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Structure and evolution of the Pieniny Klippen Belt demonstrated along a section between Jarabina and Litmanová villages in Eastern Slovakia

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Abstract

Basic features of the Pieniny Klippen Belt (PKB) structure and evolution are presented on example of a small area between Jarabina and Litmanová villages in Eastern Slovakia. T he area exhibits a rich sedimentary and structural record of the Late Cretaceous – Early Paleogene thrusting processes which generated the three main units of the PKB edifice in this region – the Šariš Unit, the Subpieniny nappe and the Pieniny nappe from bottom to top. The following essential phenomena are demonstrated at eight key localities, including field exposures and two borehole profiles: lithology and stratigraphy of the Czorsztyn-type klippen, deep-marine hemipelagic deposits and oceanic red beds of the Šariš Unit, synorogenic coarsening-upward flysch formations with bodies of tectonosedimentary breccias that register the principal thrusting events, and various structural types of superficial thrust sheets dependent on the mechanical stratigraphy and pre-thrusting morphology of the sedimentary successions involved.

Key words: Pieniny Klippen Belt, Pieniny sector, lithostratigraphy, structure, boreholes, representative localities, Western Carpathians

Introduction

The Pieniny Klippen Belt (PKB) is probably the most conspicuous structural zone of the entire Carpathian arc. Picturesque landscape and abundance of especially Jurassic fossils have been drawing the geologists' and paleontologists' attention for more than 150 years (e.g. Stur, 1860; Neumayr, 1871; Uhlig, 1890, 1903, 1904, 1907; Andrusov, 1931, 1938, 1945 etc; Birkenmajer, 1970, 1977, 1986 etc; Sikora, 1971, 1974; Mišík, 1978, 1994, 1997 etc; and many others). Looking at the general geological maps of the Western Carpathians, the PKB comes out as a backbone of the orogen, which unifies its outer and inner zones. It is positioned at the backstop of the Tertiary accretionary wedge (External Carpathian Flysch Belt), and in front of the Cretaceous nappe stack (Central Western Carpathians – CWC). The PKB involves units of two types and paleogeographic provenances – the first are nappes of the specific Oravic Superunit that are present only in the PKB (such as the Czorsztyn, Kysuca or Pieniny Unit), the second are nowadays interpreted as frontal elements of the Central Carpathian Fatric Superunit occurring mostly in Western Slovakia (Manín, Drietoma and Klape nappes; the Haligovce Unit in the Pieniny Mts – Plašienka in Froitzheim et al., 2008). In a broader sense, the PKB and the neighbouring Magura Unit represent elements of the Penninic tectonic system, while the CWC units continue to the Eastern Alpine (Austroalpine) thrust stack (e.g. Schmid et al., 2008; Froitzheim et al., 2008). From the paleogeographic point of view, the Oravic units were derived from a neighbourhood of a continental splinter, known as the Czorsztyn Ridge (e.g. Birkenmajer, 1986; Mišík, 1994), which was positioned between two branches the Jurassic – Cretaceous Penninic oceans – the South Penninic Ligurian-Piemont-Tauern-Rechnitz-Vahic and the North Penninic Valais-Rhenodanubian-Magura Ocean. Accordingly, the Czorsztyn Ridge (or Oravic ribbon continent – Plašienka, 2003) was analogous in position to the Middle Penninic continental fragments, such as the Briançonnais Ridge of the Western Alps (e.g. Trümpy, 1988).

All along its length of up to 600 km, the as narrow as merely several km PKB retains the specific features of its composition and structure. The PKB involves predominantly Jurassic, Cretaceous and Paleogene sediments with exceptionally variable lithology and intricate internal structure. During more than a century of intense research, these have been subdivided into numerous lithostratigraphic and tectonic units of distant provenances, hence witnessing excessive shortening and dispersal within this restricted zone. In general, two types of rock complexes are distinguished in the PKB. The "klippen" are formed by the rigid, nearly isometric, lenticular or lozenge--shaped blocks of Jurassic – Lower Cretaceous limestones that are ranged to several stratigraphic successions differing in lithology. The klippen are embedded in an incompetent

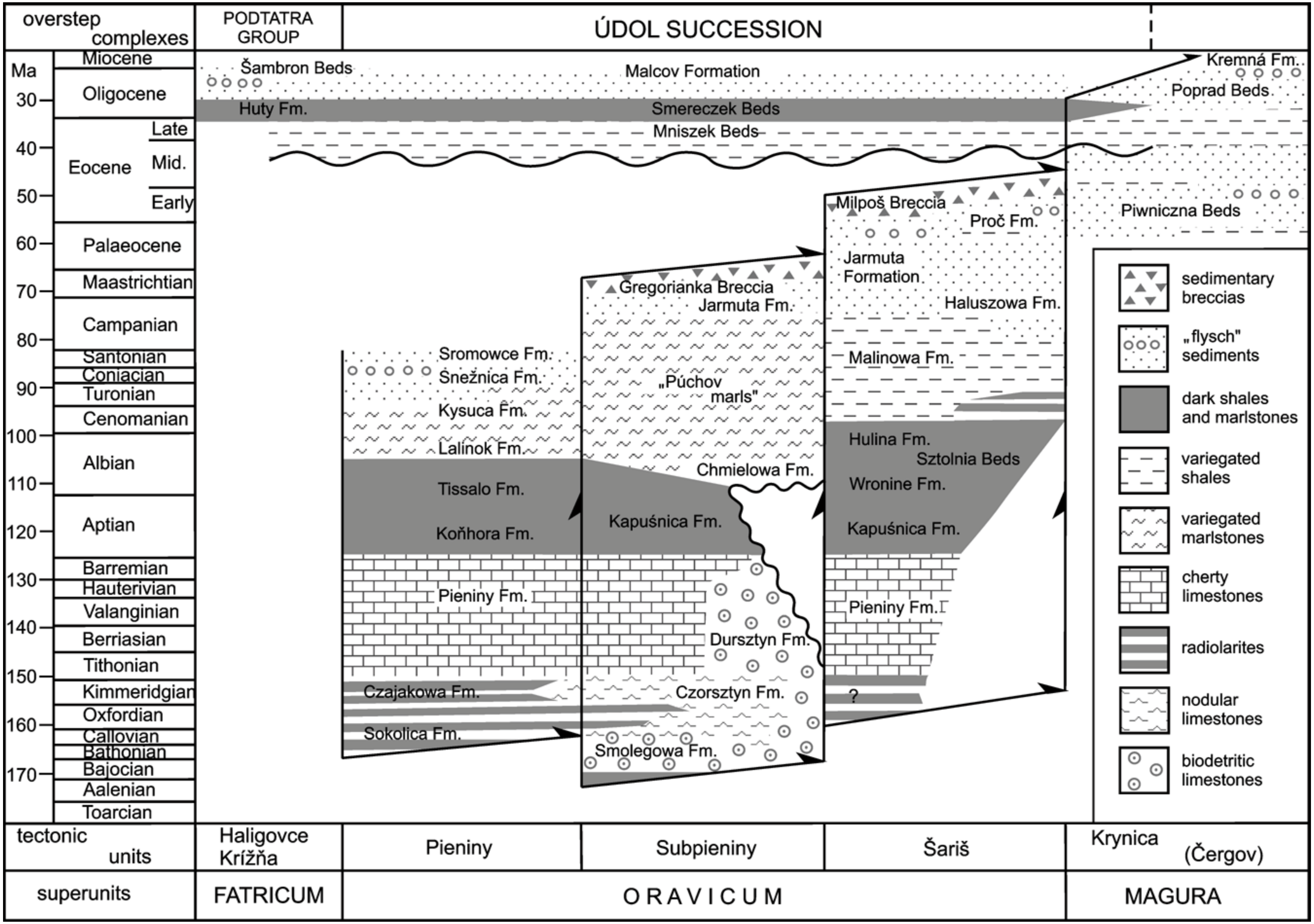

Fig. 1. Generalized lithostratigraphy of the PKB and adjacent units in the described area (after Plašienka and Mikuš, 2010, slightly modified).

matrix, the "klippen mantle", composed of various Upper Cretaceous to Paleogene marlstones, shales and flysch sediments. Owing to this, the PKB has often been characterized as a tectonic megabreccia, mélange, or even it was speculated to represent a huge chaotic sedimentary body – an olistostrome (Nemčok, 1980). This idea was partly confirmed recently by Plašienka and Mikuš (2010) who consider a part of blocky klippen of the newly-defined Šariš Unit as olistoliths. However, the peculiar "block-in--matrix" structure of substantial parts of the PKB appears to be result of dominantly tectonic processes, governed by thrusting and subsequent along-strike wrench movements. The latter obliterated, in places completely, former thrusting--related structures. Consequently, the mutual structural relationships of various PKB units and the neighbouring tectonic zones remains a matter of controversy and no general agreement has been achieved even in some fundamental questions until now.

The present paper aims at presentation of the most characteristic attributes of the PKB lithostratigraphy and tectonic structure in a rather small area, which, however, provides numerous examples of the most unusual aspects of the PKB edifice. The satellite paper (Plašienka, this issue) provides more detailed information about the character of structural elements that control the overall tectonic edifice of the PKB segment under question.

General structure and lithostratigraphy

The Polish and adjacent Slovakian Pieniny Mountains is a classic area of the PKB geology with intense research going back to 19th century. Currently, the most widely accepted model of Birkenmajer (1970, 1977, 1986) considers the presence of several "Klippen Successions" differing by their lithostratigraphic contents, but originally deposited in the united "Pieniny Klippen Basin". Three main sedimentary zones are distinguished within this basin: (1) the Czorsztyn Ridge and its slopes in the northern position; (2) the central furrow; (3) the southern Exotic (Andrusov) Ridge and its slopes. At the same time, the Klippen Successions represent individual tectonic nappe units. From the bottom to top, these are the ridge-type Czorsztyn Unit, the Niedzica and Czertezik Units representing the southern slope of the Czorsztyn Ridge, the basinal Branisko and Pieniny Units (partly deposited on an oceanic crust formed already in the Late Triassic), and the Haligovce Unit that originated at the southern margin of the Pieniny oceanic basin in the vicinity of the Andrusov Ridge, an enigmatic structure that should have fed the PKB Cretaceous basins with coarse exotic material and that completely disappeared later. Besides these, the special Grajcarek Unit is considered to be derived from the northern slope of the Czorsztyn Ridge facing the Magura Ocean to the north, which was thrust back over the Laramian structure of the PKB during the earliest Paleogene and then incorporated into the PKB structure. Further on, the Laramian nappe structure was partially sealed by the Maastrichtian, post--thrusting, molasse-type transgressive cover – the Jarmuta Fm. However, the Jarmuta Fm. should pass northwards into synorogenic flysch sediments of the Magura Basin (Grajcarek Unit) extending to the Paleocene (Birkenmajer et al., 1987). Certain aspects of this conception were questioned e.g. by Jurewicz (1997, 2005), who presumes the lowermost structural position of the Grajcarek Unit within the PKB edifice, i.e. the Laramian thrusting or sliding of the Czorsztyn Unit over the synorogenic Jarmuta Fm. Recently, Oszczypko et al. (2010) and Oszczypko and Oszczypko-Clowes (2010) have found that also the "Autochthonous Paleogene", considered by Birkenmajer (1986) as transgressive and preserved in synforms within the PKB, appears in tectonic windows together with rocks of the Grajcarek Unit and ranges stratigraphically up to the Lower Miocene. These new findings partly recall the older views of Sikora (1962, 1970). Accordingly, most of the PKB rocks younger than Lower Paleocene are considered to form the lowermost structural element of the PKB connected to the southernmost parts of the Magura Unit. This, however, does not apply for Paleogene sediments with a clear transgressive position above the highest and southernmost Haligovce Unit (Súľov-type conglomerates and biogenic sediments akin to the Myjava-Hričov Group of Western Slovakia – cf. Janočko, ed., 2000). Another point of these new views is that the principal PKB units are in a completely allochthonous position above the Magura elements, i.e. they override the rear parts of the EWC accretionary wedge. Owing to this high structural position, the PKB rocks have never been buried to considerable depths, which is in line with observations about the very low thermal reworking of the PKB rock complexes.

The Eastern Slovakian part of the PKB is characterized by a noticeably small width (5 km at maximum), by presence of the Oravic units only (with exception of the small Haligovce Unit), sharp fault boundaries, widespread incorporation of Paleogene rocks and by some 50 km long sector where the stiff klippen are missing completely (Nemčok, 1990). It is an area, where the Paleogene sediments (generally known as the Proč Fm.) were long time regarded as transgressive above the deformed klippen successions and closely related to the Magura flysch complexes (e.g. Matějka, 1963; Stráník, 1965). Only Leško (1960; Leško and Samuel, 1968) postulated a structural independence of the PKB from the Magura Unit. Later on Nemčok (1980; Nemčok et al., 1989, 1990) formulated a quite different opinion, according to which all the klippen are in fact olistoliths resting within chaotic breccias horizons (Gregorianka Breccia) composed mostly of the same material as the klippen themselves. In Nemčok's view, the breccias are members of the Maastrichtian – Lower Eocene Jarmuta-Proč Fm., which composes the matrix of the PKB megaolistostrome placed between the deposits of the Central Carpathian Paleogene Basin (CCPB), known also as the Podhale Basin in Poland, and the overriding backthrust Magura complexes.

Just in recent times, Plašienka and Mikuš (2010) presented a view fairly distinct from all previous opinions – the Jarmuta and Proč Fms. do not represent the klippen "mantle", but are constituents of an independent, newly defined Šariš Unit in the lowermost structural position

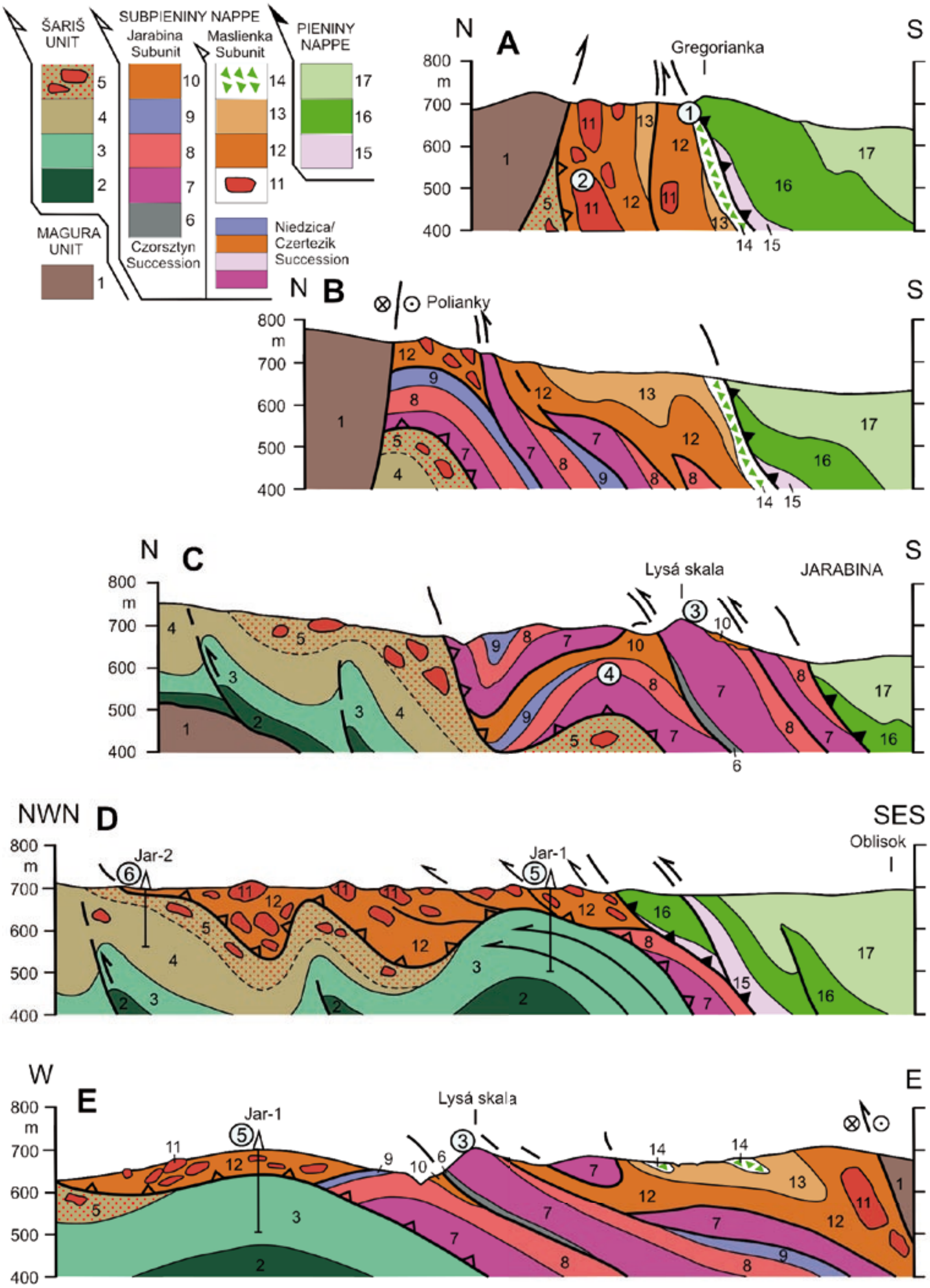

Fig. 2. Geological cross-sections **A** to **E** of the area north of Jarabina. For their approximate position see Fig. 4. 1 – Palaeogene to Lower Miocene (?) formations of the Magura (Krynica) Unit; 2–5 Šariš Unit: 2 – Lower Cretaceous marly limestones (Pieniny Fm.); 3 – various shaly, marly and distal flysch formations of Albian to Campanian age; 4 – Maastrichtian? to Lower Eocene calcareous "flysch" sandstones and shales (Jarmuta and/or Proč Fm.); 5 – the same with bodies of olistostromes and olistolites (Milpoš Breccia); 6–10 Subpieniny nappe, Jarabina Subunit: 6 – Aalenian to Lower Bajocian black spherosideritic shales (Skrzypny Shale Fm.); 7 – Bajocian sandy-crinoidal limestones (Smolegowa and Krupianka Fms); 8 – Bathonian to Lower Tithonian red nodular limestones (Czorsztyn Fm.); 9 – Upper Tithonian to Berriasian pale biomicritic limestones (Dursztyn Fm.); 10 – Albian to Campanian variegated, dominantly red marlstones ("Púchov marls," Chmielowa and Jaworki Fms); 11–14 Subpieniny nappe, Maslienka Subunit: 11 – blocky klippen of Jurassic to Lower Cretaceous formations of the Czorsztyn and Czertezik/Niedzica Successions; 12 – various marly, shaly and distal flysch formations, Albian – Campanian (Kapuśnica and Jaworki Fms); 13 – Upper Campanian – Maastrichtian calcareous sandstones, proximal flysch (Jarmuta Fm.); 14 – the same with bodies of carbonate olistostromes (Gregorianka Breccia); larger thrust imbricates with continuous, but mostly overturned "transitional" Niedzica/Czertezik Succession are shown in the area north of Litmanová (see Fig. 11); 15–17 Pieniny nappe: 15 – Callovian to Lower Tithonian radiolarite cherts (Czajakowa Fm.); 16 – Tithonian to Barremian pelagic cherty limestones (Pieniny Fm.); 17 – Aptian to Campanian variegated shales, marls and flysch deposits with bodies of exotic conglomerates in places. Numbers in circles indicate approximate positions of the respective localities.

within the PKB nappe edifice (Figs. 1, 2 and 11). The sedimentary succession of the Šariš Unit ends with Paleocene – Lower Eocene Milpoš Breccia bodies (part of the Nemčok's Gregorianka Breccia), which are composed of material dominated by clasts derived from the overriding units, including numerous sedimentary klippen – olistoliths. The overlying Subpieniny nappe (term by Uhlig, 1907) is strongly disintegrated internally, formed by numerous klippen of tectonic origin composed predominantly of the ridge-type Czorsztyn Succession, but involving also the slope-type Czertezik and/or Niedzica successions. The matrix consists of variegated Upper Cretaceous pelagic marls, the youngest member is represented by the Maastrichtian coarsening-and-thickening upward synorogenic flysch sequence (Jarmuta Fm.) with breccia bodies (Gregorianka Breccia at the type locality of Nemčok et al., 1989). These breccias are composed exlusively of material coming from the overriding Pieniny nappe. The latter thrust sheet is represented by Middle Jurassic – Upper Cretaceous, deep-water basinal succession with a comparatively simple fold-thrust structure and occurs as the southernmost structural stripe of the PKB in Eastern Slovakia. In places, the PKB tectonic units are covered by the Middle Eocene – Oligocene sediments (termed as the Údol Succession by Plašienka and Mikuš, 2010, but known also as the Ujak Facies, Ombron Group or Richvald Series), which provide a link to the CCPB sediments and coeval EWC strata of the Krosno facies. They include variegated claystones, *Globigerina* marls, menilite shales and turbiditic sandstones and shales of the Oligocene Malcov Fm. The Údol Succession partly seals the nappe structure of the Oravic units which originated by sequential stacking during the latest Cretaceous – Early Eocene, but is largely incorporated into younger, Lower Miocene deformation.

Based on these considerations, Plašienka and Mikuš (2010) and Plašienka (this issue) reconstructed the tectonic evolution of the eastern part of the PKB as follows. The outward younging synorogenic clastic formations of the three superposed Oravic units clearly record their latest Cretaceous to Early Eocene stacking progression: first the Pieniny nappe overrode the Jarmuta Basin of the Subpieniny area in the latest Cretaceous, then the Subpieniny nappe with piggy-back Pieniny Unit slid over the Proč Basin during the Late Paleocene to Lower Eocene. The post-stacking period was first governed by dextral transpression followed by extensional collapse and deposition of the overstepping, Middle Eocene – Oligocene Údol Succession, which is closely related to sediments of the CCPB. Subsequently, the PKB attained its final tectonic form by the post-Oligocene SW–NE shortening accompanied by slight dextral wrenching. This overall tectonic evolution is partially recorded also by the small-scale deformation elements developed during several deformation stages, as described in detail by Plašienka in this conference volume.

The regional structure of the area is rather complex and difficult to be recognized in places with poor outcrop conditions. Nevertheless, after a rigorous structural assessment and detailed mapping the main points become quite clear. First of all, the primary fold-and--thrust structures are fairly well preserved. In general, the area is characterized by a broad, internally complicated antiform (see Plašienka, this issue). The thrusting process progressed from foreland-propagating overthrusting of thin nappe sheets, followed by piggy-back, out-of-sequence thrusting and dextral wrenching that largely modified the original thrust structures.

Based on spatial relationships of units embracing different lithostratigraphic successions (Fig. 1), three superposed principal PKB units have been discerned in this area (Plašienka and Mikuš, 2010). The **Šariš Unit** is in the lowermost structural position, on the surface it is built mostly of hundreds metres thick calcareous flysch deposits of the Jarmuta and/or Proč Fm. of the Maastrichtian to Lower Eocene age (localities 6 and 8), including the terminating coarsening-upward sequence with bodies of the olistolith-bearing Milpoš Breccia Member (locality No. 8). Older Cretaceous members, which begin with well--bedded, marly limestones akin to the Pieniny Fm., occur in several partial anticlinal zones near Litmanová. They are followed by variegated shaly and marly formations of Albian to Campanian age, including the "black flysch" and "Fleckenmergel" deposits, weakly calcareous oceanic red beds and distal hemiturbidites (Malinowa Fm.), in part deposited below the CCD (localities No. 5 and 7). In the Polish Małe Pieniny Mts, the Šariš Unit would correspond to the Grajcarek Unit (Birkenmajer, 1970, 1986), but in the lower structural position with respect to the other PKB units, as interpreted also by Jurewicz (1997) and Oszczypko et al. (2010). Likewise the Hulina Unit and possibly also the Złatne Unit defined by Sikora (1971, 1974) appear to be analogues of the Šariš Unit.

The **Subpieniny nappe** includes, according to our investigations, not only klippen of the typical Czorsztyn Succession (locality No. 2), but also the Niedzica and Czertezik "transitional" successions (Fig. 1). The Jurassic – Lower Cretaceous rocks form the stiff klippen of tectonic origin that rest in the Albian to Maastrichtian matrix of various composition dominated by the Senonian red pelagic marlstones of the "Púchov facies". The Subpieniny successions are terminated by calcareous turbiditic sandstones (Jarmuta Fm.) and carbonate tectono--sedimentary breccias of the Maastrichtian, possibly up to early Paleocene age, which are known as the Gregorianka Breccia (Nemčok et al., 1989; Plašienka and Mikuš, 2010) – locality No. 1.

The inner structure of the Subpieniny Unit is controlled by the presence of a variously thick layer of mostly massive, competent Middle to Upper Jurassic sandy-crinoidal and nodular limestones, which are inserted between incompetent shaly and marly Lower Jurassic and Upper Cretaceous strata. In the course of thrusting-shearing deformation, this competent layer was either dismembered into numerous small imbricates and boudins floating in incompetent matrix, or, in the case the competent layer was very thick (more than 50 metres), it forms a stack of thick imbricates that are laterally continuous for several hundred metres. At the same time, these differences may have resulted also from the rugged, synsedimentary fault--controlled morphology of the Czorsztyn Ridge that was truncated by the basal detachment of the Subpieniny nappe at various levels (Fig. 3), sometimes even not reaching deep enough to attack the Jurassic rocks. This can be also the cause of a lateral discontinuity of the unit, which cannot be ascribed to the tectonic reasons only. Due to differences in the mechanical stratigraphy, the Subpieniny Unit is differentiated to two partial subunits (Plašienka and Mikuš, 2010; Plašienka, this issue). The **Jarabina Subunit** consists of thick imbrications of the typical Czorsztyn Succession forming antiformal thust stacks or duplexes in the rear part of the Subpieniny Unit (area around the Jarabina Gorge and quarry – localities No. 3 and 4, see Fig. 2). The other, **Maslienka Subunit,** is tightly imbricated with isolated, decametre-sized blocky klippen of the Czorsztyn, as well as “transitional” Jurassic – Lower Cretaceous formations embedded in a strongly sheared, scaly matrix of Upper Cretaceous shales, marls and sandstones, hence forming a typical block-in-matrix structure of tectonic origin (Fig. 2, localities 5 and 6). The peculiarity of the inner structural style of the Maslienka Subunit is that the strata succession of individual imbricates is usually overturned, which applies not only to the klippen themselves, but to the klippen matrix formations as well (see the Jar-1 borehole log at locality No. 5; Fig. 9).

The overriding **Pieniny nappe** involves basinal Jurassic – Cretaceous successions (Fig. 1) with small local variations in their lithostratigraphic content used for distinguishing of several lithostratigraphic successions (Pieniny s.s., Kysuca, Branisko; for the detailed lithostratigraphy see e.g. Birkenmajer, 1977). The Pieniny successions are composed of well-bedded pelagic radiolarites, limestones and marlstones, hence forming a multilayer prone to folding. Consequently, also the overall structural style of the Pieniny Unit is different from the other two. It obviously occurs in the uppermost structural position within the PKB edifice (Fig. 2) and forms the southernmost, internally imbricated and folded zone along the southern PKB margin.

Description of localities

The lithostratigraphic and tectonic phenomena outlined above may be examined in detail at several localities between Jarabina and Litmanová villages (Fig. 4). These localities are chosen in a way they can be passed during a one-day walking trip (6–8 hours).

<u>Locality 1</u> – Hlboký potok valley (Gregorianka Breccia)

Type locality of the Gregorianka Breccia, east of Jarabina (D. Plašienka, J. Madzin, Š. Józsa)

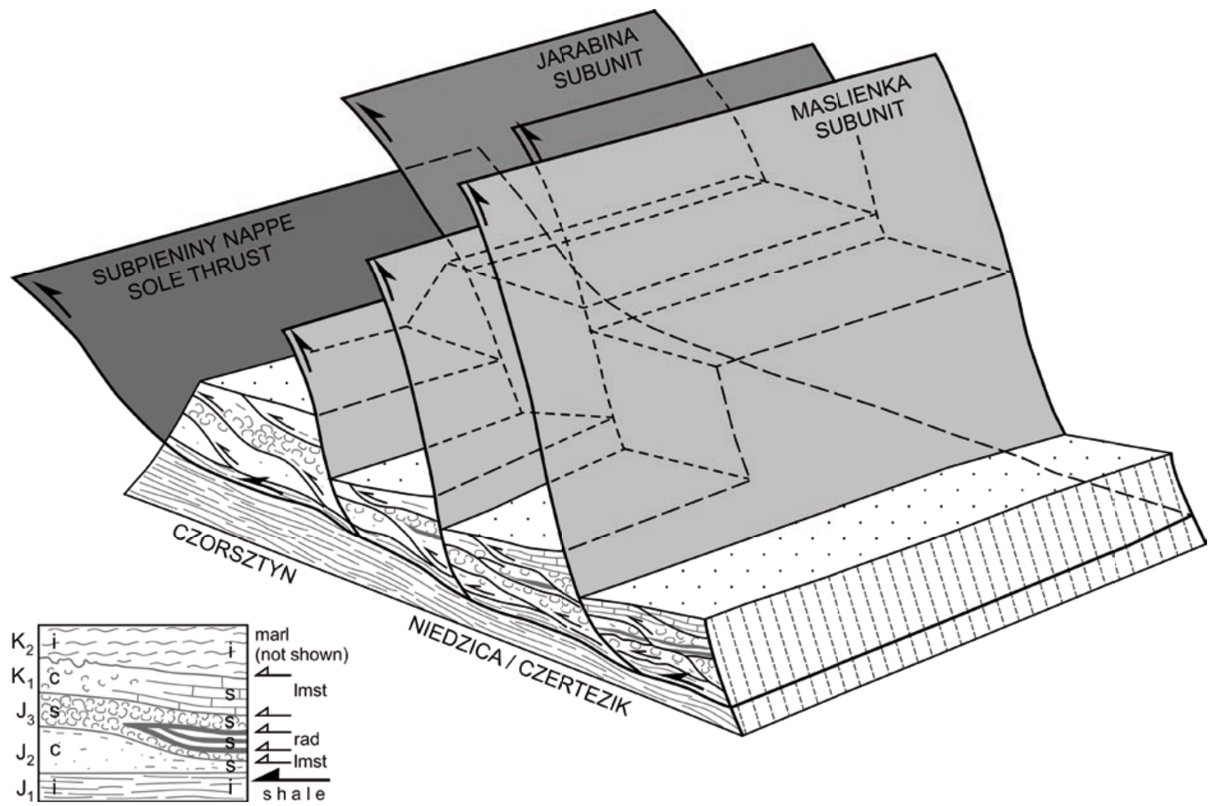

Fig. 3. Blockdiagram showing dependence of the basal detachment of the Subpieniny nappe and its partial imbricates on the pre-existing block structure and mechanical stratigraphy of the Czorsztyn-type successions. The inset indicates lithology and mechanical properties of the main formations: i – incompetent shales and marls; s – semi-competent, well-bedded limestones and radiolarites; c – competent massive or thick-bedded limestones.

Just a few tens of metres east of the last houses of the upper, NE end of Jarabina village, there is the type locality of the "Gregorian Breccia" as described by Nemčok et al. (1989). According to the current maps, the local name is "Pod Gregorankou", the original Gregorianka is the hill with the spot height 721 m some 450 metres towards the east. Outcrops of Gregorianka Breccia occur down in the valley of Hlboký potok (Deep brook – GPS N 49°20'35.8'', E 20˚39'48.3''; altitude 630 m).

At their type locality, Nemčok et al. (1989) characterized the Gregorianka breccias as monomict, composed of angular, up to 60 cm large clasts of grey Calpionella limestones, grey-green radiolarites, and less radiolarian and saccocomid limestones. The breccia bodies are intercalated by up to 2 metres thick layers of red marlstones containing hedbergellas, thalmanninellas, globotruncanas, globorotalias? and globigerinas?. Based on these, they supposed their Maastrichtian, and possibly also Paleogene age. However, Nemčok mentioned these breccias also earlier (e.g. Nemčok, 1978, 1980) and based on them his conception of the sedimentary origin of not only some klippen occurring within the Proč-Jarmuta flysch deposits, but of the entire PKB as a huge megabreccia body inserted between the Paleogene flysch formations of the Magura nappe and the CCPB. This idea, whatever erroneous in general, has its positive aspects. First of all, Nemčok drew attention to the breccia bodies that occur within the flysch or "wildflych" Jarmuta and/or Proč formations as sliding masses or olistostromes and discarded the opinion about their transgressive and cliff origin. At the same time, Nemčok noticed that numerous klippen are in fact olistoliths resting within these breccia bodies. These observations were crucial, but overlooked for the next decades.

Recently, Plašienka and Mikuš (2010) studied the composition and position of these breccias and subdivided them into two separate members – the Gregorianka Breccia "sensu stricto" from this and several other localities and the Milpoš Breccia of the Šariš Unit (see locality No. 8). The former breccias appear to represent terminal deposits of the Subpieniny nappe successions, which are most likely latest Cretaceous to earliest Paleogene? in age. Their composition reveals derivation from the overriding Pieniny nappe, thus they are interpreted as tectonosedimentary breccias that originated from debris released from the tectonized front of the overriding thrust sheet. Subsequently the breccias were deposited in the frontal trench-like basin, and finally they were superposed by their original source unit. Unlike the Milpoš Breccia, the areal extent of the Gregorianka Breccia is restricted to several localities only, as well as large olistoliths are less frequent (but present in places, e.g. near the village Demjata north of Prešov).

According to our observations and the present state of the outcrop, the breccia bodies (at least two separate in the section) occur within a strongly imbricated zone

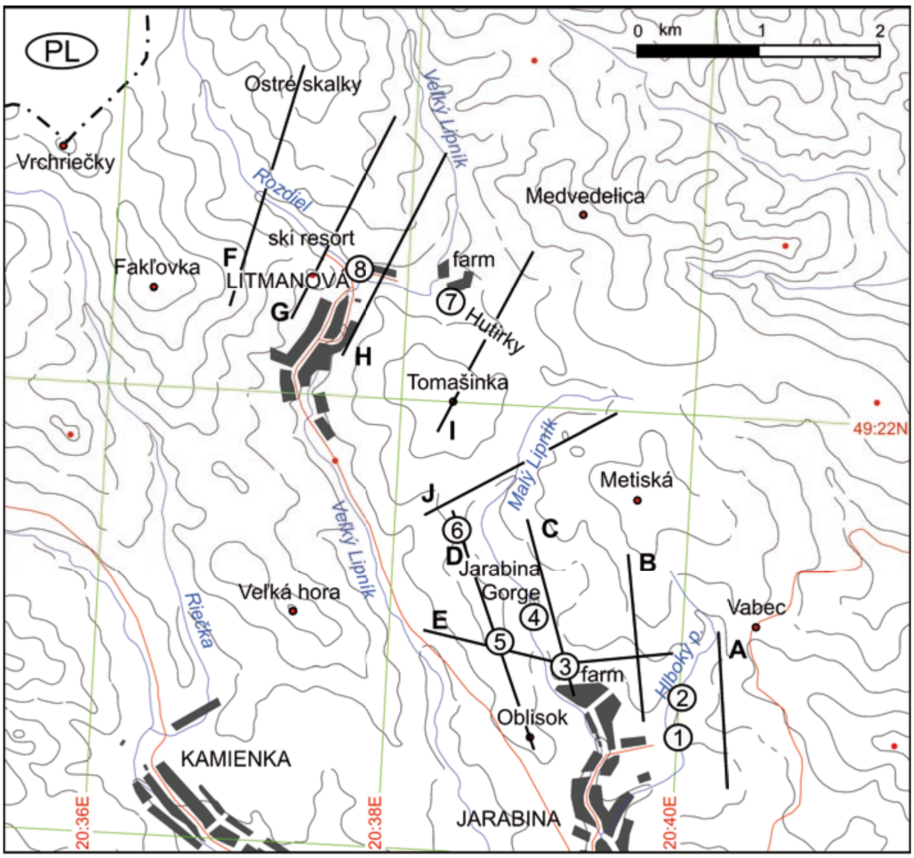

Fig. 4. Topographic map of the area with position of the representative localities described in the text and cross-sections shown in Figs. 2 and 11. Compare to the geological map depicted in the article by Plašienka (this issue).

sandwiched between the overlying Pieniny and underlying Subpieniny Unit. From south to north, the discontinuous section (Fig. 5) exposes sheared limestones of the Pieniny Fm., a sequence of variegated (grey-green, red and black) marls, then again a slice of Pieniny limestone, dark marls with limestone fragments (Upper Albian foraminifers), then, after an interruption (covered by a scree of reddish marls), the first body of breccias about 3 metres thick underlain by dark shales with thin sandstone beds (Turonian to Lower Cenomanian foraminifers). The section follows with another a few metres thick breccia body, ca 5 m thick sequence of turbiditic sandstones and marly shales underlain by 10 m of brick-red and green marlstones (planktonic foraminifers of Campanian – Lower Maastrichtian age) and grey spotted marlstones (Upper Albian – Lower Cenomanian). After a tectonic contact, the variegated marls are underlain by a thick calcareous flysch sequence of Campanian – Lower Maastrichtian age (pelagic and agglutinated foraminifers); the sequence is overturned (Helminthoid-type ichnofossils occur on upper surfaces).

According to our investigation, the clast-supported Gregorianka Breccia has a monotonous lithological composition and contains material evidently derived from the structurally higher Pieniny Unit. Grain size varies from fine (few mm) to boulder size. Most common are clasts of radiolarian limestones, wackestone to packstone texture, with abundant radiolarian skeletons. Clasts of calpionellid limestones – wackestones with Calpionella alpina Lorenz – are also frequent. Occasional non-carbonatic rock fragments are represented by siltstones and rarely metamorphic rocks (schistose quartzite). Siliciclastic imput of detrital subangular to angular quartz and feldspar grains is present as well. The voids between individual clasts are filled mainly with carbonate cement, in some cases also with silty to fine-grained sandy matrix with fine quartz and feldspar grains.

<u>Locality 2</u> – Hlboký potok valley (Czorsztyn-type klippe)

Litho-biostratigraphic profile of the Czorsztyn Succession (M. Jamrichová, D. Plašienka)

The locality is situated NE to the Jarabina village (GPS coordinates N 49˚20'44.3'', E 20˚39'52.7''; altitude 652 m) in a small gorge of the Hlboký potok stream crossing a klippe composed of Jurassic limestones of the shallow--water Czorsztyn Succession. The klippe is surrounded by variegated Cretaceous marlstones and is ranged to the Maslienka Subunit of the Subpieniny nappe (Plašienka and Mikuš, 2010). The following lithostratigraphic units can be recognized in this klippe (Fig. 6):

Alternating pink and grey-green crinoidal limestones of the thickness 4.9 m occur here instead of superposed white and red varieties of the Smolegowa and Krupianka Limestone Fms, respectively. Limestones represent crinoidal biosparites (grainstones) consisting of crinoidal ossciles, numerous clasts of micritic carbonates (mostly dolomites and dedolomites) and less numerous fragments of bivalves (in places only ghosts) and brachiopods, echinoid spines, agglutinated, lenticulinid and nubecularid foraminifers. Dispersed sandy quartz admixture is also frequent. The grainstones are evidence of a dynamic sedimentary environment where the mud was winnowed from the interstices. The crinoid ossicles are usually overgrown by clear syntaxial calcitic rims. The sediment was strongly affected by compaction, as indicated by frequent pressure-solution seams among the skeletal detritus, up to stylolites forming wavy to anastomozing, bedding-parallel foliation. This foliation formed during the latest diagenetic stage as it cuts the fully developed syntaxial rims on echinoderm particles.

Krupianka Limestone Formation is formed by bedded to massive, reddish crinoidal grainstone to packstone still containing abundant clastic admixture, mainly represented

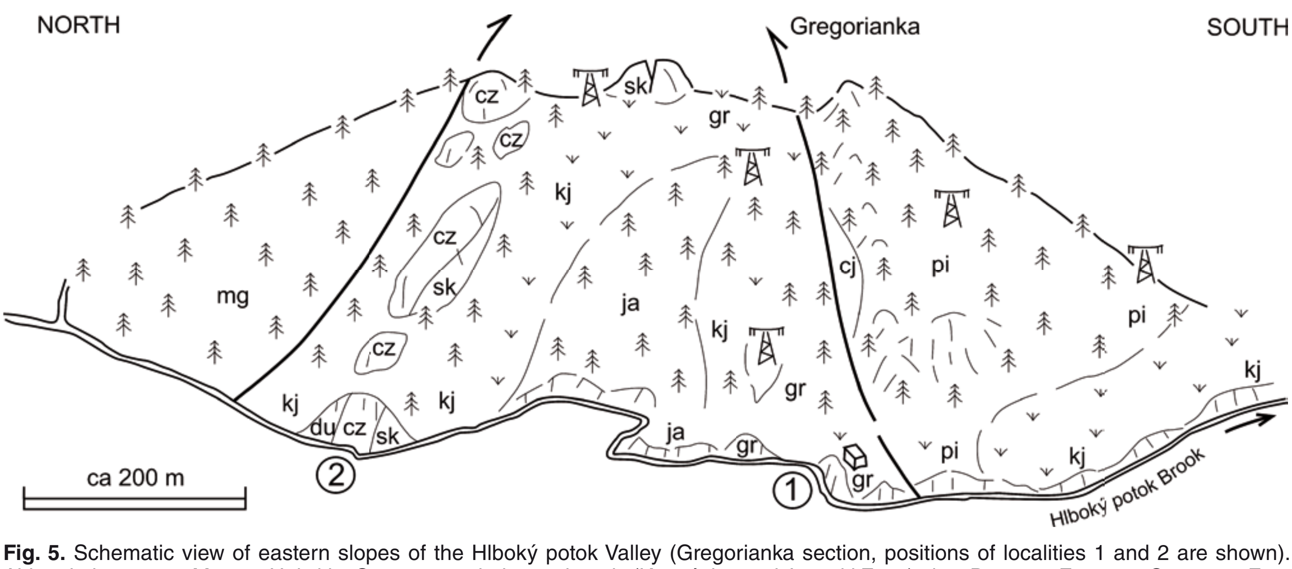

Fig. 5. Schematic view of eastern slopes of the Hlboký potok Valley (Gregorianka section, positions of localities 1 and 2 are shown). Abbreviations: mg – Magura Unit; kj – Cretaceous shales and marls (Kapuśnica and Jaworki Fms.); du – Dursztyn Fm.; cz – Czorsztyn Fm.; sk – Smolegowa and Krupianka Fms.; ja – Jarmuta Fm.; gr – Gregorianka Breccia; cj – Czajakowa Fm.; pi – Pieniny Fm.

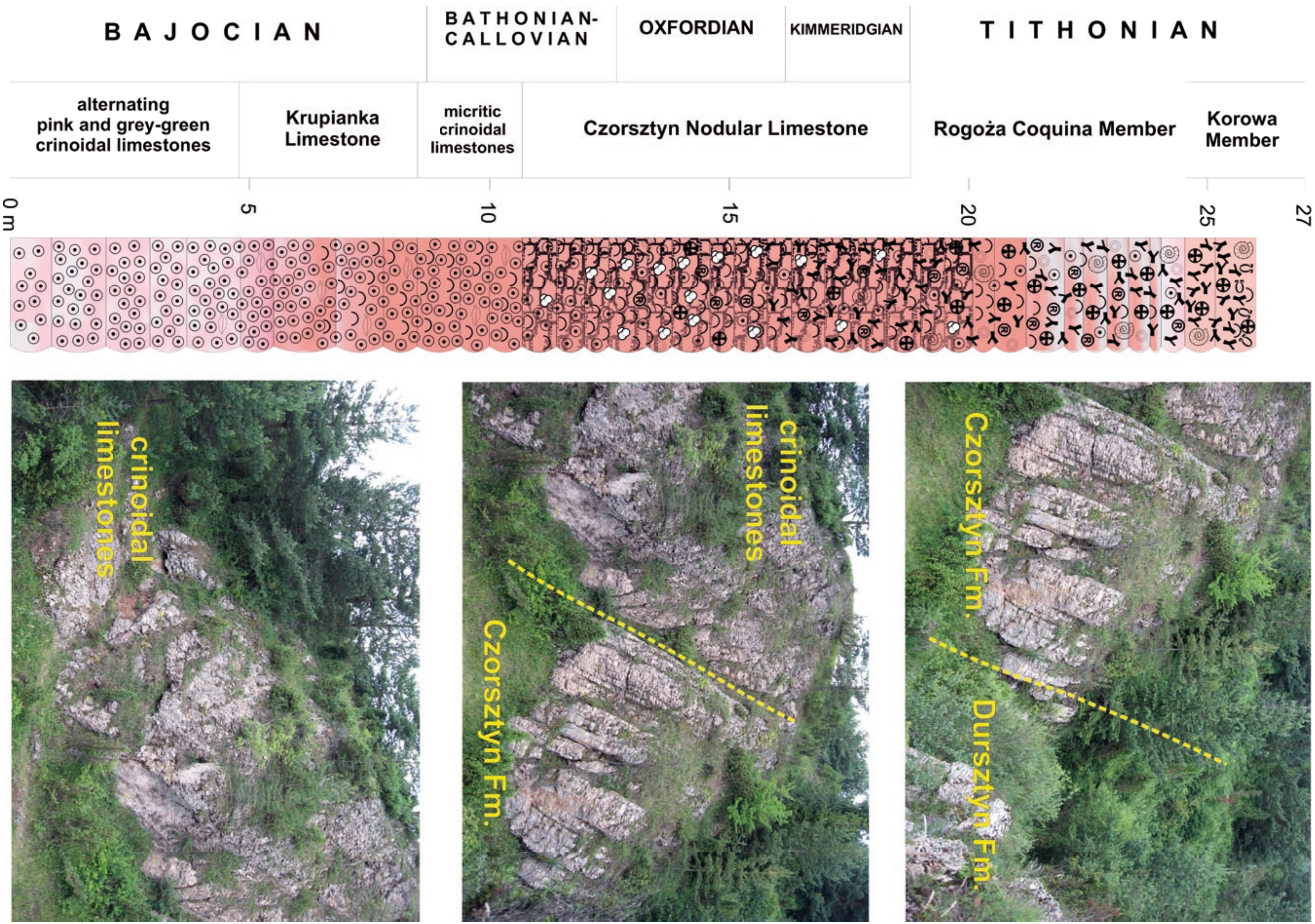

Fig. 6. Lithostratigraphic profile of the Hlboký potok klippe. The inset photos show contacts of the lithostratigraphic units described. Note subhorizontal cleavage cutting the vertical strata of the Czorsztyn nodular limestones.

by quartz grains and dolomites. The echinoderm (mostly crinoids) – filamentous (thin shelled bivalves) packstones with marly matrix are present as well. They reach thickness of around 3.4 m. The age of the alternating pink and grey-green crinoidal limestones and the Krupianka Fm. is Middle/Upper Bajocian – Bathonian (e.g. Birkenmajer, 1977). The Krupianka limestones gradually pass into the **red bedded micritic crinoidal limestones** – biomicrites (packstones) with crinoid-filamentous microfacies. In this formation, a condensed sedimentation was registred, which is indicated by the Fe-Mn crusts, marking the hiatus between the crinoidal and red micritic limestones. Their thickness reaches almost 2 m.

Czorsztyn Limestone Formation – after the sedimentary break, the Czorsztyn Nodular Limestone with filamentous microfacies sedimented. The deposits contain mainly thin-shelled bivalves (filamentous packstones), juvenile gastropods, benthic foraminifers and crinoidal ossicles. Thin-shelled ostracods, foraminifers (*Ophthalmidium* sp., *Lenticulina* sp., *Patellina* sp, *Spirillina* sp., *Dorothia* sp.), sessile nubecularid foraminifers, nodosariid foraminifers and "microforaminifers" also occur. Detritus from thicker-walled bivalves (commonly dissolved and replaced by micrite) and brachiopods, rare gastropods, juvenile ammonites, echinoid spines are quite common. Rare quartz grains occur, too. Filamentous microfacies are replaced by the *Protoglobigerina* microfacies, suggesting their Oxfordian age. This passes gradually into *Saccocoma* microfacies. The upper part of the formation contains microfossils *Cadosina parvula* Nagy, *Stomiosphaera moluccana* Wanner, *Colomisphaera pieniniensis* Borza, *C. pulla* Borza, *C. carpathica* (Borza), *C. nagyi* (Borza), *Schizosphaerella minutissima* (Colom), *Carpistomiosphaera borzai* (Borza) documenting Early Kimmeridgian Parvula Zone and Late Kimmeridgian Moluccana Zone. Thickness of the Czorsztyn Limestone Formation is around 7.5 m.

The **Dursztyn Limestone Formation** consists of massive, red and pinkish, micritic limestones up to 8 m thick. Locally, they can be rich in crinoidal ossicles (forming lenses of crinoidal packstones) and fine shelly debris (Rogoża Coquina Member). The deposits are formed by radiolarian-*Saccocoma-Globochaete* microfacies (packstones, wackestones). Calcareous dinoflagellate cysts (*Carpistomiosphaera tithonica* Nowak, *Colomispahera pulla*, *C. carpathica*, *C. nagyi*, *Cadosina radiate* Vogler, *Parastomiosphaera malmica* Borza, *Schizosphaerella minutissima*) indicate Early Tithonian to Middle Tithonian Pulla, Tithonica and Malmica Zone. Early calpionellid forms with microgranular lorica (*Chitinoidella dobeni* (Borza), *C. tithonica* (Borza), *Borziella slovenica* (Borza), *Daciella danubica* Pop, *Longicollaria dobeni* (Borza), *Dobeniella bermudezi* (Furrazola-Bermudez)) characterize the Dobeni and Boneti Subzone of the Chitinoidella Zone (Middle Tithonian). The *Saccocoma-Globochaete* microfacies passes gradually into the calpionellid-*Globochaete* microfacies of the Korowa Limestone Member. Calcareous dinoflagellate cysts are represented by *Schizosphaerella minutissima*, *Colomisphaera carpathica*, *C. nagyi*, *C. tenuis* Nagy, *Cadosina semiadiata semiradiata* Wanner. The occurrence of the *Crassicollaria intermedia* (Durand Delga), *C. massutiniana* (Colom), *C. parvula* Remane, *Tintinopsella remanei* (Borza), *T. carpathica* (Murgeau et Filipescu), *Calpionella grandalpina* Nagy and rare *Calpionella alpina* Lorenz indicate Intermedia Subzone of the Crassicollaria Zone (Late Tithonian). The Early Tithonian to Late Tithonian age of the formation is based in calcareous dinoflagellates and calpionellids.

The strata of the klippe are steeply south-dipping with younging direction towards the north. A distinct, subhorizontal cleavage may be observed, particularly in the red nodular limestones (Fig. 6). The cleavage formed by pressure solution early in the deformation process, probably during the incipient phases of layer-parallel shortening and detachment of a more competent packet of Middle Jurassic – Lower Cretaceous limestones from the underlying, incompetent shaly and marly deposits (see Plašienka, this issue).

The area provides numerous alternative profiles of Jurassic to Lower Cretaceous formations representing the Czorsztyn, Niedzica and/or Czertezik Successions. Some of them have been already evaluated litho-biostratigraphically in detail by M. Jamrichová, e.g. the spectacular Čertova skala klippe ca 1 km to the north. Each klippe appears to show some, at least subtle, but sometimes abrupt differences in their lithostratigraphic profiles, hence indicating sudden lateral and vertical changes in sedimentary environments within the Czorsztyn Ridge and its slopes. Particularly, the uneven thicknesses and differing rheological properties of individual formations, as well as of the whole rigid limestone package, were variously expressed in formation of the tectonic structures (see Fig. 3).

<u>Locality 3</u> – Jarabina quarry, top stage (Czorsztyn Succession)

Transgressive contact of Cretaceous marls with Jurassic limestones (D. Plašienka)

In the sporadically active Jarabina quarry (Lysá skala klippe, Fig. 2 – GPS N 49˚20'48.5'', E 20˚39'01.1''; altitude 660 m), the pale, yellowish and pinkish sandy-crinoidal limestones (Smolegowa Limestone Formation) are excavated for building purposes. Limestones are massive to thick-bedded with strata dipping moderately to the south. At the foot of the cliff near entrance to the quarry, the Smolegowa limestones are overlain by red micritic, weakly nodular limestones of the Bohunice Fm. (Bathonian – Kimmeridgian; Aubrecht et al., 2006). This layer is thinning upslope, thus in the upper quarry stages it is reduced to several dm (see Aubrecht et al., 2006, their Fig. 12 – however, after the recent exploitation in the upper quarry levels, the younger deposits were removed completely). The Bohunice limestones are uncomformably overlain by the Albian to Cenomanian marlstones (Chmielowa and Pomiedznik Fms.), marly limestones and breccias, which also form fissure fillings in underlying limestones. Besides limestone fragments from underlying formations, including Upper Aptian – Lower Albian hedbergellids-bearing limestones not known from primary occurrences, there are frequent phosphatic oncoids and small quartz pebbles. The deep pre-Albian erosion, reworking of older breccias and multiple fissure fillings point to the oscillating sea level and emersion, subaerial erosion and karstification of the shallowest parts of the Czorsztyn Ridge during the Hauterivian – Aptian. As this event roughly corresponds to the global sea-level fall, it would be logical to ascribe the uplift to it. However, it is questionable if solely the eustatic lowstand in the order of tens of metres could account for the relatively deep erosion documented in several Czorsztyn profiles. Shallowing of the Czorsztyn Ridge started already in the Valanginian (Walentowa Breccia, crinoidal limestones of the Spisz Fm.) and its uplift seems to exceed the estimated value of the Barremian sea-level drop. Alternatively, a tectonic trigger could be considered as well – either extensional due to the rift shoulder uplift during breakup of the Magura Ocean (Plašienka, 2003), or due to the passive margin inversion generated by far-field compressional stresses transferred from the Central Carpathians.

Very interesting is the composition of heavy minerals extracted from the basal Chmielowa marls from this locality. Aubrecht et al. (2009) have found that association is dominated by Cr-spinels (more than 40 %) and garnet (30 %), other stable minerals of the zircon-rutile-tourmaline assemblage occur in concentrations below 10 %. Chemistry of garnets indicates their origin from high-grade metamorphic rocks as eclogites, granulites, gneisses and amphibolites, which are similar sources as in established for the Jurassic PKB sediments. Aubrecht et al. (2009) therefore suppose that the sources of garnets should be looked for in the Czorsztyn Ridge basement. On the other hand, the spinels were likely derived from oceanic crustal sources similar to the Meliaticum. Relying on this, Aubrecht et al. (2009) elaborated a completely new paleogeographic scheme of the PKB (Oravic) realm – the Czorsztyn Ridge basement was rifted off the Moldanubian Zone of the Bohemian Massif during the Middle Jurassic to create the Magura Ocean in between, while other Oravic units (e.g. Niedzica, Kysuca-Pieniny) were facing this ocean, i.e. they were located paleogeographically north of the Czorsztyn Ridge. The latter, on the other hand, was juxtaposed to the exotic Andrusov Ridge (source of spinels – a laterally translated part of the Meliata suture) that neighboured the northern CWC margin. This strange arrangement should have resulted from pre-Albian, large-scale sinistral translations along the CWC/PKB intervening zones.

The first description of transgressive contact of Cretaceous marls and Jurassic limestones from this area was published already by Andrusov et al. (1959). However, they mentioned a "small klippe" north of Jarabina, which was probably not the presently quarried large klippe Lysá skala. Above a corroded surface on saccocomid limestones, they observed a tiny limonite crust followed by a thin layer of red marly limestones of the "globigerinid-radiolarian microfacies" with *Ticinella roberti* (Albian, Rudina Beds) and then by variegated globotruncanid marls (Cenomanian).

<u>Locality 4</u> – Jarabina Narrows of the Malý Lipník brook (duplex in the Subpieniny nappe)

Lithostratigraphic-structural profile (D. Plašienka)

The Jarabina Narrows is about 500 metres long gorge excavated by the Malý Lipník brook in massive Jurassic limestones of the Czorsztyn Succession. It is an epigenetic valley modelled by the karst and river erosion processes. Its local Ruthenian name is "Medžy pecy"; the klippe is called Dutkova skala. The gorge is accessible by a touristic path, but it is hardly passable during the high water stand. It ends by a canyon as narrow as 2–3 metres with rocky cliffs more than ten metres high built by the "ammonitico rosso" limestones, the bottom is formed by an interconnected system of deep potholes.

The upper part of the gorge starts in the gently north-dipping, thick-bedded red nodular limestones of the Czorsztyn Fm. (Bathonian – Kimmeridgian). The main part is cut in subhorizontally lying massive pale crinoidal limestones of the Smolegowa Fm. (Bajocian), the terminal canyon at the southern end of the gorge struggles through Czorsztyn limestones again, moderately south-dipping in this case (Fig. 7). Thus the Jurassic limestones form a wide anticline and are overlain, behind the gorge edges, by variegated Upper Cretaceous marlstones of the "couches rouges" facies known also as the "Púchov marls" in the PKB. The uppermost layer of the rocky cliff on the right (western) side is formed by the pink biomicritic limestones of the Tithonian – Berriasian Dursztyn Fm. Below the canyon mouth to the south, the Jarabina quarry and the

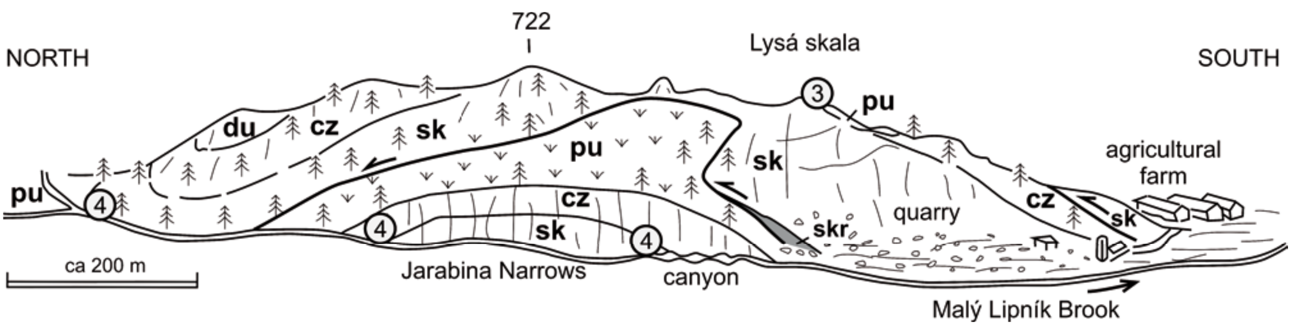

Fig. 7. Schematic view of the eastern slopes of the Malý Lipník brook Valley (Jarabina Narrows section, localities 3 and 4). Abbreviations: pu – "Púchov marls"; du – Dursztyn Fm.; cz – Czorsztyn Fm.; sk – crinoidal limestones (Smolegowa and Krupianka Fms.); skr – Skrzypny Shale Fm.

above Lysá skala klippe exposes a similar Czorsztyn Succession (locality No. 3), but forming a higher slice of this large-scale duplex structure. At the sole of this thrust imbricate, dark shales of the Aalenian – Lower Bajocian Skrzypny Fm. were exposed (Fig. 7). At the entrance to the quarry, this Lysá skala slice is overridden by the still higher, third imbrication of the same composition. Altogether, these imbricates create an antiformal thrust stack that is typically composed of ridge-type Czorsztyn Succession. We differentiate it as the Jarabina Subunit of the Subpieniny nappe (Fig. 2). In addition to the Jarabina area, similar duplex structures of the Jarabina Subunit are present north of Stará Ľubovňa (Nemecký vrch Hill) and on the Kamenica castle hill further to the east (Plašienka & Mikuš, 2010). Analogous structures are likely present also in the Polish Pieniny Mts., where they were defined as the "Czorsztyn imbricated unit" by Książkiewicz (1977) – for example the Homole Block near Jaworki (cf. Birkenmajer, 1970; Jurewicz, 1994, 1997). Unlike the Maslienka small-scale imbricates, the Jarabina Subunit consists of duplex structures, in which the individual large slices are reinforced by a thick competent layer of Jurassic limestones, and which are always in the normal position.

Locality 5 – Jar-1 borehole (Maslienka Subunit and Šariš Unit)

Position, lithology and stratigraphy of the borehole log (D. Plašienka, J. Soták, D. Pivko, M. Jamrichová, Š. Józsa, E. Halásová, V. Mikuš)

The Jar-1 drilling was bored on a flat top of a low ridge W about 500 m NW of the northern end of Jarabina village (Fig. 4 – altitude 703 m a.s.l., coordinates N 49°20.882, E 20°38.646). The drilling was realized by the company Envigeo a. s., Banská Bystrica, in winter 2009. Financing was provided by the Slovak Research and Development Agency (project APVV-0465-06 "Tectogen"). The borehole

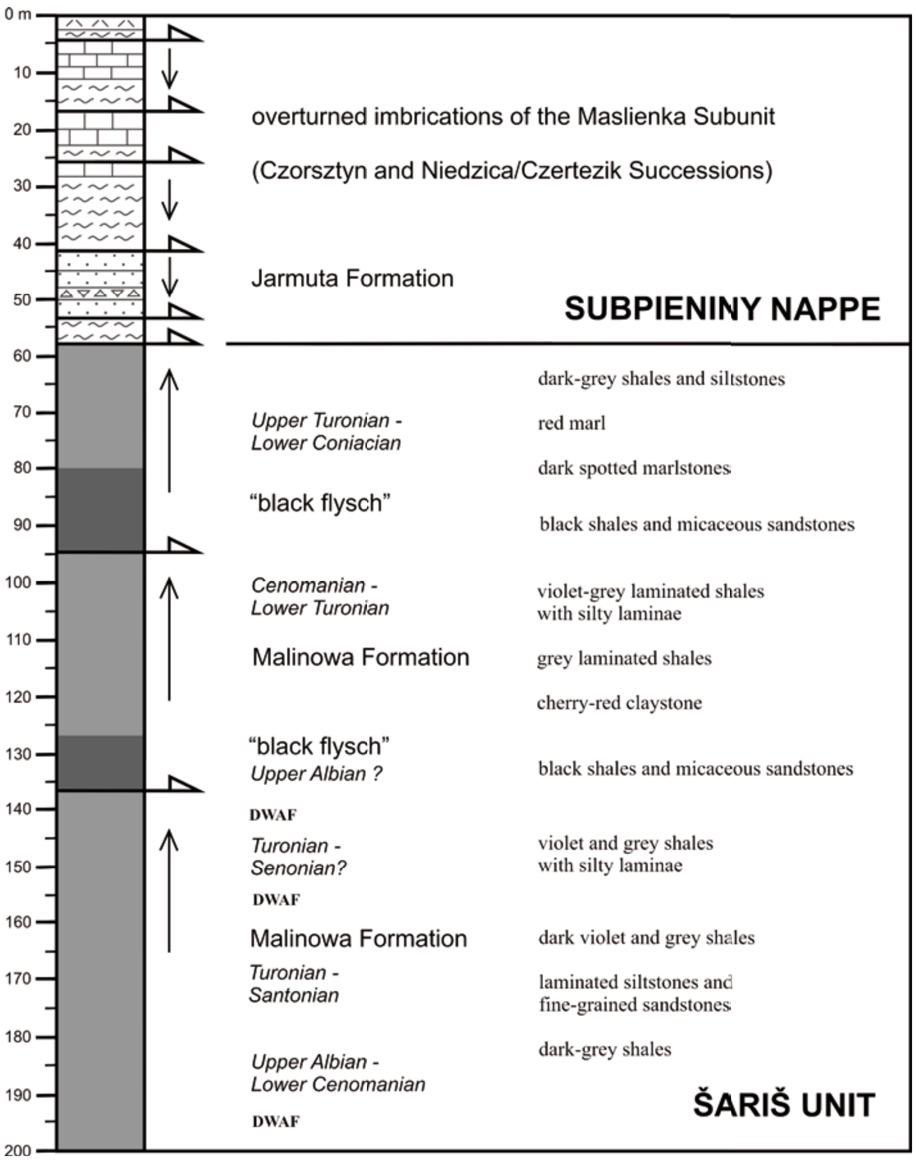

Fig. 8. Overall lithostratigraphic log of the Jar-1 borehole. For detail of the upper part see Fig. 9.

was continuously cored up to final depth 200 m with a core diameter 4 cm. The core material is stored at the Faculty of Natural Sciences, Comenius University in Bratislava. Here we briefly present the preliminary results of lithologic and biostratigraphic investigations of the core material, which is still in progress.

The drilling site was chosen after comprehensive geological mapping and structural research of the area and following interpretation of geophysical profiles (vertical electric sounding, detailed gravimetric profiling – Equis ltd, Bratislava) carried out in the area between Jarabina and Litmanová villages (Mikuš, 2010). The primary aim was to obtain new material for further analytical investigations, especially from the "klippen matrix", which is poorly outcropped in this area, and to ascertain the deeper structure of the PKB in a morphologically not very expressive, grassy region mostly covered by soil and weathering products.

The geological structure of the vicinity of the Jar-1 borehole is rather complex with features typical for the PKB. The grass-covered flat ridge is full of isolated small knobs composed of Jurassic limestones – sandy crinoidal limestones (Smolegowa and/or Krupianka Fms), red nodular limestones (Czorsztyn Fm.) and pink and white biodetrital limestone (Dursztyn Fm.). The matrix of these small klippen is not visible at the surface. It was partly revealed by several shallow drills (up to 7 m) around, which uncovered variegated, mostly dark marlstones with occasional sandstone intercalations. On the other hand, just a few hundred metres east of the drilling site, there is a prominent canyon-like valley (Jarabina Narrows) excavated in a thick, flat-lying sequence of Jurassic

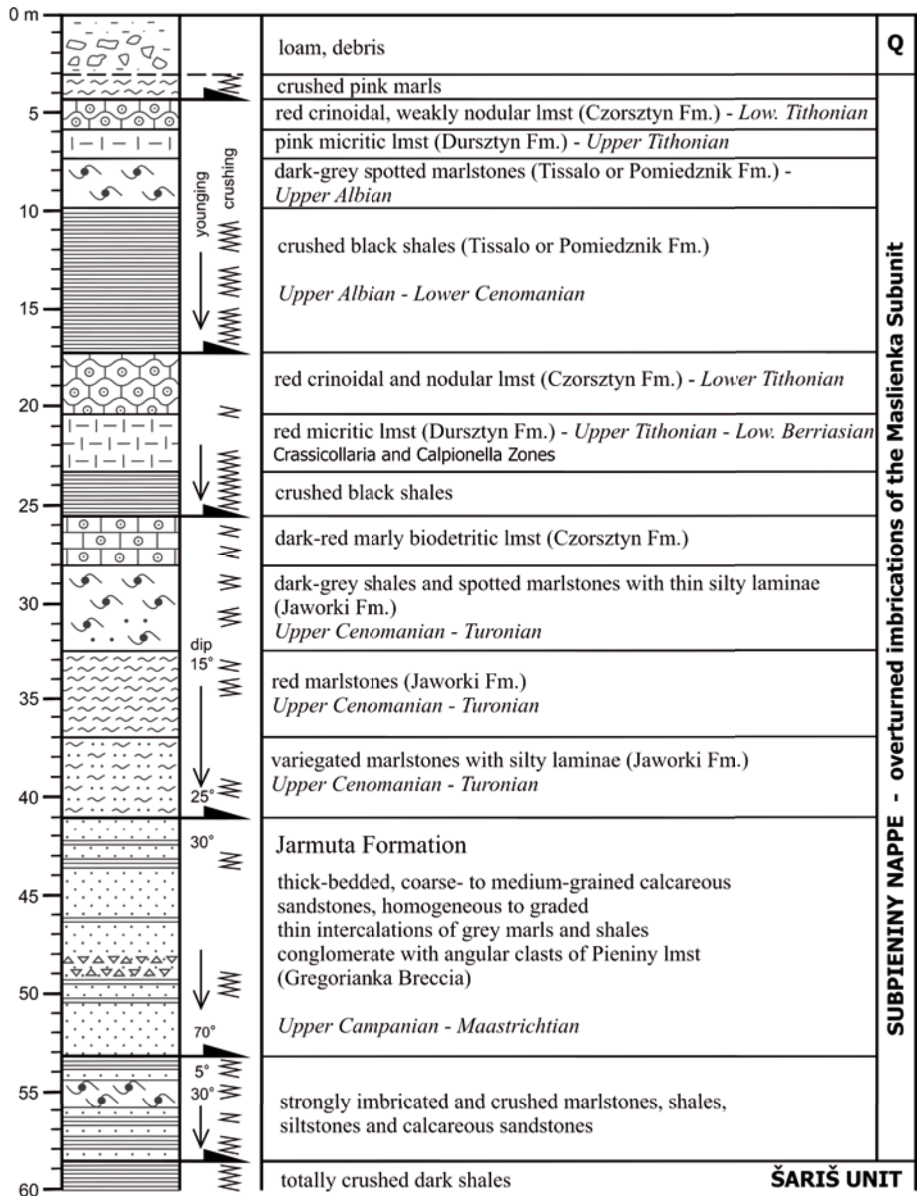

Fig. 9. Lithostratigraphic profile of the upper part of the Jar-1 borehole. Note several slices with repeating, but overturned successions.

limestones typical for the Czorsztyn Succession (see Fig. 6). Thus the intention was to reach this continuous thick Czorsztyn sequence and to find out the inner structure of the Subpieniny nappe. However, as described below, the borehole results, particularly from its lower part, were very different from this supposition.

The generalized profile of the Jar-1 drilling is as follows (Figs. 8, 9):

4–17.5 m: an overturned succession of 2 m of red biodetritic, weakly nodular micritic limestone of saccocomid-radiolarian microfacies (packstone) of most probably Lower Tithonian age (Czorsztyn and/or Dursztyn Fms.); 1 m of grey-green and pink calpionellid-saccocomid biomicritic limestone (wackestone to packstone) of the Upper Tithonian Crassicollaria Zone (Dursztyn Fm.); 2.5 m of dark spotted marlstones and 13 m of crushed black calcareous shales with foraminifers indicating Upper Albian – Lower Cenomanian age: *Hedbergella delrioensis* (Carsey), *Praeglobotruncana delrioensis* (Plummer), *Rotalipora balernaensis* (Gandolfi), *R. appeninica* (Renz), *R. gandolfi* Luterbacher & Premoli-Silva, *R. deckei* (Franke), *R. globotruncanoides* Sigal, *R. cushmani* (Morrow), *Tritaxia gaultina* (Neagu) – Tissalo or Pomiedznik Fm.;

17.5–25.5 m: another overturned slice of red to brown nodular limestone (3 m), crinoid packstone to grainstone of Lower Tithonian age (Czorsztyn Fm.); 3 m of reddish biomicritic limestone (wackestone and mudstone) with calpionellid microfacies of the Upper Tithonian Crassicollaria Zone and Lower Berriasian Calpionella Zone (Dursztyn Fm.), this age is confirmed also by calcareous nannofossils; the slice also contains 2 m of strongly crushed black shales at the base;

25.5–41 m: next overturned slice consists of 2.5 m of dark-red marly biodetritic limestone (Czorsztyn Fm.); 4.5 m dark-grey shales and spotted marlstones with silty laminae; 8.5 m of red and variegated marlstones (Jaworki Fm.), which yielded rich microfossil evidence for the Late Cenomanian – Turonian age, including calcareous nannofossils and planktonic foraminifers *Rotalipora montsalevensis* Mornod, *R. cushmani* (Morrow), *R. gandorfi* Luterbacher & Premoli-Silva, *Praeglobotruncana delrioenisis* (Plummer), *P. gibba* Klaus, *Dicarinella oraviensis* (Scheibnerová), *D. algeriana* (Caron), *D. hagni* (Scheibnerová), *Helvetoglobotruncana helvetica* Bolli, *Marginotruncana coronata* (Bolli), *M. marginata* (Reuss), *M. schneegansi* (Sigal), *M. pseudolinneiana* Pessagno;

41–53 m: probably overturned slice dominated by calcareous, medium- to coarse-grained sandstones, homogeneous to graded in places, forming several metres thick amalgamated packets with thin intercalations of grey shales and marls; at the depth 48–49 m there are several dm-thick beds of clast- or matrix-supported conglomerates composed of up to 3 cm angular clasts of whitish Pieniny-type limestones (Gregorianka Breccia); the assemblage of planktonic foraminifers *Globotruncana arca* (Cushman), *Globotruncana marieri* Banner & Blow and *Gansserina gansseri* (Bolli) encountered in the depth 49.1 m, as well as large foraminifers *Orbitoides aff. gensacicus* (Leymerie), *Pseudosiderolites vidali* (Douvillé) and *Lepidoorbitoides* sp. point to the Upper Campanian – Maastrichtian age of this sandstone-rich sequence, which is classified to the Jarmuta Fm.;

53–58.5 m: strongly deformed zone of crushed spotty dark marlstones, shales, siltstones and calcareous sandstones

58.5–61 m: tectonic breccia – cataclasite of black shales;

61–80 m: dark-grey, calcite-poor shales with thin beds of siliceous shales, laminated siltstones and fine-grained sandstones, intervals of dark spotted and reddish-grey marlstones with sporadic foraminifers *Dicarinella oraviensis* (Scheibnerová), *D. concavata* (Brotzen), *Archaeoglobigerina* sp. (Upper Turonian to Lower Coniacian at 75.8 m), the sequence is ranged to the Malinowa and/or Haluszowa Fm.;

80–95 m: black shales with occasional mica flakes, rarely beds of dark, fine-grained, siliciclastic, micaceous sandstones – this sequence resembles the “black flysch” described under various names and stratigraphic ages from the Polish PKB (Grajcarek Unit – e.g. Birkenmajer, 1977, 2008; Oszczypko et al., 2004);

95–127 m: violet and dark-grey, laminated, carbonate-free or poor shales with silty laminae, grey laminated shales and cherry-red claystones, characterized by the DWAF (Deep Water Agglutinated Foraminifers) associations, with the index fossil *Uvigerinammina jankoi* (97.5 to 106 m) indicating Late Cenomanian to Early Campanian age (Turonian biozone – Morgiel & Olszewska, 1997; Olszewska, 1997); this shaly sequence is ranged to the Malinowa Formation;

127–137 m: “black flysch” – black shales and muscovitic sandstones, occasionally with crinoidal detritus, Lower Albian?;

137–200 m: cherry-red, violet-grey to dark-grey, calcite-poor shales with silty laminae and sporadic thin beds of siltstones and fine-grained sandstones of the Late Cretaceous age (Malinowa Fm.): calcareous nannofossils from 172.1 m indicate Turonian to Santonian age and foraminifers of DWAF association from 187.4 m point to the Late Albian – Cenomanian age: *Bulbobaculites problematicus* (Neagu), *Ammobaculites carpathicus* (Geroch); the lowermost drilled part is composed of dark-grey shales.

The profile of the Jar-1 borehole is interpreted as composed of two parts belonging to different units. The upper, approximately 60 metres consist of at least 5 imbrications with internally overturned successions embracing members typical for the Czorsztyn and/or Czertezic/Niedzica successions (cf. e.g. Birkenmajer, 1977; Wierzbowski et al., 2004). The lower imbrication involves Jarmuta-type sandstones with a few beds of Gregorianka-type breccias. Strata are gently to moderately dipping (15–30°), only the lower part of the Jarmuta Fm.-bearing slice shows steep dips up to 70°. Taking into account the surrounding geological structure, we range this imbricated package to the Maslienka Subunit of the Subpieniny nappe (Fig. 2).

The lower profile, from ca 60 m to the final depth 200 m probably involves three imbrications composed of Cretaceous deep-water, hemipelagic sediments (Fig. 8). These are carbonate-poor, dark-grey and violet shales with occasional distal turbidite beds. Based on poor DWAF associations, they are ranged to the Upper Cretaceous Malinowa Fm. The mid-Cretaceous "black flysch" sediments form the lower parts of the imbrications. Accordingly, sediments should be generally in sequence, in spite that in places overturned and steeply dippnig beds indicate some tectonic disturbances. We interpret these sediments as belonging to the Šariš Unit (see Plašienka and Mikuš, 2010).

<u>Locality 6</u> – Jar-2 borehole (Maslienka Subunit and Šariš Unit)

Position, lithology and stratigraphy (D. Plašienka, J. Soták, E. Halásová, D. Pivko, M. Jamrichová, Š. Józsa, V. Mikuš)

The Jar-2 drilling was situated on the same ridge as the Jar-1 borehole, about 1 km north of it (Figs. 2 and 4 – altitude 704 m a.s.l., coordinates N 49°21.395, E 20°38.302). It reached the 140 m depth, all other characteristics are the same as for the Jar-1 indicated above (stop 5). The borehole penetrated about 6 m of eluvial loams and then a sedimentary complex that is preliminarily divided into four sequences ranged to two units (Subpieniny nappe and Šariš Unit – see Fig. 10).

6–19.6 m, Sequence 1: strongly deformed grey and red marly shales with fragments of dark spotted marlstones, siltstones and sandstones containing clasts of *Calpionella* and *Saccocoma*-bearing limestones and decimetric to metric blocks of reddish massive limestone – biomicrite (wackestone and packstone) of the calpionellid-radiolarian microfacies, Crassicollaria Zone (Upper Tithonian, Dursztyn Fm.), as well as red nodular limestones (Czorsztyn Fm.?); calcareous nannoplankton from 3.2 and 5.6 m is of Albian – Maastrichtian age, the

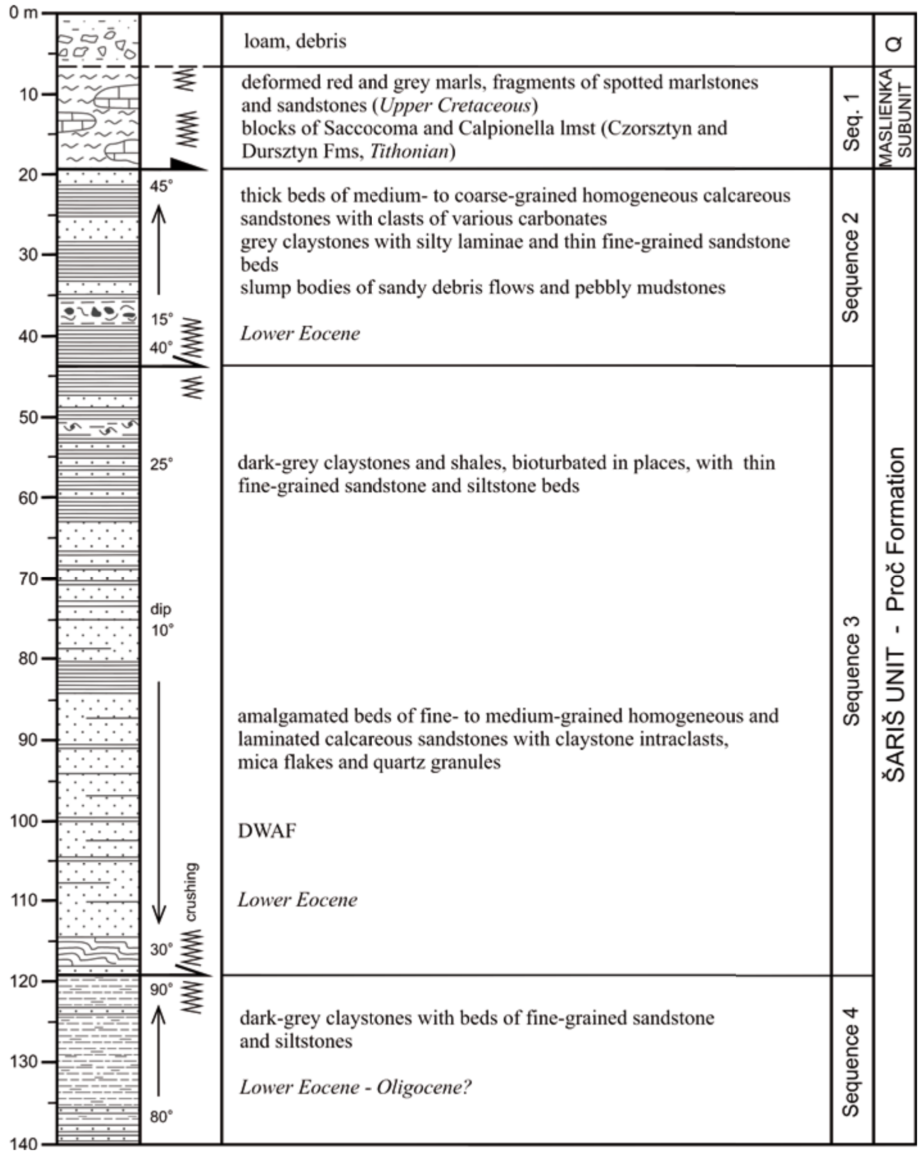

Fig. 10. General log of the Jar-2 borehole.

poorly preserved foraminifers *Rotalipora* cf. *cushmani*, ?*Rotalipora* cf. *appenninica* from the matrix marls indicate Upper Albian? – Cenomanian (13.2 m) to Campanian – Maastrichtian age (19.6 m);

19.6–44.1 m, Sequence 2: crushed grey, greenish and seldom pinkish, massive and laminated, sometimes sandy claystones with silty laminae and thin fine-grained sandstone beds, intercalated by several 10–150 cm thick intervals of homogeneous, medium- to coarse-grained calcareous sandstones with mm-sized, scattered clasts of various limestones, a few thin slump bodies of sandy debris flows and pebbly mudstones; mostly normal position is indicated, strata dips with respect to the borehole axis are gentle to moderate (up to 45°);

44.1–119.4 m, Sequence 3: dark-grey, carbonate--poor claystones and shales, occasionally bioturbated, with several metres thick intervals of fine- to medium--grained, homogeneous, in places laminated calcareous sandstones, which are sometimes mica-rich, or containing quartz granules, with claystone intraclasts and slumping structures (hydroplastically deformed laminae), traces of bitumens (around depth 100 m); the whole sequence seems to be overturned according to sedimentary structures, gentle dips 10–30°;

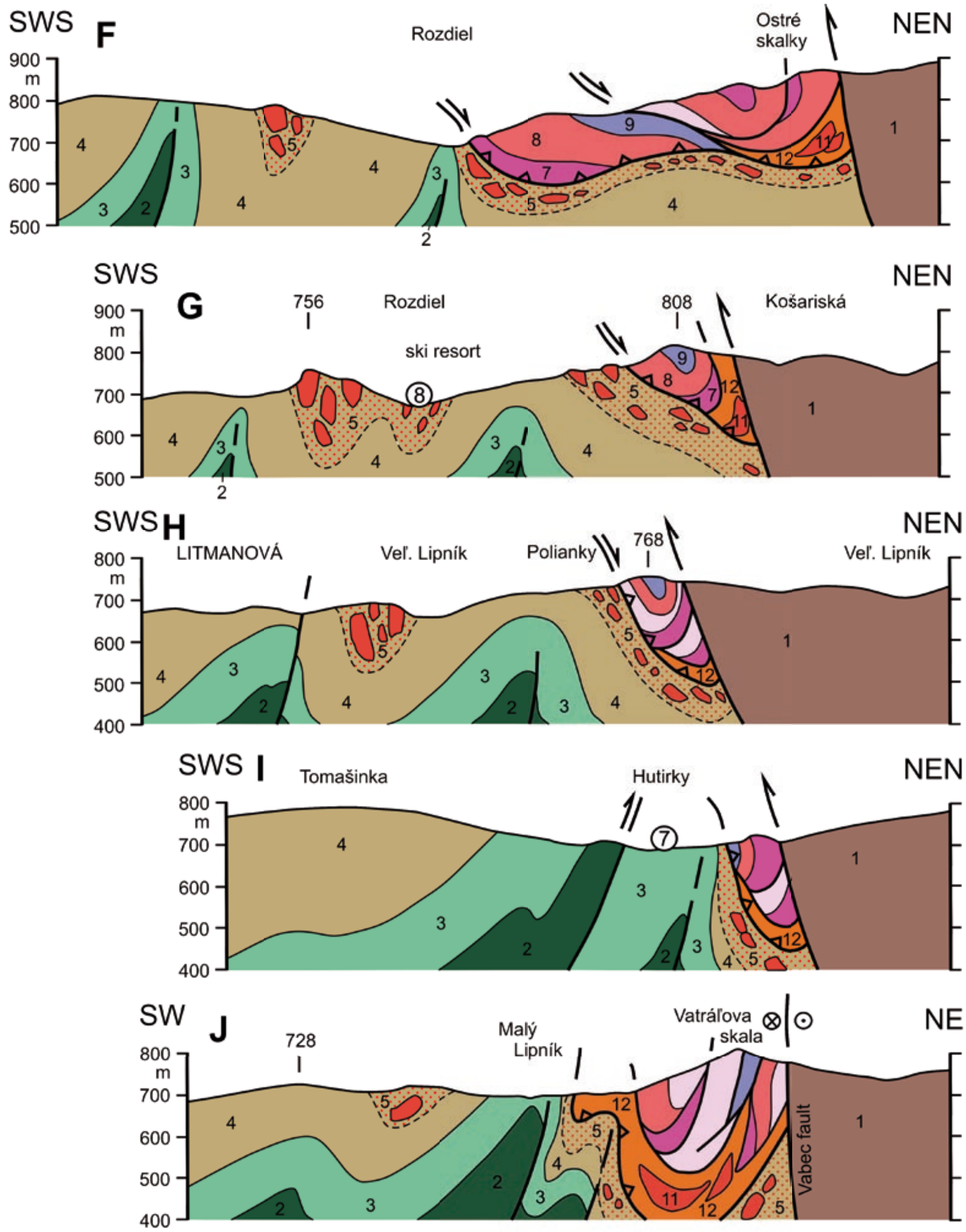

Fig. 11. Geological cross-sections **F–J** of the area north and east of Litmanová. For the legend see Fig. 2 and for their approximate position see Fig. 4.

119.4–140 m, Sequence 4 occurs after a tectonic boundary indicated by a crushed zone, it is composed of dark-grey claystones that prevail over fine-grained sandstones and siltstones; strata are strongly disturbed probably due to both syn-sedimentary and tectonic processes, dips are variable, often steep to vertical, but the sequence is generally in a normal position.

The upper ca 20 m of the borehole profile (Sequence 1) is interpreted as a tectonized block-in-matrix complex of Jurassic limestone fragments embedded in Upper Cretaceous marly matrix. By this it corresponds to the Maslienka Subunit of the Subpieny nappe. The two middle sequences likely represent separate imbrications of Paleogene flysch sediments ranged to the Šariš Unit (Proč Fm.). The age and affiliation of the lowermost Sequence 4 remains problematic.

The Lower – Middle? Eocene age of the Sequence 2 is corroborated by foraminifers *Subbotina boweri*, *Acarinina pentacamerata* and nannofossil species from 29.2 m indicating Lower Eocene and from 39.7 m Eocene age. In the underlying flysch deposits (Sequence 3), agglutinated foraminifers of the abyssal DWAF assemblage occur (genera *Paratrochamminoides*, *Bathysiphon*, *Karrerulina*, *Glomospirella*, *Trochammina* and others), nannofossils are Eocene in age (samples from 47.7, 51.6, 57.3 and 82.2 m). At around 100 m depths, the species Turborotalia cerroazulensis Cole and Lower Eocene nannoplankton were encountered. The lowermost Sequence 4 is characterized by tiny planktonic foraminifers *Paragloborotalia nana* Bolli, *Pseudohastigerina naguewichiensis* Myatliuk, *Tenuitella*, *Protentella*, *Chiloguembelina*, which would not exclude a younger, possibly Oligocene age. On the other hand, only the Eocene age is indicated based on nannoplankton (samples from 123, 132, 134.4 and 139.8 m).

Locality 7 – Hutirky valley northeast of Litmanová

Cretaceous formations of the Šariš Unit (D. Plašienka, Š. Józsa, J. Soták)

Hutirky is a wide, flat valley 1 km east of the Litmanová ski resort, near the agricultural farm. Here, the temporal small outcrops in meandering creeks occasionally expose various Cretaceous shaly and marly formations that occur in the core of a large-scale antiform. In its centre, steeply dipping and heavily folded Lower Cretaceous thin-bedded, marly limestones similar to the Pieniny Fm. occur. Owing to the slightly asymmetric shape of the antiform with northern vergency, its limbs are different – the northeastern is formed by a verticalized outlier of the Maslienka Subunit composed of blocky klippen with Niedzica/Czertezik Succession embedded in matrix of Cretaceous marlstone formations (sections H, I and J in Fig. 11). This limb is strongly reduced also due to the immediate contact with the Magura Unit which is partially thrust back. The southwestern limb is less steep and the Cretaceous formations are overlain by the Jarmuta/Proč Fm. with bodies of Milpoš olistostromes including the Litmanová group of klippen (locality No. 8).

From the upper to the lower section of a small creek passing along the eastern fence of the farm, we have observed and partly dated by means of foraminifers the following formations: variegated red and grey marly shales (Cenomanian to Turonian), dark spotted marlstones and black shales, reddish and dark-grey spotted marls (Upper Albian), reddish and grey claystones with thin sandstone beds (Cenomanian), red marly shales, grey shales with silty laminae (Upper Cenomanian – Lower Turonian), dark-red shales (DWAF Turonian – Santonian). The continuation of the profile along the Malý Lipník Strean down from the agricultural farm towards the Litmanová klippen again shows multiple alteration or red and grey pelagic shales and marls. Red marls are very rich in planktonic foraminifers of the Turonian – Coniacian age, while the grey marly shales contain both planktonic and agglutinated foraminifers of Turonian age. In red, non-calcareous shales only Turonian agglutinated foraminifers were found.

The strata are sheared and the contacts between individual formations are always tectonic, therefore it is difficult to reconcile their mutual relationships. Most probably all these strata represent mid- and Upper Cretaceous deposits comparable to those encountered by the Jar-1 borehole (e.g. red pelagic shales with Upper Cretaceous DWAF fauna of the Malinowa Fm. – see loc. 5), consequently we consider them to belong to the Šariš Unit.

Locality 8 – Rozdiel valley, ski resort Litmanová (Milpoš Breccia)

Situation, lithological profiles and composition of breccias (J. Madzin, D. Plašienka, Š. Józsa)

The carbonate breccias from this locality were allegedly known already to Uhlig (1890), Andrusov (1945) mentioned them as a "breccia facies" of the Santonian Upohlav conglomerates. A more detailed description comes from Nemčok et al. (1989). It was one of their four localities of Gregorianka breccias (the other were Jarabina – our stop No. 1, Milpoš and Terňa). In their lithological profile, the breccias occur in seven, variously thick layers within a flysch sequence. They described also olistolith of nodular limestone and a body of pebbly mudstone. The flysch sandstones are turbiditic calcareous greywackes with typical with T_{a-b-c} Bouma intervals. Among the pebble material they described crinoidal and filamentous limestones, *Saccocoma* and *Calpionella* limestones, variegated *Globotruncana* marls and rare radiolarites. In the sandy matrix of breccias and in marly shales they found Paleogene foraminifers (*Globorotalia* cf. *crassata*, *Globigerina* sp., *Turborotalia* sp.).

Our new investigation confirmed that the Milpoš breccias form here lenticular to tabular bodies inserted within turbidite sandstones and shales of the Jarmuta-Proč Fm. (Fig. 12). Rare planktonic foraminifers of Upper Paleocene to Lower Eocene age were found in the claystones. Breccias are unsorted, coarse-grained, clast-supported with chaotic internal structure. Occasional matrix consists mainly of fine-grained sandstone, but mostly it is lacking and the space between individual clasts is filled with carbonate cement. Clasts are unsorted; their size ranges from a few mm to boulder dimensions. Roundness of clasts varies from angular to subrounded shape. The pebble analysis showed

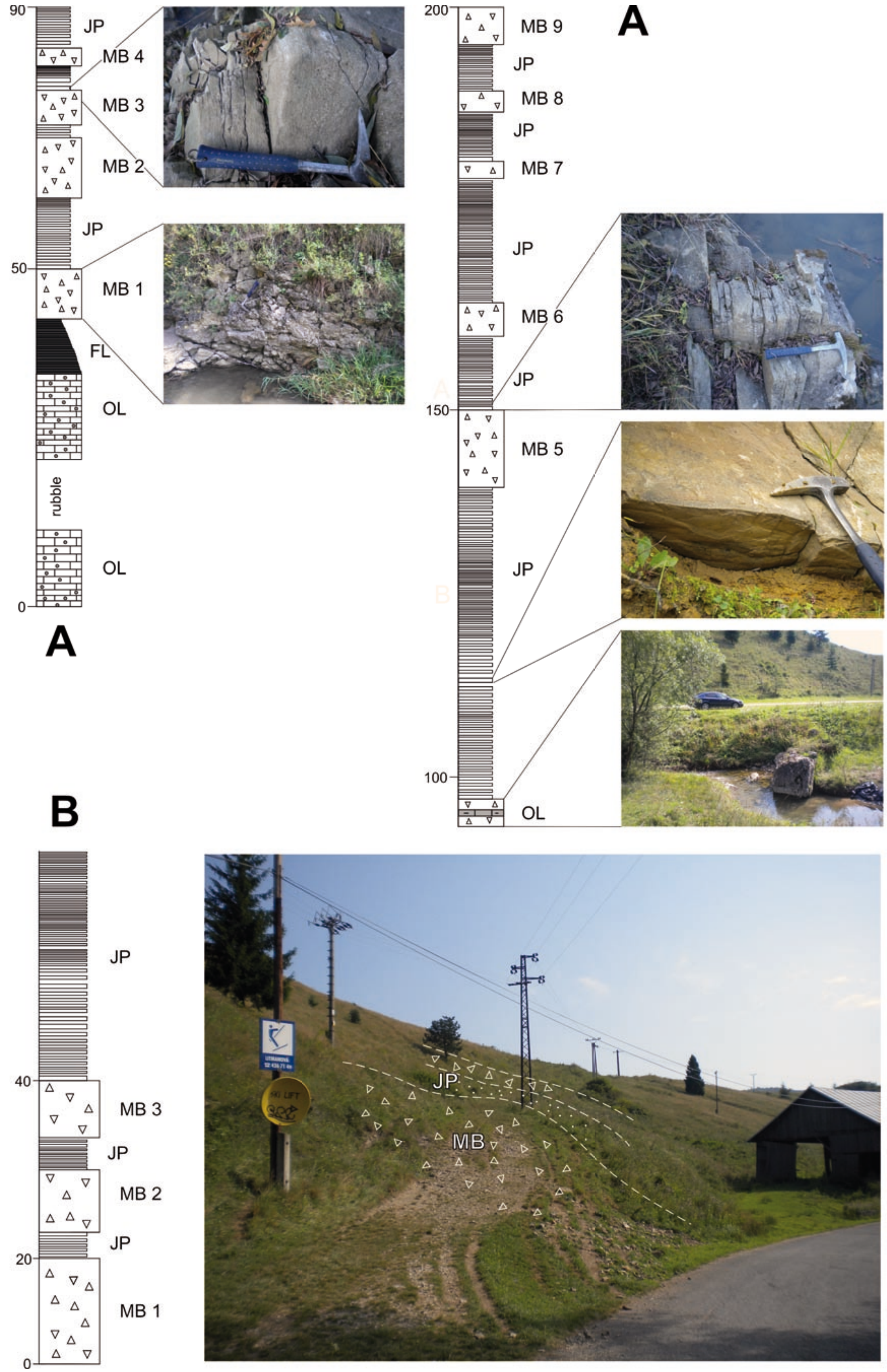

Fig. 12. Lithological sections of the Milpoš Breccia Member, Jarmuta-Proč Fm., around the ski resort Litmanová in the Rozdiel valley. **A** – profile upstream the Rozdiel brook; **B** – profile along a field trail towards the north from the Rozdiel and Malý Lipník brooks junction. FL – dark marlstones of the Fleckenmergel lithofacies; MB – Milpoš Breccia bodies; OL – olistolites of the Upper Jurrasic red nodular limestones of the Czorsztyn Fm.; JP – the Jarmuta-Proč Fm., fine to coarse-grained calcareous sandstones, mainly massive – facies of the proximal sandy debris flows.

that the most common clasts are the Jurrasic red and white crinoidal limestones, red nodular limestones, the Lower Cretaceous light *Calpionella* limestones, red radiolarites and radiolarian limestones and black shales (Skrzypny Fm.?). The youngest identified clasts are brick-red marls, well known as the Púchov marls of the Upper Cretaceous age; however, these occur sporadically. In addition to the material derived from the klippen successions, the breccia contains also rock fragments of siltstones, dolomites, metamorphic rocks, rare clasts of basic volcanics and relatively abundant quartz and feldspar grains.

The breccias are closely juxtaposed to the spectacular row of the Litmanová group of blocky klippen. A closer observation reveals that it is in fact a chaotic mixture of blocks of various sizes (up to 100 m), with variously oriented internal fabric. Majority of blocks are decametric and include only one formation (mostly red modular limestones), but the largest klippe just at the Rozdiel-Veľký Lipník junction contains a complete Jurassic to lowermost Cretaceous succession, which was studied in detail by Wierzbowski et al. (2004, their Fig. 6) and was classified as the Czertezik Succession. However, these authors indicated that the differences between the Czertezik and Niedzica (Pruské) successions, as originally defined by Birkenmajer (1977), are very subtle. They also reconstructed the paleogeographic arrangement of these successions in a new way – Czorsztyn-Niedzica-Czertezik-Branisko (Kysuca) from north to south. However, this concept was criticized by Birkenmajer (2007) who provided arguments in favour of his older scheme Czorsztyn-Czertezik-Niedzica--Branisko. In any case, we have not distinguished between the Niedzica and Czertezik klippen successions during our mapping research, since possible differences can only be recognized by detailed biostratigraphic profiling, which is seldom possible, and klippen with both successions, along with the typical Czorsztyn Succession as well, are usually mixed together either in the Maslienka Subunit of the Subpieniny nappe, or as olistoliths in the Jarmuta/Proč Fm. of the Šariš Unit. Only locally, e.g. in the Ostré skalky klippen NW of Litmanová, the Niedzica/Czertezik Succession forms more-or-less continuous imbricated thrust sheet of the Maslienka Subunit resting on the Czorsztyn-type sheet (see sections F and G in Fig. 11). These structural circumstances are analogous to those of the Czajakowa skala klippe just a few km to the west in Polish territory, where the nappe outlier of the Niedzica nappe overrides the thick Czorsztyn Unit of the “Homole Block” (cf. Birkenmajer, 1970).

The Litmanová klippen occur in a narrow pinched syncline squeezed between two narrow anticlines of Cretaceous formations of the Šariš Unit (cross-sections F, G and H in Fig. 11). They are resting in various matrix – most commonly in various Cretaceous marlstones, Jarmuta/Proč-type sandstones, and around the klippe described by Wierzbowski et al. (2004), also by black spherosideritic shales of the Skrzypny Fm. (Murchisonae Beds in older literature). The Litmanová locality of these shales (bedrock of the Veľký Lipník Stream from the northern side of the klippen) is famous by occurrences of excellently preserved pyritized ammonites in the cores of pelocarbonatic, disc--shaped concretions, which prove their Aalenian to Lower Bajocian age (Scheibner, 1964, 1967). Owing to the poorly outcropped matrix of the Litmanová blocky klippen, it is difficult to recognize whether they represent tectonic slices in the Maslienka Subunit, or olistoliths in the Milpoš Breccia. The latter possibility is preferred here, since klippen are closely related to outcrops of the Milpoš-type breccias. However, as suggested by Plašienka and Mikuš (2010), this differentiation is partly artificial – the tectonic and sedimentary processes were closely related, since the olistoliths and sliding masses were derived from the tectonically dismembered front of the Subpieniny nappe (see also Jurewicz, 1997). Thus the blocky klippen, which are at least partly embedded in their original Cretaceous (and also Jurassic) marly and shaly matrix and overlie the flysch deposits of the Jarmuta/Proč Fm., may be equally considered either as gravitational nappe outliers (tectonosomes), or as mass-transport sliding masses (olistostromes) in a tectonically active sedimentary setting. Each of the process caused their internal disorganization, maybe a bit more pronounced in the latter case.

Another important feature of the klippen is their structural record. As described in the collateral structural paper (Plašienka, this issue), both the Maslienka blocky klippen and Milpoš olistoliths bear the same structural elements, namely the bedding-perpendicular cleavage indicative for layer-parallel shortening. This is interpreted as a result of an early contraction event resulting in detachment of mechanically stratified sedimentary successions and their subsequent thrusting along weak décollement horizons (as e.g. the Skrzypny shales – see Fig. 3). The competent layers of mostly massive limestones show only the very low-grade deformation mechanisms like the mass-transfer by pressure solution and precipitation, while the incompetent “scaly” shales and marls are strongly sheared in places. This partly applies also for the post-nappe deformation events dominated by the dextral transpression that finally shaped the present structure of the PKB in Eastern Slovakia (e.g. Ratschbacher et al., 1993).

Conclusions

Based on detailed lithological and structural mapping, geophysical profiling, logs of two boreholes up to 200 metres deep, as well as biostratigraphical data from the majority of formations distinguished, we have defined three superposed thrust sheets in the investigated part of the PKB in Eastern Slovakia. All three are ranged to the Oravic Superunit, which paleogeographically represents an independent domain surrounding the Czorsztyn Ridge in the Middle Penninic position. The stacking progression of Oravic units is documented by the sedimentary record – by tectonosedimentary breccias that terminate the coarsening- and thickening-upward synorogenic sequences of individual nappe units. Among the most prominent features of these breccias are their ages and compositions. The Maastrichtian to possibly Lower Paleocene Gregorianka Breccia is a member of the Subpieniny Unit that was overridden by the Pieniny nappe at that time, as it is documented by their composition. Similarly, the Maastrichtian to Lower Eocene Milpoš Breccia of the lowermost Šariš Unit consists of material, including also huge olistoliths in this case, which was derived from the overthrusting Subpieniny nappe carrying also the piggy-back Pieniny sheet.

Summing up, the area presented here at eight localities provides a beautiful field example of sedimentary recording of superficial thrusting processes. The structural record, whatever important in general, can offer merely supplementary information in this particular case. Earlier structural works from this area (Ratschbacher et al., 1993; Nemčok and Nemčok, 1994) emphasized the role of transpression processes in formation of the intricate PKB structure. Indeed, dextral transpression was crucial for formation of the present shape of the PKB. However, the PKB sector presented in this paper, as well as in papers by Plašienka and Mikuš (2010) and Plašienka (this issue), clearly preserves relics of deformation and sedimentary structures inherited from the early thrusting stages of the PKB development.

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