to be closely related to extensional processes and enhanced basin bottom topography connected with the renewed activity of the normal faults flanking the elevated Czorsztyn Ridge in mid-Cretaceous times (Fig. 18). Extensional tectonic processes and slumping were possibly accompanied also by seismic events that initiated compensation of gravitational instabilities by downslope mass gliding of unstable, poorly-lithified, sedimentary packets. Since slumping masses in the Pieniny Formation seem to largely retain internal coherence, we infer that slumping was rather slow and not catastrophic. Most probably creeping at the slump sole and passive folding of the slump mass were the governing deformation mechanisms that controlled the initiation, translation, and cessation of slumping events. On the other hand, the later Hauterivian slumps in the Pieniny Formation found at Istebné, directly underlying Barremian–Aptian black shales of the Koňhora Formation, were accompanied by first breccias, whose sedimentation continued in the form of the Tvrdošín Breccia at the base of the Urgonian-type limestones (Nižná Formation).

5.2.2. New occurrence of the Tvrdošín breccia and its relationship with exotic conglomerates

The Tvrdošín Breccia exhibits clasts of the Maiolica-type limestones, *Saccocoma* limestones, and radiolarites, which indicate erosion extending down the Callovian–Oxfordian strata. Its newly-found occurrence in the Krivoklát Valley is lithologically identical with the previously reported occurrences in the Orava territory (Józsa and Aubrecht, 2008); however, it differs in its position as a block in exotic conglomerates.

The problem of the exotic conglomerates is very complex and is one of the longest time-persisting problems in the geology of the Western Carpathians. Therefore, it deserves a short introduction. These exotic conglomerates have appeared since the Albian (Upohlav Formation) and their sedimentation continued into the Coniacian–Santonian (Sromowce Formation) in an almost unchanged regime (Marschalko, 1986). The conglomerates contain near-pure exotic material, whose origin is unknown, e.g., Neotethys-like ophiolites and sedimentary rocks which are typical for the southernmost zones of the Carpathians, Eastern Alps, and

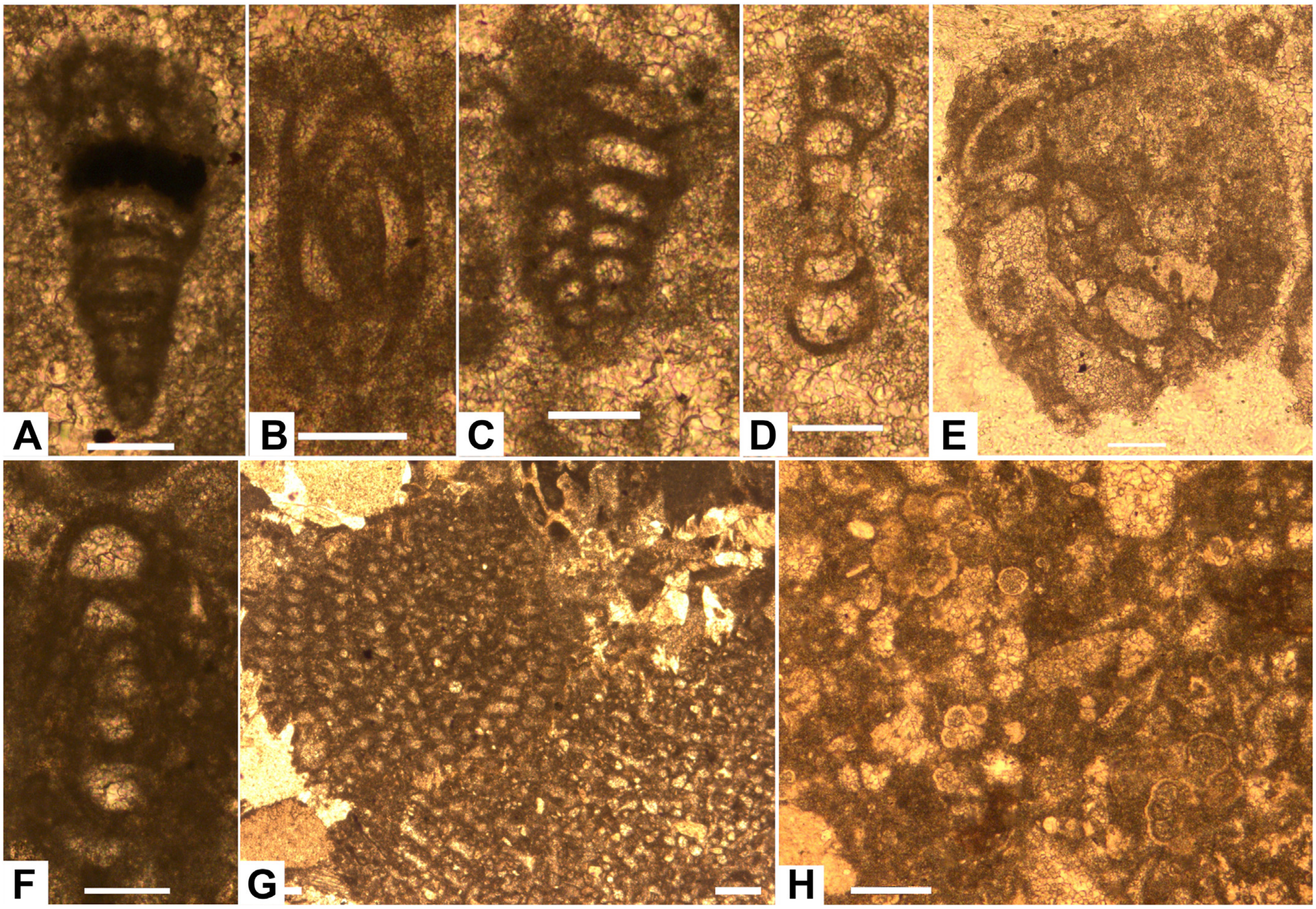

Fig. 14. Foraminifera from the organodetritic limestone matrix (Urgonian-type) of the Tvrdošín Breccia from Krivoklát Valley. (A) *Vercorsella scarsellai* (De Castro), sample KrD3. (B) *Quinqueloculina* sp., sample KrD9. (C) *Novalesia producta* (Magniez), sample 16vz2. (D) *Cornuspira* sp., sample KrD11vz4. (E) *Melathrokerion* cf. *valserinensis* Brönnimann & Conrad, sample KrD17vz1. (F) *Nautiloculina* cf. *bronnimanni* Arnaud-Vanneau & Peybernés, sample KrD9. (G) Organodetritic microfacies containing fragments of larger orbitolinoid foraminifera, sample KrD16b. (H) Fine grained variety of organodetritic limestone with larger many-chambered *Globigerinelloides* spp., sample KrD9a. Scale bars A–B, D–F. 100 μm, C, G–H. 200 μm.

for Dinarides (e.g., Krivý, 1969, Kamenický et al., 1974, Kamenický and Kráľ, 1979, Mišík and Sýkora, 1981; Šímová, 1982, 1985a,b,c; Šímová and Šamajová, 1982; Birkenmajer et al., 1990; Mišík and Marschalko, 1988; Uher and Marschalko, 1993; Dal Piaz et al., 1995; Ivan et al., 2006; Zaťko and Sýkora, 2006). Pebbles derived from the neighboring West Carpathian internides or Oravic units are almost completely absent. The clastics derived from the Oravic units described in this study are, in fact, the last which clearly contain Oravic-derived material until their re-appearance in the syn-collisional Maastrichtian–Paleocene Jarmuta-Proč Formation, which accompanies the first known collisional event of in the Pieniny Klippen Belt (Birkenmajer, 1956, 1977; Marschalko et al., 1979; Jablonský and Halásová, 1994). Therefore, the Tvrdošín Breccia, which is known from the Oravic unit and rests as an olistolith inside the exotic conglomerate complex, is atypical. There is a flysch with exotic material that used to be attributed to the Nižná Unit (Scheibner, 1967), but its precise age and relationship to this unit is uncertain (Aubrecht et al., 2021). According to Scheibner (1967), deposition of the flysch started in the Albian–Cenomanian, but later, some authors (Gross et al., 1993; Starek et al., 2010) attributed it to the Sromowce Formation of the Coniacian–Santonian age. The age of the exotics is of key importance for the paleogeographic and paleotectonic reconstructions. The exotic material, in the form of sand-fraction chrome-spinels derived from exotic ophiolites, appears in the internides already in the Hauterivian (Jablonský, 1992; Jablonský et al., 2001). Later, it continues during the Albian, not only in the internides, but also in the Klape Unit of unknown original position. It must have represented the closest area to the exotic source because its deposits are dominated by conglomerates with pebbles sometimes reaching meter size. In the Oravic realm, the exotic deposition was considered to start later. However, description of the Albian Trawne Member in the Kysuca (Branisko) succession (Birkenmajer, 1987) containing chrome-spinels (Winkler and Ślączka, 1994) and the discovery of a chrome-spinel detritus in the Czorsztyn Unit in the sedimentary rocks directly overlying the pre-Albian paleokarst (Aubrecht et al., 2009) indicated that the Oravic domain was already within the transport range of the exotic ophiolitic material at that time, although only of psammitic size. Conglomerates appear in the Oravic realm (Kysuca Basin) as late as the Coniacian–Santonian (Sromowce Formation). The block in the Krivoklát Valley rests within the exotic conglomerates of this age. It is one of the rare examples when clasts or even olistoliths of the Oravic units occur within the exotic conglomerates. The pebble lithologies like the Middle Jurassic crinoidal limestones, Ammonitico Rosso-type limestones, Callovian–Oxfordian radiolarites, and Maiolica-type limestones, which are specific of the Oravic units, are also widespread in other paleogeographic units. Therefore, their

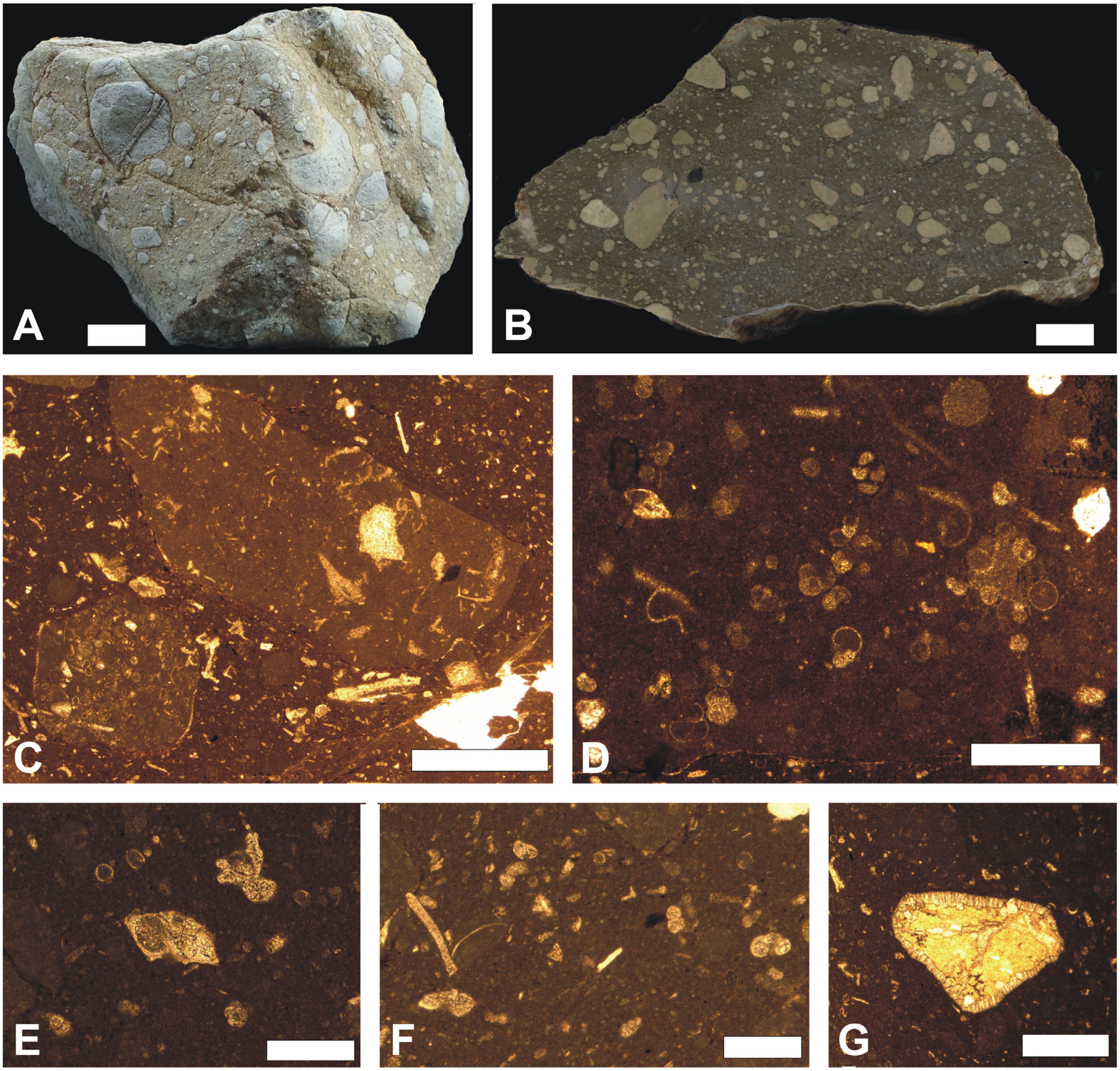

Fig. 15. (A) Weathered surface of the Upper Albian–Cenomanian breccia block found in the Racibor Valley. Scale bar = 2 cm. Archive name of the sample RD. (B) Slab of the breccia documenting its matrix-supported structure. Scale bar = 2 cm. (C) Clasts of the limestones with calpionellid-radiolarian microfacies (left) and with *Saccoccoma* microfacies (right). Scale bar = 0.5 mm. Thin section 20584. (D) Clast with *Globuligerina* microfacies. Scale bar = 0.5 mm. Thin section 20584. (E) A single-keeled planktonic foraminifera belonging to Rotaliporinae gen. et spec. indet. Note the reworked calpionellids in the upper left part of the picture. Scale bar = 0.2 mm. Thin section 20584. (F) Single-keeled and globular chambered planktonic foraminifera. Scale bar = 0.2 mm. Thin section 20585. (G) A void rimmed with short-bladed fibrous calcite. Scale bar = 0.5 mm. Thin section 20585.

derivation from the Oravic realm cannot be proved. Hence, this olistolith of specific breccia is the first confirmed Oravic material in the exotics.

5.2.3. Other possible effects of the Mid-Cretaceous erosion and slumping

Erosion and slumping might have potentially influenced further evolution of the Oravic units. Due to a relatively thin, post-Aalenian sedimentary cover in some parts of the Czorsztyn Unit (e.g., Stankowa skała – Sidorczuk, 2005, Sidorczuk and Nejbert, 2008; Velyky Kamenets 2 – Aubrecht et al., 2017), the mid-Cretaceous erosion could have reached and uncovered the Aalenian black shales (Skrzypny Formation). The same is theoretically possible for the basinal Kysuca–Pieniny and Grajcarek (Šariš) units where similar shales and black flysch (Harcygrund Formation, Szlachtowa Formation) could have been unroofed by slumps. Recently, many examples of close contact and mixing of Aalenian black shales with Albian and younger black or red shales have been revealed (Plašienka et al., 2021; Molčan-Matejová and Gedl, 2022) without involvement of the Bajocian–Hauterivian lithostratigraphic units.

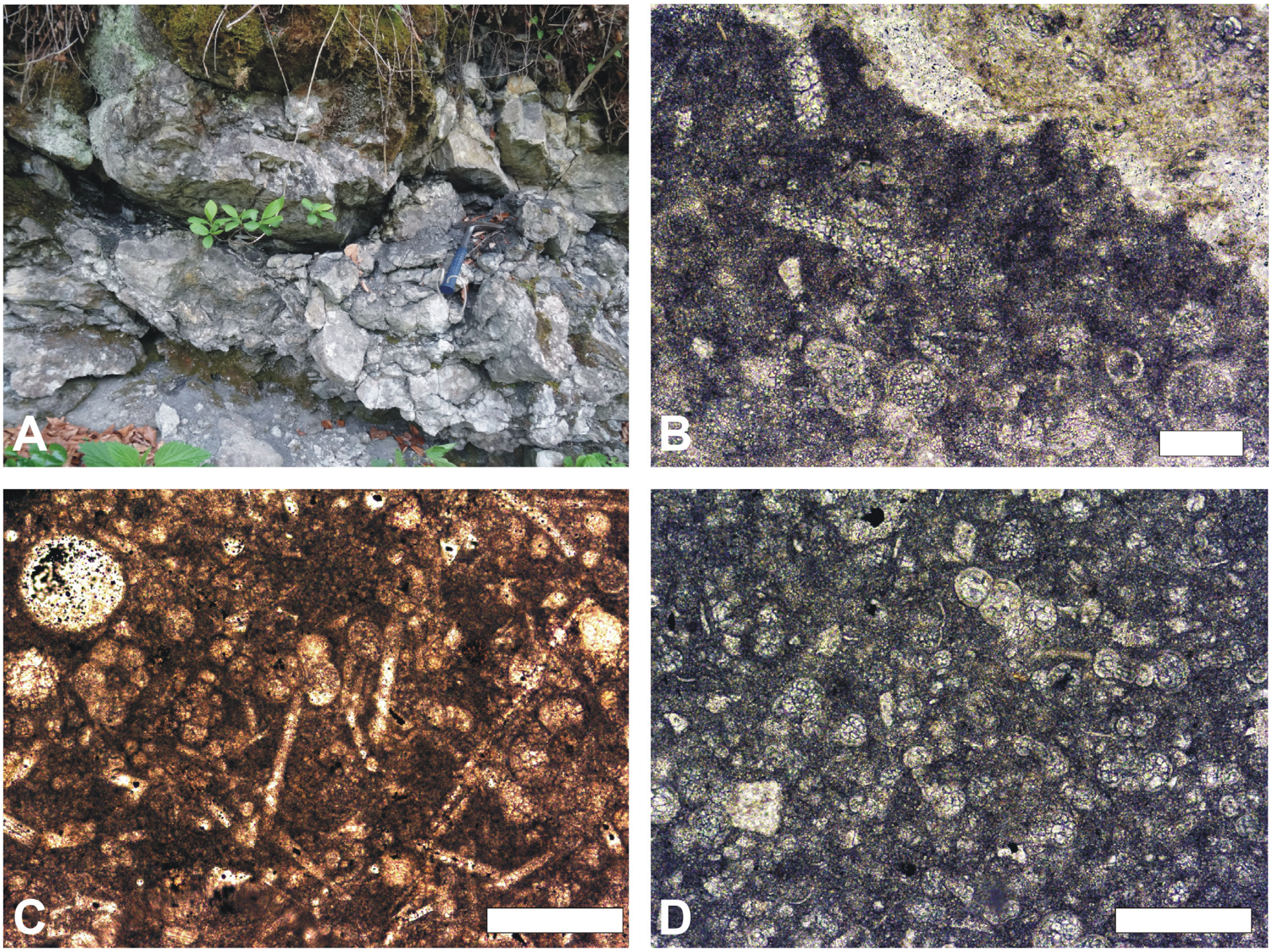

Fig. 16. Cenomanian oligomictic clast-supported breccia with black-shale matrix between Dlhá nad Oravou and Krivá. (A) Field photo of the breccia outcrop. Hammer marks the sampling place. (B) Thin-section showing contact between silicitic clast (pale) and black-shale matrix (dark). Scale bar = 0.1 mm. Thin section KD11. (C) Clast of packstone with radiolarians, sponge spicules and planktonic foraminifers. Scale bar = 0.2 mm. Thin section KD17. (D) Clast of packstone with planktonic foraminifers. Scale bar = 0.2 mm. Thin section KD22.

The mid-Cretaceous events discussed in this study may thus elucidate a long-lasting problem of stratigraphic attribution of black flysch (Szlachtowa Formation) in the Pieniny Klippen Belt, which produces controversial views from various authors. One group of authors prefers its Jurassic age (Birkenmajer, 1977; Krawczyk et al., 1992; Birkenmajer and Gedl, 2007, 2017; Birkenmajer et al., 2008; Barski et al., 2012) based on ammonites and dinocysts, whereas another group of authors points to Cretaceous microfaunal elements found in the black shales (Oszczypko et al., 2004, 2008). These contradicting opinions often concern the same localities, or at least localities from the vicinity close by.

5.3. Comparison with some coeval events in other parts of the Tethys (tectonics vs. eustasy)

The Cretaceous was the time with considerable extension of paleokarst all over the Tethys. On the main land, mostly large-scale depressions (sinkholes, dolines) were formed, often filled with bauxites (D'Argenio and Mindszenty, 1991, 1995 and the references therein). The Cretaceous paleokarst hosts the largest bauxite deposits in the world (Bárdossy, 1982). On isolated island chains, non-bauxitic karst often developed. The most similar paleokarst to that described in this paper is present in the Betic Cordillera, Spain (Martín-Algarra and Vera, 1995, 1996). It displays polyphase karst phenomena formed during the Jurassic and Cretaceous (Molina et al., 1999). The main Cretaceous karstification phase from the Hauterivian to the Albian is coeval, with that in the Oravic domain. Moreover, similarly to the paleokarst discussed in this paper, it is a relatively small-scale paleokarst devoid of bauxites or other terrestric filling, for instance, lithified paleosoils (e.g., caliche), etc. (Esteban and Klappa, 1983). Moreover, the paleokarst is capped by hemipelagic to pelagic red beds (Marín-Algarra and Vera, 1996), with phosphatic stromatolites and oncoids on the base (Marín-Algarra and Vera, 1994). According to the authors, the Betic Cordillera represented an isolated pelagic swell in these times. Therefore, this paleokarst indicates a similar process of emersion and rapid drowning as in the Oravicum, and the authors mostly related these phenomena to a coincidence between tectonics and eustasy (Martín Algarra and Vera, 1996).

Barremian-Aptian ridges, which had emerged and then suddenly drowned in the Albian, also occurred in the West Carpathians internides. However, none of them underwent such a long period of

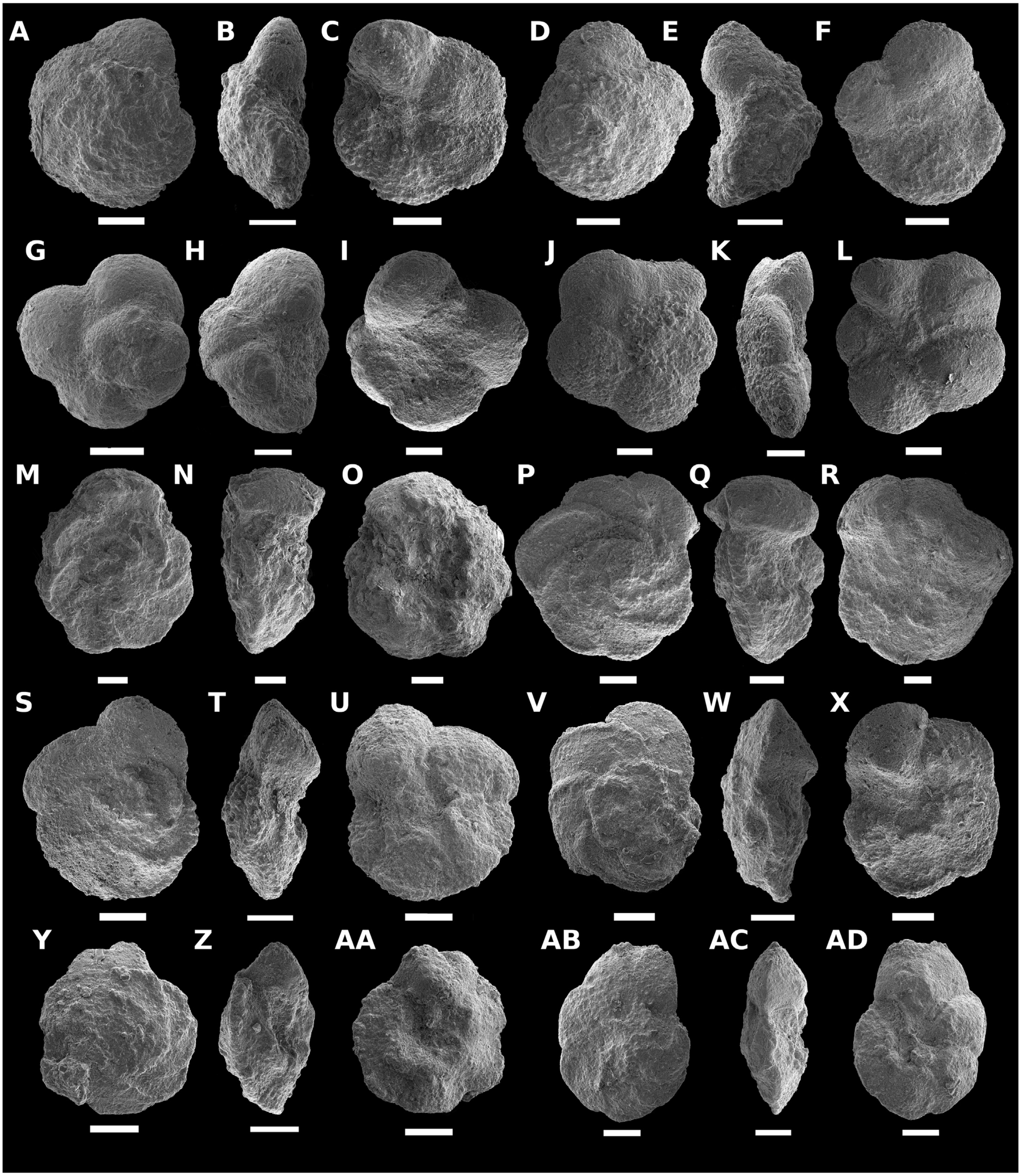

Fig. 17. Planktonic foraminifera from the black-shale matrix of the breccia found between Dlhá nad Oravou and Krivá. (A–C) *Praeglobotruncana stephani* (Gandolfi). (D–F) *Praeglobotruncana gibba* (Klaus). (G–I) *Praeglobotruncana* cf. *inermis* Hasegawa. (J–L) *Rotalipora* cf. *montsalvensis* (Mornod). (M–R) *Thalmanninella reicheli* (Rat). (S–U) *Thalmanninella brotzeni* Sigal. (V–X) *Thalmanninella globotruncanoides* (Sigal). (Y–AA) *Thalmanninella* cf. *greenhornensis* (Morrow). (AB–AD) *Parathalmanninella* cf. *appenninica* (Renz). A, D, G, J, M, P, S, V, Y, AB – dorsal views. B, E, H, K, N, Q, T, W, Z, AC – peripheral views. C, F, I, L, O, R, U, X, AA, AD – umbilical views. Scale bars 100 μm. Archive number of the sample: JSC01 T23.

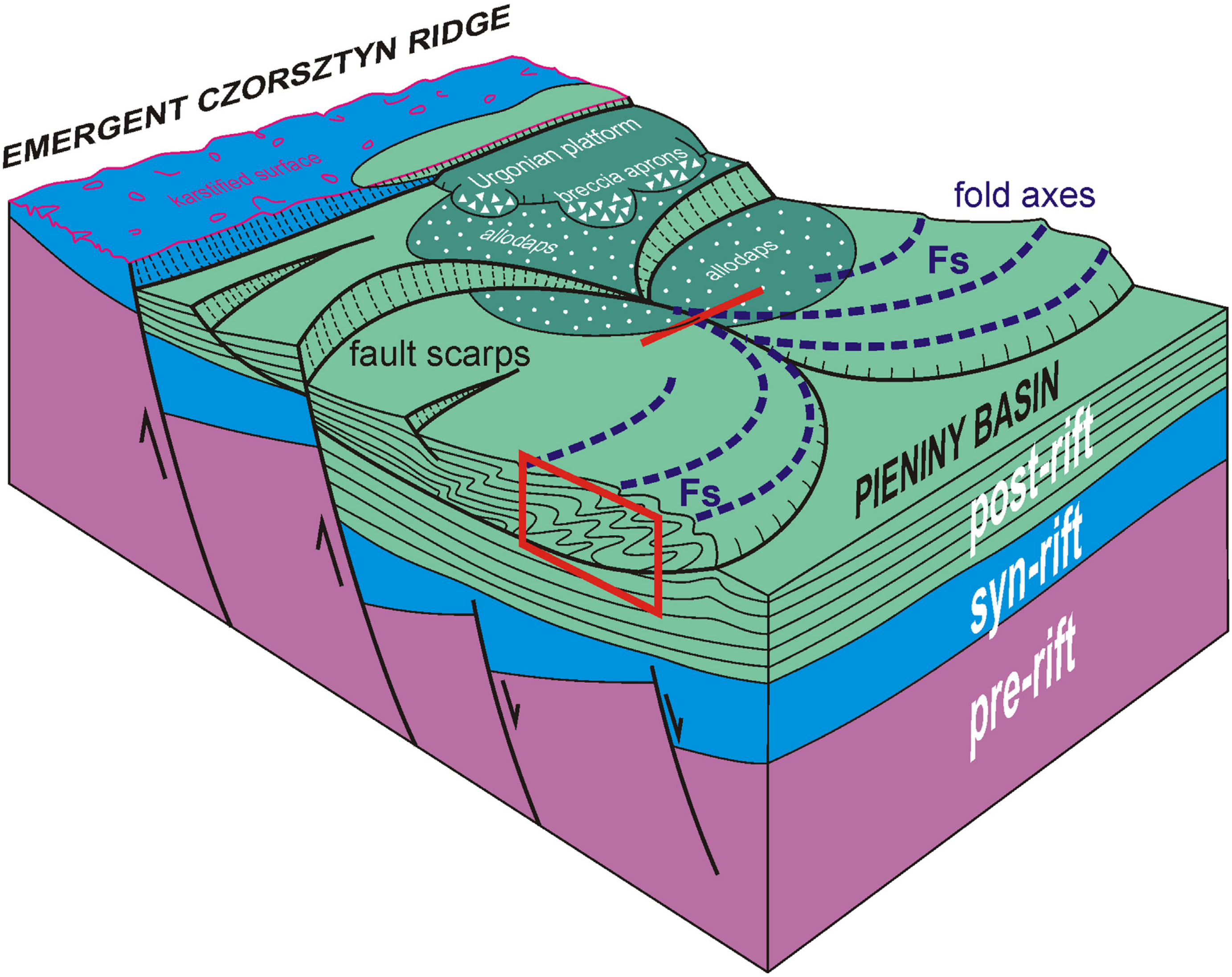

Fig. 18. Synthesizing model of the phenomena generated by the mid-Cretaceous uplift of the Czorsztyn Ridge. Note that the Cretaceous normal faults possibly reactivated mid-Jurassic syn-rift normal faults. The red line indicates the inferred position of the cross-section of slump structure depicted in Fig. 12B; the red rectangle frames complex fold structures at the slump toe exemplified by Fig. 12A, D, E and F. Detachment of slump bodies was accommodated by normal faulting at the slump heads. Pre-, syn- and post-rift deposits refer to the main Middle Jurassic rifting phase. Not to scale. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

emersion. The ridges were mostly characterized by shallow-marine, Urgonian-type carbonate platform sedimentation, with subsequent rapid drowning in the Albian. Their examples can be seen in various units of the internides. In the Fatric units (Krížna Nappe), the Urgonian-type sedimentation occurred mostly in the partial nappes of Havran (Belianske Tatry Mts.) and Belá (Strážovské Vrchy Mts.). In the Havran partial nappe, the deposition of shallow-water Urgonian-type limestones (Muráň Lst.) began as early as the early Hauterivian (Michalík and Soták, 1990; Gedl et al., 2007) and ended by drowning in the early Aptian with subsequent pelagic marly sedimentation (Muránska Lúka Formation). In the Belá partial nappe (Borza, 1980; Maheľ, 1985), the Urgonian-type limestones are of Aptian age and they are covered by lower Albian pelagic cherty limestones, and then later by upper Albian shales.

In the Tatric units, the Urgonian-type limestones are covered by the Zabijak Marl Formation, whose sedimentation started in late early Albian (Lefeld et al., 1985; Masse and Uchman, 1997). The Manín Unit of unknown provenance, which is presently included in the Fatric units, displays carbonate platform demise, drowning, and covering by pelagic Butkov Marls of late the Albian age (Michalík and Soták, 1990; Fekete et al., 2017). The age of the capping of pelagic deposits marks the latest possible drowning event. Although there might have been some previous events of submergence as well, they are difficult to discern in carbonate platform limestones. Similarly, it is difficult to calculate the eventual non-deposition period after drowning.

All these successions display rapid drowning without any transitional facies or basal clastics. The majority of the drowning episodes, except of the Havran Nappe, were more or less coeval with the Oravic drowning. On the other hand, all these drowning events coincided with the largest global Phanerozoic transgression, which occurred in the Albian–Cenomanian (see the latest synthesis of Cretaceous eustasy adapted to the latest chronostratigraphic chart by Haq, 2014). In the long-term eustatic curve, it is visible that there was a highstand approximately at the Hauterivian/Barremian, followed by a continuous sea-level drop with a lowstand in the late Aptian. The rest of the Aptian and all the Albian is a time of repeated sea-level rise of about 100 m in global scale. There was a small culmination of the sea-level at the Albian/Cenomanian transition and finally the main culmination in the late Cenomanian.

Although it is obvious that the global eustasy might have contributed to the Oravic drowning in the Albian, such a rapid collapse cannot be explained exclusively in this way. The erosional surface on the Czorsztyn Swell is capped by Púchov Marls, which are the first described red marls (Stur, 1860). In Poland, this formation is named the Jaworki Marl Formation by Birkenmajer (1977). Cretaceous red beds were deposited in various depths and include non-calcareous red clay sedimented on deep-oceanic plains to hemipelagic Globotruncana marls (Couches Rouges, Scaglia Rossa, Capas Rojas) deposited on shelves (Hu et al., 2005). These facies occur in the Oravic units as well. Deep sea, non-calcareous red clays of the Malinowa Formation occur mostly in the Grajcarek (Šariš) Unit (Birkenmajer, 1977; Birkenmajer and Gedl, 2017), whereas more marly facies called the Púchov Marls in Slovakia, or Jaworki Formation in Poland, occur in all other units. In the Czorsztyn Unit, the shallowest types of these red marls occur (Pustelnia Marls Member of the Jaworki Formation). Despite being calcareous, their deposition probably took place in bathyal depths, as evidenced by foraminiferal assemblages and the presence of *Zoophycos* ichnofossils formed mostly in the Campanian (Bąk, 1995a; Bąk in; Hu et al., 2005; Plašienka et al., 2021). This is also supported by radiolarite beds known from the Cenomanian and Turonian (Bąk, 1995b; Sýkora et al., 1997; Smrečková, 2011). The denivelation during the drowning is thus over 1 km, much less than the estimated denivelation in the global sea-level curve of ca. 100 m (Haq, 2014). This indicates that tectonics might have played a substantial and dominant role in the Oravic drowning, as well as in the drowning of the Urgonian-type platforms in the internides, since they preceded the main orogenic nappe thrusting in this domain.

5.4. Possible tectonic triggers of the mid-Cretaceous events in the Oravicum

The main problem in reconstruction of the events leading to the Oravic collapse in the Albian is the uncertain paleogeographic and paleotectonic position of the Oravicum during this time. There are numerous paleogeographic studies in which the Oravic crustal segment was placed in various positions during its evolution with no considerable consistence (e.g., Rakús et al., 1988; Dercourt et al., 1990; Michalík, 1994; Stampfli et al., 1998; Csontos and Vörös, 2004). There are even different concepts that were published by some members of our team of authors, e.g., Plašienka (2003) and Aubrecht et al. (2009). Plašienka (2003) assumed that in the Barremian–Aptian period, rifting and separation of the Oravic segment from the European mainland began with thermal subsidence after the rifting being responsible for the collapse. However, later paleomagnetic data point to a much earlier, Middle Jurassic separation from the position at about 40–45° of the northern paleolatitude, and rapid transport of the Oravic segment to low latitudes of about 25° in the Oxfordian (Lewandowski et al., 2003, 2004; Jeleńska et al., 2011). The Oxfordian lowest paleolatitudes coincide well with the closure of the more southern Meliata-Hallstatt Ocean (Kozur, 1991). Afterwards, a continuous backward movement of the Oravic segment to the north was registered, reaching about 30–33° of northern latitude (Lewandowski et al., 2003; Grabowski et al., 2008). During the Albian to Santonian, the Oravic red beds still show a mean paleomagnetic inclination of about 53°, which represents approximately 35° of the northern paleolatitude (Márton et al., 2013). There are still insufficient data for full reconstruction of the Oravic paleogeography, but it is evident that it did not collapse when it was an isolated ribbon in the ocean, but instead, it had to be in contact already with the Alpine–Carpathian internides. This is also evidenced by the presence of a new, ophiolitic detritic material in the uppermost Aptian deposits (Aubrecht et al., 2009). Such material is typical of the Carpathian internides in the Albian times (Bellová et al., 2018; Aubrecht et al., 2020).

All of the above-mentioned data and interpretations indicate that the Oravic collapse occurred due to convergence and compressional events rather than extensional. The process itself (shallowing and tilting followed by collapse) best fits with the subcrustal erosion, a process suggested by Wagreich (1995) for the Coniacian–Maastrichtian evolution of the Gosau Basin in the Eastern Alps. The process involves subduction of an elevation on the sea-floor (a continental crust stripe or, more likely, a mid-oceanic ridge) beneath the overriding plate, erosion of its bottom crustal part and subsequent crustal collapse. The same process likely affected the Carpathian internides as evidenced by the collapse of Urgonian platforms. Many of those platforms (except for the High Tatric elevation) have pelagic, Maiolica-type limestones beneath them, which indicates that a shallowing pre-dated the final collapse.

Although the paleogeographic evolution of the Oravicum is still far from final reconstruction, the data presented herein advance the knowledge and must be taken into account in further, more elaborated, new paleogeographic schemes.

6. Conclusions

The previously published and new data presented and reviewed in this paper shed more light on tectonic processes that affected the Oravic crustal segment during the Hauterivian–Albian period. They indicate that:

1. There was an uplift and tilting starting from the Hauterivian onward, which resulted in shallowing and emersion, erosion and karstification of the Czorsztyn Ridge for about 20 Ma, as well as slumping and redeposition in the Kysuca Basin, which locally lasted up to the Cenomanian. An Urgonian-type platform originated at its edge. Although the tilting affected the entire Oravicum, preservation of relatively thin pre-Albian sedimentary cover indicates that the Oravic crust was not tilted as a whole, but the tilting was compensated by a series of smaller listric faults.
2. The karstification is evident despite the isotopic data show no clear evidence of purely fresh-water speleothems.
3. Subsequent Albian collapse caused drowning of the entire Oravicum to neritic/bathyal depths with deposition of oceanic red beds, black shales, and flysches. Since that time, the Czorsztyn elevation has never been restored again.
4. A block of Urgonian-type limestone with basal Tvrdošín breccia found in the exotic flysch shows that some material in the exotics has been derived also from the Oravicum, which had not been proved before.
5. Slumping of sediments in the deeper parts of the Oravicum (Kysuca and Grajcarek basins) might have led to local unroofing of the older, Aalenian black shales, with subsequent deposition of Cretaceous black and red shales on them, which explains the frequent tectonic mixing of these two similar, but strongly diachronous facies.
6. The synthesis of all facts indicates that the Oravic segment lost at least part of its basement in Albian times. It might have occurred only when it was not an isolated ribbon fragment, but

had to be in contact with the Carpathian internides. Subcrustal erosion by a subducting mid-oceanic ridge beneath the overriding Carpathian plate is inferred as the most plausible explanation of this process. It is typically initiated by shallowing of the sedimentary area leading to deposition of shallow-marine sediments or emersion and subsequent collapse to neritic/bathyal depths. This process likely affected the Carpathian internides as well, where Urgonian-type platforms display the same evolution pattern.

Acknowledgments

The authors acknowledge the financial support from the projects APVV 21-0281, APVV 20-0079, APVV 17-0170 and VEGA 1/0435/21. The comments and corrections by Michał Krobicki (AGH Kraków), an anonymous reviewer and the CR editors considerably helped to improve the quality of the paper and are warmly acknowledged. The authors also acknowledge the language correction by M.J. Sabo.

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