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Geological structure and evolution of the Pieniny Klippen Belt to the east of the Dunajec River – a new approach (Western Outer Carpathians, Poland)

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The area studied, known as the Małe (Little) Pieniny Mts., belongs to the Pieniny Klippen Belt (PKB), a suture zone that separates the Central Carpathians from the Outer Carpathian accretionary wedge. Along its northern boundary the PKB is separated from the Paleogene to Early Miocene flysch deposits of the Magura Nappe by a narrow, strongly deformed belt belonging to the Grajcarek tectonic Unit. This unit is composed of Jurassic, Cretaceous and Paleocene pelagic and flysch deposits. The Klippen units of the PKB are represented by Jurassic–Lower Cretaceous carbonate deposits overlain by Upper Cretaceous variegated marls and flysch deposits. We describe geological and biostratigraphic evidence concerning the palaeogeographic, stratigraphic and structural relationships between the Pieniny Klippen Belt and the Magura Nappe, that significantly modify previously held views on the evolution of the Małe Pieniny Mts. and the Polish sector of the PKB.

Key words: structure, evolution, Pieniny Klippen Belt, Magura Nappe, Grajcarek Unit.

INTRODUCTION

The Pieniny Klippen Belt (PKB) is a 600 km long suture zone that separates the Central Carpathians from the Outer Carpathians (Książkiewicz, 1977; Maheľ, 1981; Birkenmajer, 1986; Nemčok et al., 1998; Plašienka, 2012a, b; Márton et al., 2013). In a structural and genetical sense the PKB links two nappe-systems: the Palaeoalpine Central Carpathians and the Neoalpine Flysch Belt (Maheľ, 1989). The PKB successions are built up of Lower/Middle Jurassic to Upper Cretaceous pelagic and flysch deposits (Birkenmajer, 1977, 1986, 2001).

The Małe Pieniny Mts. of the Polish Western Carpathians are located between the Dunajec River valley to the west and Polish/Slovak state boundary to the east. These mountains are up to 12 km long and 5 km wide (Fig. 1). The Małe Pieniny Mts. have a significantly different tectonic style than the Pieniny Mts. This is visible on different geological maps (see Uhlig, 1905; Birkenmajer, 1979; Golonka and Rączkowski, 1983; Kulka et al., 1985). The compact geological structure of the PKB essentially ends at the Dunajec Fault (see Birkenmajer, 1979; Jurewicz, 2005). To the east of the Dunajec River the PKB clearly narrows, while the Peri-Klippen Zone, represented by the Grajcarek thrust-sheet, expands. At the same time the structure of the PKB is changed from a fold- and-thrust belt into a block structure. Further to the east the large blocks of Mesozoic rocks disappear and their place is taken by numerous small klippen (Nemčok, 1990a; Plašienka, 2012a). At the same time, east of Szczawnica, the area of occurrence of the "autochthonous Magura Paleogene" significantly broadens. In the Małe Pieniny Mts. (Fig. 1), the Magura Nappe and PKB are separated by the narrow, strongly deformed Peri-PKB Zone, known as the Grajcarek Unit (Birkenmajer, 1977, 1979, 1986) or the Grajcarek thrust-sheet (Oszczypko et al., 2010). This unit is composed of Jurassic, Cretaceous and Paleocene, pelagic and flysch deposits belonging to the Magura succession (Birkenmajer, 1977, 1986). The relationship between the PKB and the Magura Nappe, as well as the nature and position of the Grajcarek Unit, have been the subject of many disputes and wholly different interpretations, as is outlined below. Recent geological studies carried out in the Małe Pieniny Mts. have led to the conclusion that current views on the evolution cannot be any further sustained (e.g., Oszczypko and Oszczypko-Clowes, 2010, in print; Oszczypko et al., 2010, 2012a; Plašienka, 2012a; Plašienka et al., 2012).

This paper provides new data resulting from studies carried out by the authors. The results of these studies allow for a new interpretation of the structure and tectonic evolution of the area studied, based on new detailed, geological mapping and new biostratigraphical data obtained by authors. That involves: a revised geological structure of PKB and revised stratigraphic profile of the Grajcarek Unit; a new age interpretation and position of the "autochthonous Magura Paleogene"; and identification of the Kremná Formation (Early Miocene) within the Magura Nappe.

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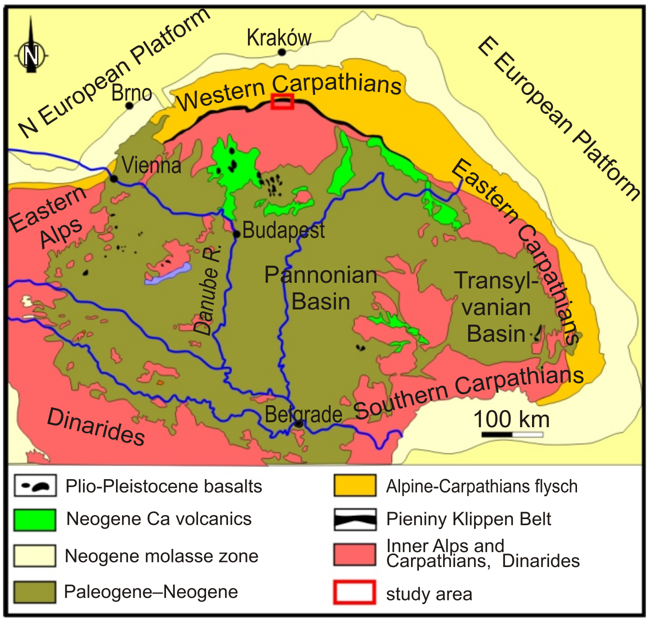

Fig. 1. Position of the study area in the Alpine–Panonian–Carpathian System

PREVIOUS WORKS

Geological studies of the Małe Pieniny Mts. have been carried out for more than 100 years. The first modern geological research in this area carried out by Uhlig (1903, 1905, 1907), who distinguished the "Nördliche Flysch Zone". During the time between the first and second world wars Horwitz and Rabowski (1930) and subsequently Horwitz (1935) distinguished the "Intra-klippen flysch" and concluded that the "Nördliche Flysch Zone" dips under the Jarmuta and Homole units, now regarded as the Grajcarek Unit and Czorsztyn Nappe, respectively.

From the beginning of the 1950s to the present, a fundamental geological survey of the PKB was carried out by Birkenmajer and his collaborators (Birkenmajer and Pazdro, 1968; Birkenmajer, 1970, 1977, 1979, 1983, 1986, 2001; Birkenmajer et al., 2008, and references therein). These studies mainly focused on Klippen successions of the PKB, and to a lesser extent on the Paleogene of the Magura Nappe. They concerned such topics as; the age of the "black flysch"; the role of the Laramian movements; and the Eocene transgression in the PKB. The ideas were partially qustioned by Sikora and collaborators (Sikora, 1962, 1970, 1971a, b; Morgiel and Sikora, 1975, see also Golonka and Rączkowski, 1983, 1984), as well as by Książkiewicz (1972, 1977).

On the base of previous work, Birkenmajer (1986, 1988) presented a new structural and evolutionary model for the PKB including:

– Late Cretaceous (Subhercynian) north-verging thrust folding, and formation of the Pieniny, Branisko, Niedzica, Czertezik and Czorsztyn units with simultaneous deposition of flysch and of synorogenic molasse deposits (Jarmuta Formation);
– Early Paleocene (Laramian) retro-arc thrusting of the Grajcarek Unit onto folded and nappe PKB structures;
– Eocene transgression from the Magura Basin onto the PKB;
– Early Miocene (Savian) refolding of the PKB Cretaceous nappes together with the Maastrichtian "Klippen Mantle" and the "autochthonous Magura Paleogene", strike-slip movements along the northern and southern boundary of the PKB and development of megabrecciation and megaboudinage (klippen structures);
– Middle Miocene (Styrian) compression and development of transverse strike-slip faults cutting the PKB and the southern part of the Magura Nappe.

Jurewicz (1997) proposed that in the terminal phase of thrust-nappe folding (until the Late Paleocene) the Czorsztyn and Niedzica units were transported through gravitational sliding, onto the foreland, forming numerous olistoliths and olistostromes, for example the Homole and Biała Woda blocks, the largest olistoliths in the Małe Pieniny Mts. (see Cieszkowski et al., 2009). Simultaneously Jurewicz (1997) referring to Birkenmajer's (1986) views questioned the overthrusting of the Grajcarek upon the Magura Nappe, considered that a transition existed between these units.

In the Małe Pieniny Mts., systematic lithostratigraphical and biostratigraphical research into the Paleogene flysch of the Magura succession was initiated by Bogacz and Węcławik (1962) who found the "Nördliche Flysch Zone" of Uhlig (1903, 1907) in Krościenko area as an equivalent of the Beloveža Formation of the Magura succession. Watycha (1965) distinguished the refolded sub-Magura Beds and Magura Sandstone at the front of the PKB in the Szczawnica area, south of the Homole Block and near Stachorówka Hill. Birkenmajer (1970) also described a transgressive contact between the Złatne (Szczawnica) Beds and crinoidal limestone of the Czorsztyn Unit. This point of view was challenged by Sikora (1970), which showed that the Zlatne Beds are the youngest member of the Złatne succession of the PKB (Morgiel and Sikora, 1975).

Golonka and Rączkowski (1983, 1984) in flysch deposits of the Szczawnica area distinguished a number of Paleogene lithostratigraphical units underlain by Cretaceous-Jurassic strata of the Grajcarek succession. A few years later Birkenmajer and Oszczypko (1989) introduced a formal lithostratigraphy for the PKB and Krynica Zone, partly based on Early Eocene calcareous nannoplakton (Birkenmajer and Dudziak, 1981).

Oszczypko et al. (2005a) and Oszczypko and Oszczypko-Clowes (2010) studied the Paleogene deposits of the "Klippen Mantle" in relation to the neighbouring strata of the Magura Nappe and established an earliest Miocene age for the newly-defined Kremná Formation. According to them, the Kremná Formation together with the underlying Eocene–Oligocene Magura Formation form the terminal deposits of the Magura Nappe (Krynica facies Zone). Oszczypko et al. (2010), based on work in the Małe Pieniny Mts. (Poland) and the Stará Ľubovňa area (E Slovakia), recognized that the flysch deposits of the Jarmuta-Proč Formation are the youngest sedimentary member of the lower tectonic unit covered by the PKB nappes. This unit, corresponding to Grajcarek thrust-sheet in Poland, named here as the Fakľovka Unit, involves also mass flow deposits and olistoliths of the typical Klippen successions, which record thrusting events in the overlying Subpieniny and Pieniny nappes. Accordingly, many klippen and blocks of sedimentary rocks in this area are not of tectonic origin. In the eastern sector of the Slovak PKB as the semi-counterpart of the Grajcarek Unit, the Fakľovka/Šariš Unit has been distinguished (Plašienka and Mikuš, 2010; Plašienka, 2012a, b; Plašienka et al., 2012).

METHODS

During the last decade, new integrated geological studies have been carried out by the authors in the Małe Pieniny Mts. These studies consisted of detailed geological mapping at 1:10,000 scale, and lithostratigraphical and biostratigraphical studies of the Grajcarek succession, of the youngest deposits of the Magura Nappe and of the “autochthonous Magura Paleogene” within the PKB.

GEOLOGICAL MAPPING

In 2003, the authors began detailed geological mapping at the 1:10,000 scale of the Małe Pieniny Mts. and directly adjacent part of the Magura Nappe, on the southern slope of the Radziejowa Range. Initially, the traditional “step by step route” method of geological mapping was performed and since 2008 digital mapping with GPS was applied. In total, the geological observations made at least 2,000 way-points (WP). Mapping was supported by litho- and biostratigraphical studies. Finally, the digital map was completed in 2013 (Fig. 2) and will be printed at scale 1:15,000 with short explanatory text (Oszczypko and Oszczypko-Clowes, in press).

STRATIGRAPHIC INVESTIGATIONS

In course of these litho- and biostratigraphical studies a special emphasis has been placed on the Grajcarek succession (1) and the youngest deposits of the Krynica facies Zone of the Magura Nappe (2), as well as on the position and age of the “Intra-klippen flysch” formations (“autochthonous Magura Paleogene”; 3):

1. Age of the “black flysch”. On the basis of litho- and biostratigraphical studies on Early Cretaceous age of the “black flysch” (“Aalenian flysch”, Sztolnia and Opaleniec formations of Birkenmajer, 1977) has been documented (Oszczypko et al., 2004, 2012a). Results of litho- and biostratigraphical studies have resulted in a new stratigraphic profile of the Grajcarek thrust-sheet in the Małe Pieniny Mts. The transitional beds, composed of green and black, bituminous shales, green and red radiolarites and spotted limestones, are established as of the Late Cenomanian (OAE-2) Bonarelli Level (Uchman et al., 2013).

2. The litho- and biostratigraphical studies of the Magura Nappe (Krynica Zone) enabled discovery of the Early Miocene Kremná Formation near Stará Ľubovňa (Eastern Slovakia), which is the youngest member of the Magura succession of the Krynica facies Zone (Oszczypko et al., 2005a and references therein).

3. Lithostratigraphical and biostratigraphical studies of the “autochthonous Magura Paleogene” within the PKB.

During the field work, 51 samples from the Magura Formation, Kremná Formation and “Intra-klippen flysch” formations were examined for calcareous nannofossil content. Their location is shown in Table 1.

All samples were prepared using standard smear slide techniques for light microscope (LM). The investigation was carried out using a *Nikon-Eclipse E 600 POL* microscope at a magnification of 1000 using parallel and crossed polarizers. The taxonomic frameworks of Perch-Nielsen (1985), Aubry (1984, 1988, 1989, 1990, 1999) and Bown (1998 and references therein) have been followed. The biostratigraphy is based on the standard zonation of Martini and Worsley (1970). However, the marker species for the Early Miocene zones are absent or very rare at high latitudes. In such cases secondary index species, proposed by Fornaciari and Rio (1996), Fornaciari et al. (1996) and Young (1998), had to be applied.

Nannofossil preservation was visually estimated using the criteria proposed by Roth and Thierstein (1972). The categories are based on the degree of etching and/or calcite overgrowth observed during light microscopy and are: VP – very poor, etching and mechanical damage is very intensive, specimens mostly as fragments; P – poor, severe dissolution, fragmentation and/or overgrowth; specific identification of the specimens is difficult; M – moderate, etching or mechanical damage is apparent but most of specimens are easily identifiable; G – good, little dissolution and/or overgrowth; diagnostic characteristics are preserved, the specimens could be identified to species level without trouble.

Estimate of the nannofossil abundance for individual samples was established using the following criteria: VH – very high (>20 specimens per view field), H – high (10–20 specimens per view field), M – moderate (5–10 specimens per view field), L – low (1–5 specimens per view field), VL – very low (<5 specimens per 5 view fields).

RESULTS: CALCAREOUS NANNOFOSSILS FROM THE MAGURA AND KREMNÁ FORMATIONS

SPECIES DIVERSITY AND PRESERVATION

The calcareous nannofossils recorded are listed in Appendix 1*, and their distribution is shown in Appendix 2. The most characteristic species are illustrated in Figure 3.

The preservation of the calcareous nannofossils studied varies. The degree of coccolith preservation is between predominantly moderate to very poor (M–VP) in all samples investigated (Appendix 2). In some samples, nannofossils show etching and minor to moderate overgrowth.

The abundance pattern varies from more than 25 species per observation field in sample WP242/1/2010 to less than 5 species (per observation field) in samples WP138/1/2008. Sixteen samples were devoid of calcareous nannofossils (Appendix 2). The abundant and very abundant assemblages may result from high coccolithophore productivity in surface waters or from low coccolith dissolution in the water, or both. On the contrary, low coccolith accumulation may be caused by low surface-water productivity or high dissolution.

For each sample the autochthonous versus reworked nannofossils ratio was estimated.

To distinguish reworked from in-place nannofossils the full stratigraphic ranges of species were used. Individual species older than the youngest assemblage were identified as reworked taxa. The autochthonous assemblages are mainly constituted by: *Coccolithus pelagicus, Coronocyclus nitenscens, Cyclicargolithus luminis, Discoaster deflandrei, Helicosphaera compacta, Ponthosphaera plana, P. multipora, Reticulofenestra dictyoda, Sphenolithus disbelemnos, S. dissimilis, S. conicus* and *S. moriformis.* A semi-quantitative study of autochthonous nannoplankton assemblage indicates a dominance of placoliths over asteroliths, spenoliths, helicospheres. The assemblage is dominated by *Coccolithus pelagicus* and *Sphenolithus moriformis* (at least one specimen per observation field) whereas *Reticulofenestra dictyoda, Sphenolithus*

* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1177

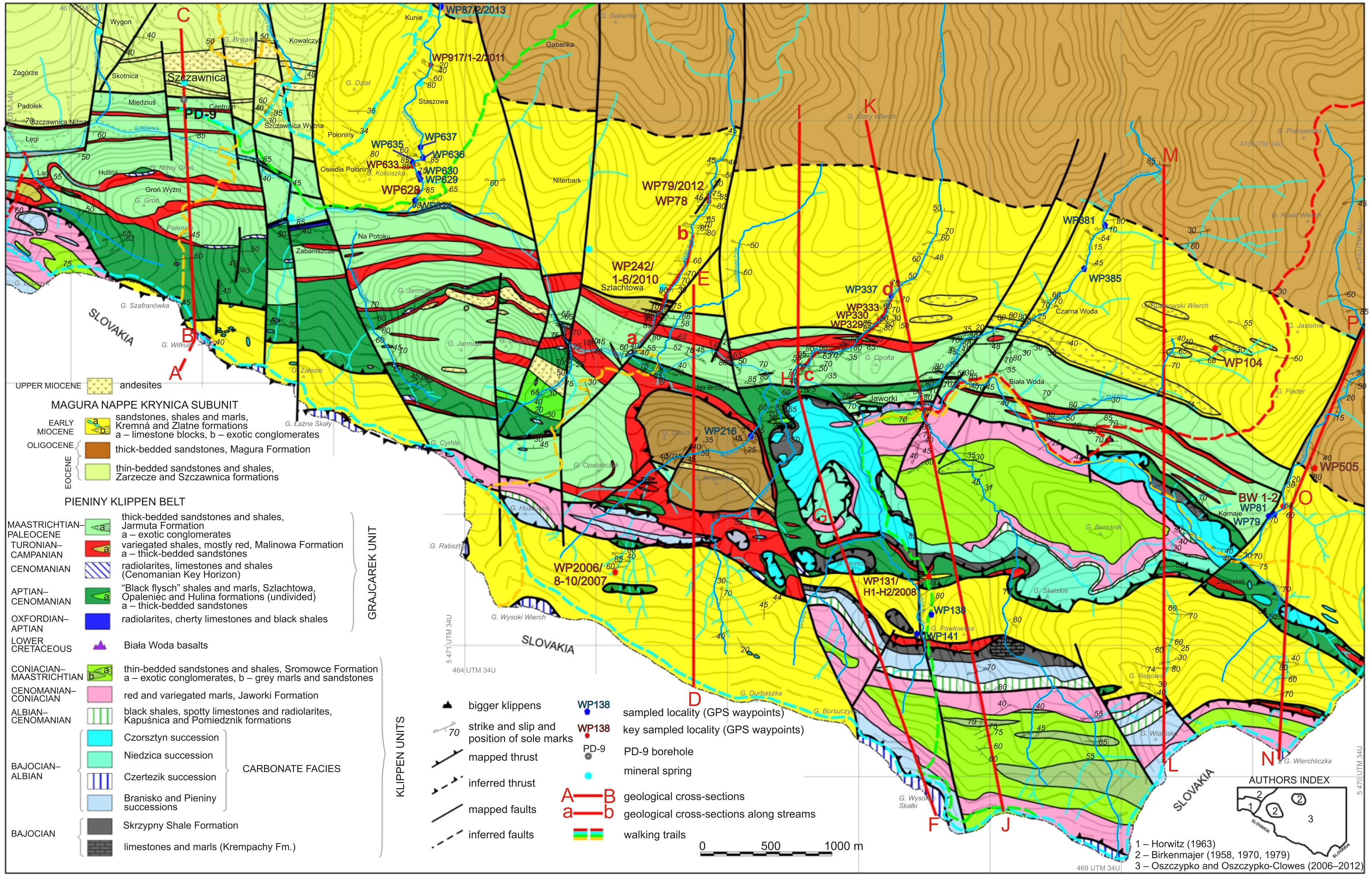

Fig. 2. Geological map of the Małe Pieniny Mts. and adjacent part of the Beskid Sądecki Range (based on Oszczypko and Oszczypko-Clowes, in press)

Table 1

GPS coordinators for collected samples

Locality name	Samples	GPS cordinate
Sielski Stream	WP242/1–6/2010	N49°24.881’ E20°31.664’
	WP78/2012	N49°25.292’ E20°31.919’
	WP79/2012	N49°25.302’ E20°31.924’
Stary Stream	WP329/2010	N49°24.757’ E20°32.952’
	WP330/A–E/2010	N49°24.760’ E20°32.958’
	WP333/2010	N49°24.775’ E20°33.004’
	WP337/2010	N49°24.950’ E20°33.169’
Biała Woda	BW-1	N49°23.826’ E20°35.307’
	BW-2	N49°23.826’ E20°35.307’
	BW 505-1–2	N49°24.191’ E20°35.711’
	WP79/2007	N49°23.976’ E20°35.481’
	WP81/2007	N49°24.013’ E20°35.556’
	WP79b/2007	N49°23.976’ E20°35.481’
	WP83/2007	N49°24.033’ E20°35.591’
	WP216/2007	N49°24.308’ E20°32.202’
	104a–c/2010	N49°24.685’ E20°35.130’
Homole	WP138/1–2/2008	N49°23.585’ E20°33.314’
	WP141	N49°23.485’ E20°33.282’
Czarna Woda	WP381	N49°24.767’ E20°29.212’
	WP385	N49°25.016’ E20°29.293’
Sztolnia	WP2006/7/2007	N49°23.441’ E20°31.173’
	WP2006/8/2007	N49°23.441’ E20°31.174’
	WP2006/9/2007	N49°23.441’ E20°31.175’
	WP2006/10/2007	N49°23.441’ E20°31.176’
Sopotnicki Stream	WP624/2011	N49°25.263’ E20°30.065’
	WP628/2011	N49°25.336’ E20°30.129’
	WP629/2011	N49°25.364’ E20°30.105’
	WP630/2011	N49°25.372’ E20°30.083’
	WP633/2011	N49°25.412’ E20°30.054’
	WP635/2011	N49°25.423’ E20°30.046’
	WP636/2011	N49°25.440’ E20°30.072’
	WP670/2011	N49°25.201’ E20°27.750’
	WP917/1/2011	N49°24.545’ E20°31.018’
	WP917/2/2011	N49°24.545’ E20°31.018’

conicus and *S. disbelemnos* are present at much less frequency.

The percentage of allochthonous assemblages oscillates between 30 and 40% and may be even higher due to long-ranging taxa such *Braarudosphaera bigelowii*, *Coccolithus pelagicus* and *Sphenolithus moriformis* frequently occurring as reworked nannofossils of Cretaceous and Paleogene age.

BIOSTRATIGRAPHY

The nannofosssil assemblages were modified by dissolution, though they contain enough information to apply biostratigraphical analyses. For this purpose the standard zonation of Martini (1971) was used. In cases where index species were not observed it was necessary to use secondary index and characteristic species.

The oldest assemblage from all samples investigated was observed in sample WP87/2/2013 from the base of the Poprad Sandstone Mb. of the Magura Formation (Skotnicki Stream, Sewerynówka Waterfall; Figs. 2 and 4). This sample contains an assemblage not older than Middle Eocene. It is characterized by the presence of *Chiasmolithus gigas*, *Ch. grandis*, *Coccolithus pelagicus*, *Discoaster barbadiensis*, *D. saipanensis*, *Ericsonia formosa*, *Neococcolithes dubius*, *Sphenolithus moriformis* and *Zygrhablithus bijugatus.*

Triquetrorhabdulus carinatus Zone (NN1)

D e f i n i t i o n. – The base of the zone is defined by the last occurrence of *Helicosphaera recta* and/or *Sphenolithus ciperoensis*, and the top by the first occurrence of *Discoaster druggii.*

A u t h o r. – Bramlette and Wilcoxon (1967), emend. Martini and Worsley (1970)

A g e. – Early Miocene and/or latest Oligocene.

R e m a r k s. – This zone was identified in the following lithological units: Poprad Sandstone Mb. of the Magura Formation (samples: WP 505/1-2) and Kremná Formation (samples: BW-1-2).

The samples WP 505/1-2 were collected in the Biała Woda Stream from an intercalation of dark grey marly shales in thick-bedded Magura-type sandstone. This unit forms the uppermost part of the Poprad Sandstone Mb. of the Magura Formation. Both samples contain the same assemblages. The zonal assignment of NN1 is based on the continuous range of *S. conicus* and *S. dissimillis* following the disappearance of *D. bisectus*. Traditionally the last occurrence (LO) of *Helicosphaera recta* has been used to define the base of NN1 (Martini and Worsley, 1970). It is now well-known that this species was also present in the Early Miocene. As a result, Perch-Nielsen (1985), Berggren et al. (1995), Fornaciari and Rio (1996) and Young (1998) suggested redefining the base of NN1 as the LO of *D. bisectus.* The biostratigraphic range of *S. delphix* is also problematic. According to Young (1998), this species is only characteristic of the upper part of NN1, although this taxon was reported by Aubry (1985) from NP25 and NN1.

Samples BW-1-2 were collected from grey marly shales in the basal portion of the Kremná Formation.

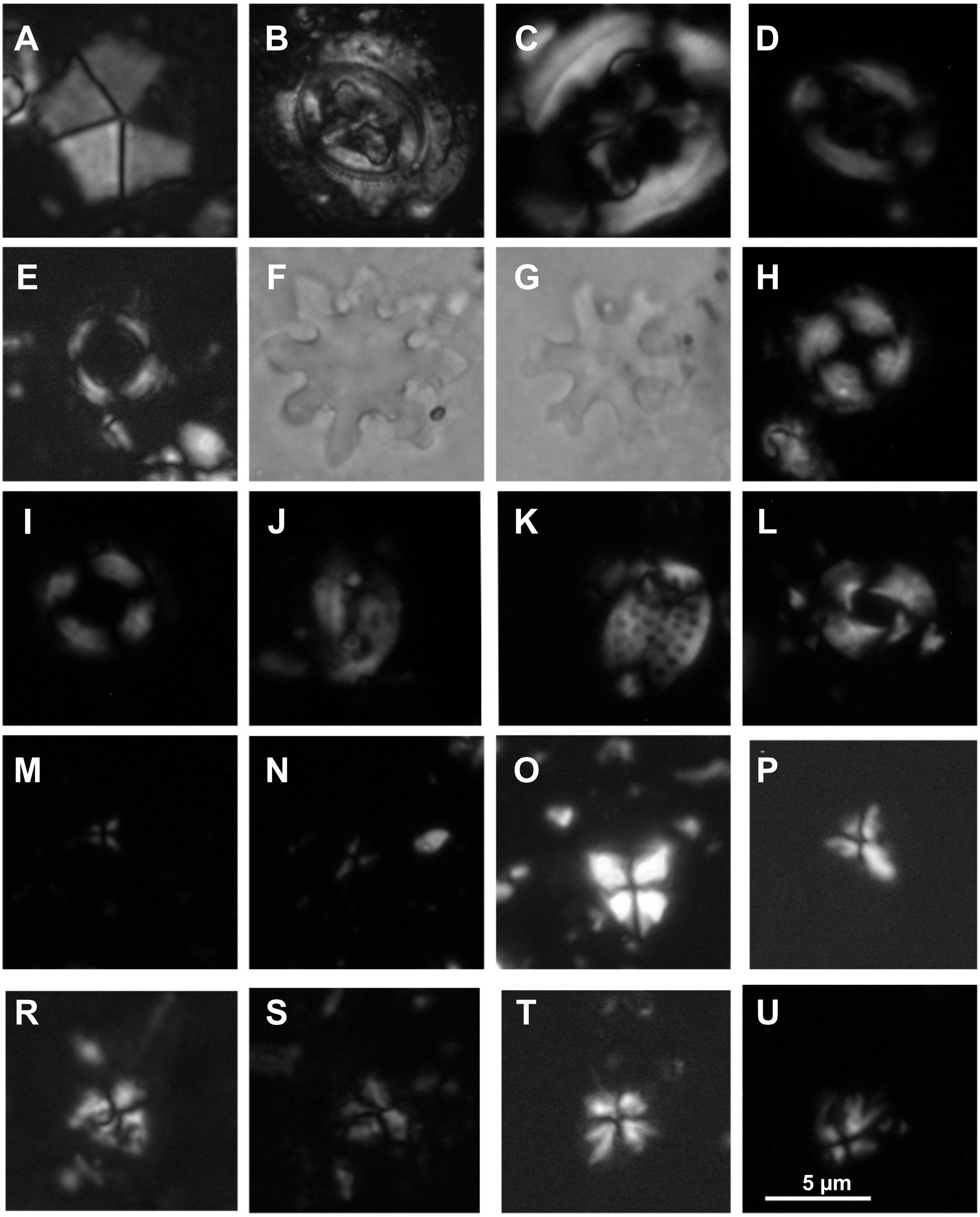

Fig. 3. LM microphotographs of typical species

A – *Braarudosphaera bigelowii* Kremná Fm., sample WP242/1/2010; **B** – *Chiasmolithus gigas* Kremná Fm., sample WP329/2010; **C** – *Chiasmolithus grandis* Kremná Fm., sample WP330/B/2010; **D** – *Chiasmolithus solitus* Kremná Fm., sample WP330/B/2010; **E** – *Coronocyclus nitescens* Poprad Sandstone Mb. of Magura Fm., sample BW 505-1; **F** – *Discoaster binodosus* Kremná Fm., sample WP330/C/2010; **G** – *Discoaster deflandrei* Kremná Fm., sample 104b/2010; **H** – *Ericsonia formosa* Kremna Fm., sample WP2006/9/2007; **I** – *Ericsonia robusta* Kremná Fm., sample WP917/2/2011; **J** – *Helicosphaera compacta* Poprad Sandstone Mb. of Magura Fm., sample BW 505-2; **K** – *Ponthosphaera multipora* Kremná Fm., sample H 1; **L** – *Reticulofenestra dictyoda* Kremná Fm., sample WP79/2007; **M**, **N** – *Sphenolithus calyculus* Kremná Fm., sample WP330/C/2010; **O** – *Sphenolithus conicus* Kremná Fm., sample 104b/2010; **P** – *Sphenolithus delphix* Bukry, Magura Fm., sample BW 1; **R**, **S** – *Sphenolithus disbelemnos* Kremná Fm., sample WP633/2011; **T**, **U** – *Sphenolithus dissimilis* Kremná Fm., sample 104c/2010; scale bar is the same for all photographs

Discoaster druggii Zone (NN2)

D e f i n i t i o n. – The base of the zone is defined by the first occurrence of *Discoaster druggii,* and the top by the last occurrence of *Triquetrorhabdulus carinatus.*
A u t h o r. – Martini and Worsley (1970)
A g e. – Early Miocene.
R e m a r k s. – This zone was identified in the Kremná Fm. (samples: WP242/1–6/2010, WP78/2012, WP79/2012, WP329/2010, WP330/A–E/2010, WP79/2007, WP81/2007, WP104a–c/2010, WP385, WP628/2011 WP633/2011 and WP917/2/2011) and from the "Intra-klippen flysch" (samples: WP2006/8–10/2007, WP131/H1/2008).

The NN2 assignment is based on the co-occurrence of the following species: *Sphenolithus conicus*, *S. disbelemnos*, *Reticulofenestra pseudoumbilica* and *Triquetrorhabdulus carinatus*. At the same time *Dictyococcites bisectus*, *Cyclicargolithus abisectus* and *Zygrhablithus bijugatus* are absent from this association. According to Young (1998), the FO of *S. disbelemnos* and/or *Umbilicosphaera rotula* are reliable biostratigraphical events, characteristic of the lower limit of the NN2 Zone. The same age – Early Miocene, based on small foraminifera, was also obtained by Soták (pers. inf., 2013), from samples collected in Sielski Stream (WP242/1–6/2010). An astronomical age of *S. disbelemnos* was proposed by Shackleton et al. (2000; see also Raffi et al., 2006). The species appears at 22.67 Ma and is an important datum level for the Paratethys region (Rögl and Nagymarosy, 2004; Oszczypko-Clowes in Oszczypko et al., 2005a).

The samples WP138/1–2/2008, WP131/H2/2008 contain very poor nannofossil assemblage with species such as *Chiasmolithus gigas*, *Coccolithus pelagicus, Discoaster barbadiensis*, *Helicosphaera compacta* and *Sphenolithus moriformis*. Such an assemblage indicates an age not older than NP17. Taking into account the lithostratigraphical position of the samples, they have to belong to the Kremná Fm. and the nannofossil assemblages contain only reworked species.

INTERPRETATION AND DISCUSSION

PIENINY KLIPPEN SUCCESSIONS

The lithostratigraphical sequence and age determination of the PKB, based mainly on Birkenmajer (1970, 1977, 1979, 2001), Golonka and Rączkowski (1983,1984), Birkenmajer and Jednorowska (1987), Wierzbowski et al. (2004), and partly on our own observation during the geological mapping, is summarised in Figures 4–6.

In the Małe Pieniny Mts. the following Jurassic–Lower Cretaceous lithofacies zones of the PKB has been recognized: Czorsztyn, Niedzica–Czertezik, Branisko and Pieniny (Figs. 4 and 6; Birkenmajer, 1970, 1977, 1977, 1986). These lithofacies have a common Middle/Upper Cretaceous sedimentary cover. Differences in sedimentary zonation remained during the Jurassic-Early Cretaceous and became more unified during the Late Cretaceous (Birkenmajer, 1977, 1986).

GRAJCAREK SUCCESSION

The Grajcarek succession is exposed both in the tectonic windows of PKB, as well as northwards from the PKB (Fig. 2, see also Golonka and Rączkowski, 1983, 1984; Jurewicz, 1997; Oszczypko et al., 2010, 2012a; Oszczypko and Oszczypko-Clowes, in print). The basal portion of this succession is represented by Upper Jurassic–Lower Cretaceous radiolarites, radiolarian shales and cherty limestones exposed on the left bank of the Grajcarek Creek at the Szczawnica-Zabaniszcze section (Oszczypko et al., 2012a; see also Sikora, 1971a, b). These strata are overlain by the Szlachtowa Formation (Figs. 2, 4, 7 and 8A). The total thickness of the Szlachtowa Formation is at least 220 m (Birkenmajer, 1977, see also Birkenmajer at al., 2008), but in the borehole PD-9 at Szczawnica (Fig. 2, see Birkenmajer et al., 1979) the incomplete thickness of the "black flysch" was about 310 m (120 m and 190 m of the Szlachtowa and Bryjarka formations, respectively). The Szlachtowa Formation is composed of turbiditic sandstones with intercalations of black and dark grey marly mudstones and shales (Figs. 7 and 8A). Local intercalations of siderite have also been observed (Krawczyk and Słomka, 1986). Thin- to medium-bedded, micaceous sandstones are fine to coarse-grained and contain many crinoidal fragments. The Szlachtowa Fm. (Aptian–Albian, see Oszczypko et al., 2012a) is overlain by a 10 to 16 m thick packet of light grey spotted shales and marls with pyrite concretions and sideritic limestone intercalations belonging to the Opaleniec Formation of Albian-Cenomanian age (Oszczypko et al., 2004, 2012a).

Between the Opaleniec Formation and the Malinowa Formation Oszczypko et al. (2012a) recognized red and green radiolarites followed by spotted limestones (Figs. 2, 4, 7 and 8B, E–G) of Cenomanian age (Oszczypko et al., 2012a). These strata, 3–10 m thick, were previously described by Sikora (1962, 1971b) as the "Cenomanian Key Horizon" (CKH), which contains the Bonarelli Level (Uchman et al., 2013).

The Malinowa Formation (Figs. 2, 4, 7 and 8C), composed of non-calcareous red and green argillaceous shales, locally replaced by massive red marls in the Sztolnia sections (Oszczypko et al., 2012a). The thickness of the Malinowa Formation is variable and varies from a few metres on the southern slope of Jarmuta Mt., to 20–70 m in the Grajcarek Creek sections up to 220–250 m in the Sielski and Stary streams (Fig. 7).

The Malinowa Formation is overlain by coarse-clastic deposits of the Jarmuta Formation (Birkenmajer, 1977, see also Figs. 2 and 7), distributed along the northern edge of the PKB. Locally the variegated shales are intercalated with Jarmuta-type sandstones and conglomerates. The typical Jarmuta Fm. is represented by thick-bedded turbidites (0.5–5 m thick) conglomerates and sandstones (Fig. 8D, E) with subordinate intercalations of grey marly shale. In the mouth of the Sielski Stream, the Grajcarek Creek and along the lower reaches of the Czarna Woda Creek (Oszczypko et al., 2012a) the basal portion of the Jarmuta Fm. contains debris flow paraconglomerates with clasts of red shale, Lower/Middle Cretaceous limestone and radiolarite. A very diverse suite of Mesozoic rocks of the PKB is known from Jaworki near the church (Birkenmajer, 1979, 2001). According to Birkenmajer and Wieser (1990) the Jarmuta conglomerates from the Biała Woda section are dominated by volcanic rocks and carbonates as well as by sedimentary clastic rocks (see also Krobicki and Olszewska, 2005). In the Szczawnica and Biała Woda sections the heavy mineral assemblages of the Jarmuta Fm. contain relatively high contents of chromian spinels of ophiolite provenance (Oszczypko and Salata, 2005).The thickness of the formation varies widely from about 100 m (e.g., Jarmuta Wyżnia and Niżny Groń), the several tens of metres in the Grajcarek valley to 400 m north of this valley. The age of the formation has been estimated as Maastrichtian–Middle Paleocene (Birkenmajer, 1977; Birkenmajer et al., 1987). The palaeocurrent measurements show a supply of clastic material from the SE.

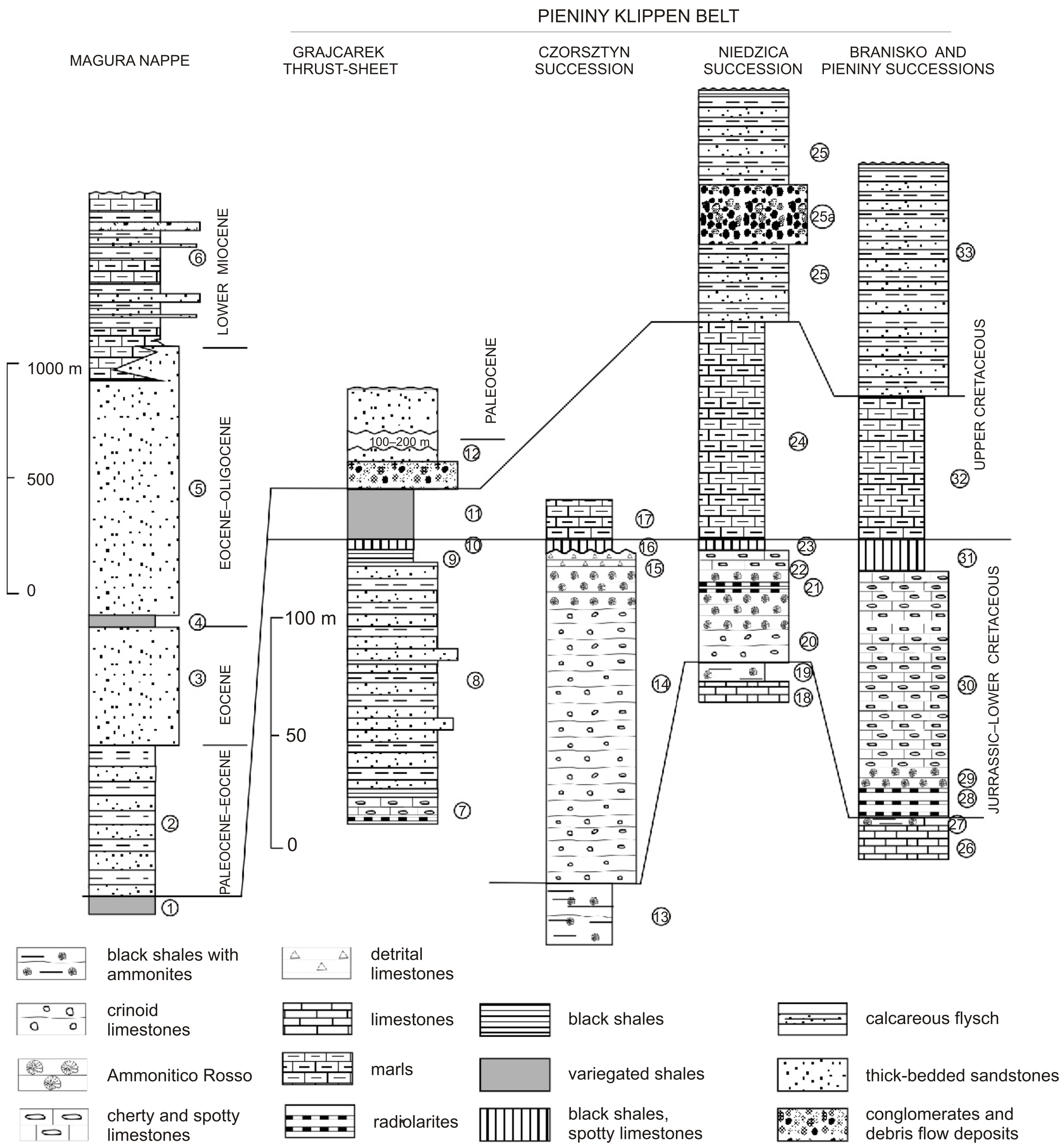

Fig. 4. Lithostratigraphic logs of the Małe Pieniny Mts. and the southern slope of the Radziejova Mt.

Magura Nappe–Krynica succession: 1 – Malinowa Sh. Fm., 2 – Szczawnica and Zarzecze fms., Magura Fm.; 3 – Piwnicza Ss. Mb. 4 – Mniszek Sh. Mb., 5 – Poprad Ss. Mb. Mb. 6 – Kremná Fm.; Grajcarek thrust-sheets: 7 – Czajakowa and Sokolica Rad. fms., Czorsztyn and Pieniny Lm. fms., and Kapuśnica and Wronine fms. 8 – Szlachtowa Fm., 9 – Opaleniec Fm., 10 – Cenomanian Key Horizon, 11 – Malinowa Sh. Fm., 12 – Jarmuta Fm.; Klippen successions (partly after Birkenmajer, 1977): Czorsztyn succession: 13 – Skrzypne Sh. Fm., 14 – Smolegowa Lm. Fm. and Krupianka Lm. Fm., 15 – Czorsztyn, Dursztyn, Lysa and Spis Limestones fms., 16 – Chmielowa and Pomiedznik fms., 17 – Jaworki Marls; Niedzica succession: 18 – ?Krempachy Marl Fm., 19 – Skrzypne Sh. Fm., 20 – Smolegowa, Krupianka and Niedzica Limestone fms, 21 – Czajakowa Rad. Fm., 22 – Czorsztyn and Dursztyn Limestone fms., Pieniny Limestone Fm., 23 – Kapuśnica Fm., 24 – Jaworki Marl Fm., 25 – Sromowce Fm., 25 a – Bukowiny Gravelstone Mb.; Branisko and Pieniny successions: 26. – ?Krempachy Marl Fm., 27 – ?Skrzypny Sh. Fm., 28 – Czajakowa and Sokolica Rad. fms., 29 – Czorsztyn Lm. Fm., 30 – Pieniny Lm. Fm., 31 – Kapuśnica Fm., 32 – Jaworki Marl Fm., 33 – Sromowce Fm.

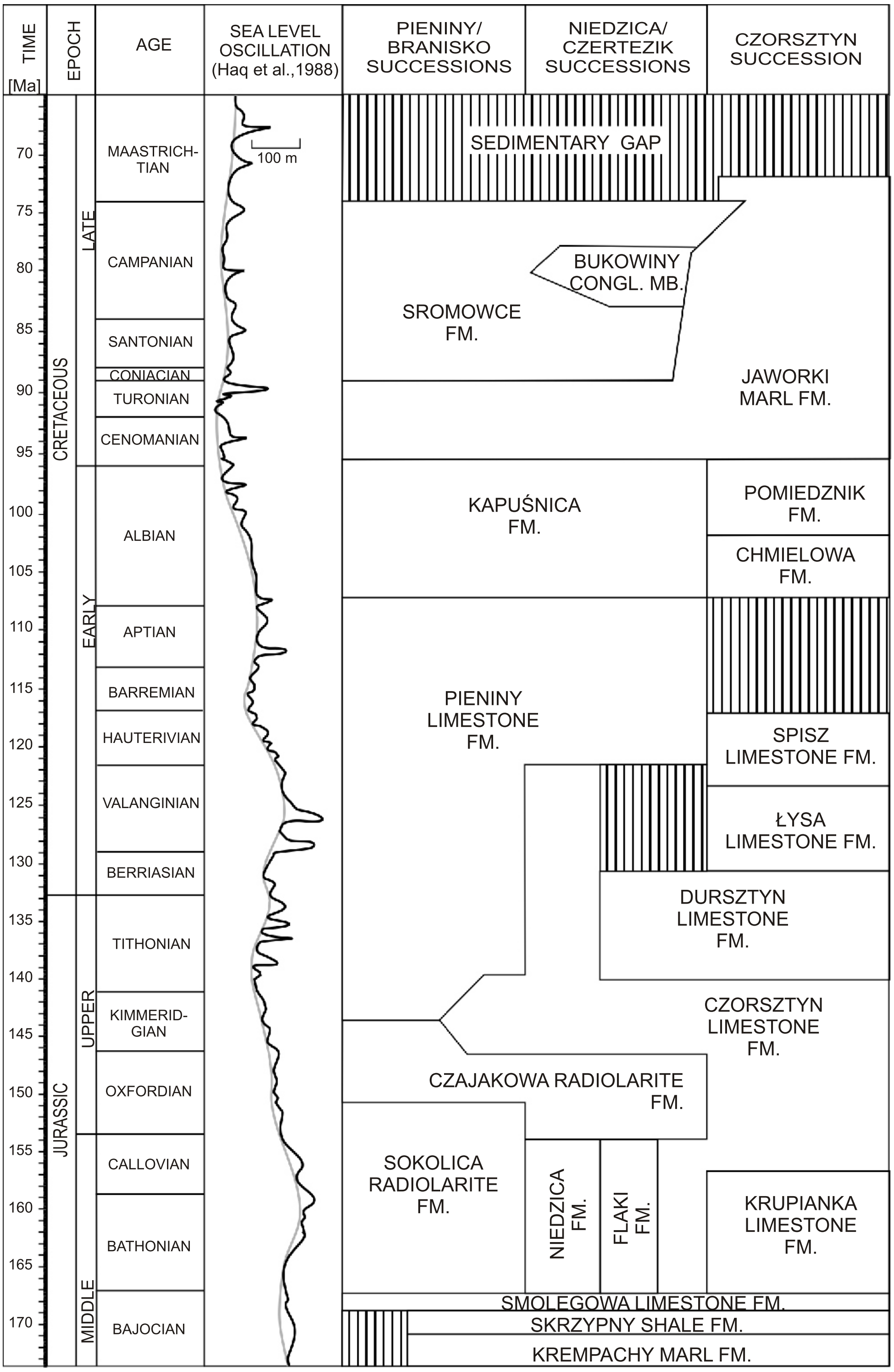

Fig. 5. Distribution and age of Jurassic and Createaceous lithostratigraphic units from the Małe Pieniny Mts. (based on Birkenmajer, 1977, 2001, simplified)

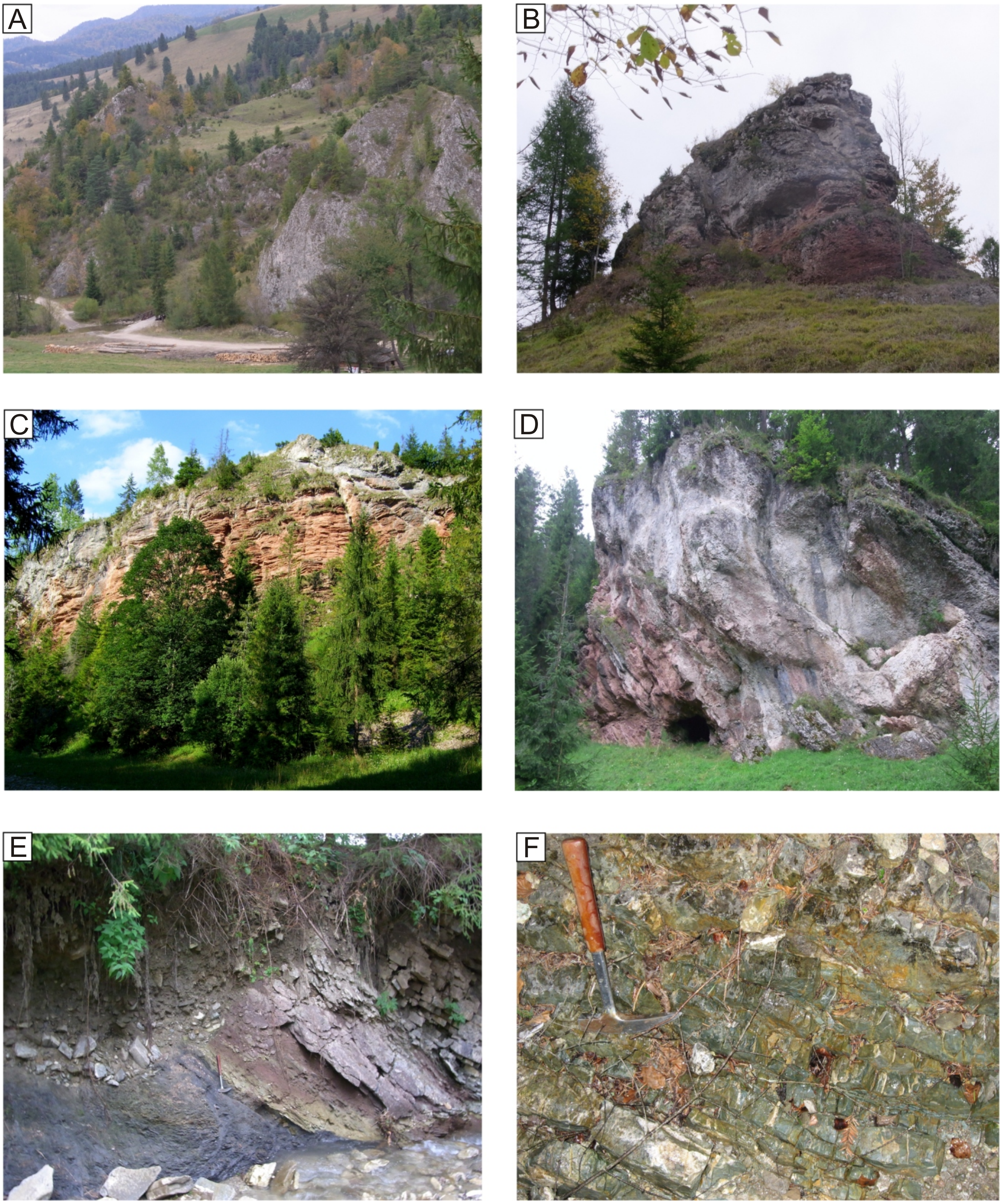

Fig. 6. Typical lithofacies of the Klippen succesions

A – Smolegowa Limestone Fm. (Middle–Upper Bajocian), Czorsztyn succession at the Biała Woda Creek; **B** – Smolegowa Limestone Fm. (Middle–Upper Bajocian) at the base, Krupianka Limestone Fm. (Bajocian), Czorsztyn Limestone Fm. (Callovian–Lower Tithonian), Dursztyn Limestone Fm. (Lower Tithonian–Berriasian), Łysa Limestone Fm. (Upper Berriasian–Valanginian) at the top, Czorsztyn succession at the Biała Woda Creek; **C** – Czorsztyn Limestone Fm. (Kimmeridgian–Valanginian) at the base and Pieniny Limestone Fm. (Hauterivian–Barremian) at the top, Niedzica succession at right bank of Skalski Creek; **D** – Czajakowa Radiolarite Fm. (Oxfordian) and Czorsztyn Limestone (Kimmeridgian) of Niedzica succession at the left bank of Skalski Creek; **E** – tectonic contact of the Skrzypny Sh. Fm. and Czajakowa Rad. Fm., left bank of Skalski Creek; **F** – the basal portion of the Branisko succession in the middle section of Skalski Creek – green radiolarites of the Sokolica Radiolarite Fm. (Bathonian–Calliovian)

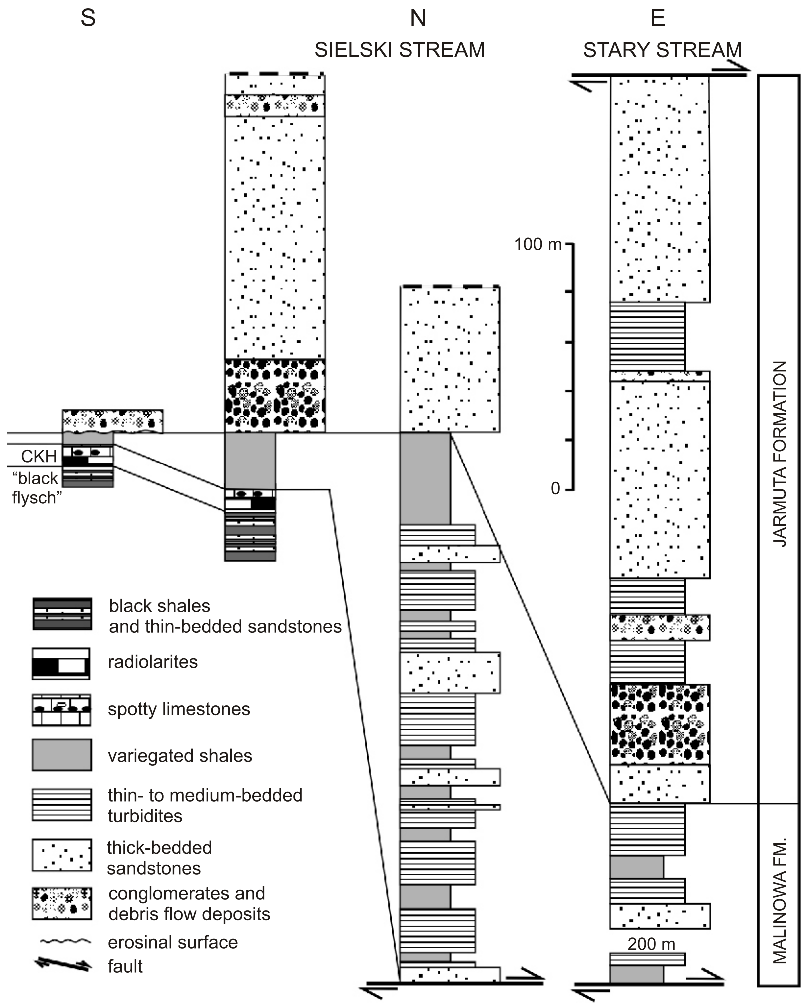

Fig. 7. Lithostratigraphic log of the Malinowa and Jarmuta formations (Sielski and Stary streams at Szlachtowa)

CKH – Cenomanian Key Horizon

MAGURA SUCCESSION

In the Beskid Sądecki Range the thickness of the Magura succession reaches at least 2.5 km (Golonka and Rączkowski, 1983, 1984; Alexandrowicz et al., 1984). On the southern slopes of this range the Paleogene deposits have been included into the Szczawnica, Zarzecze and Magura formations of Late Paleocene/Late Eocene age (Birkenmajer and Oszczypko, 1989). The discovery, in the area of Stará Ľubovňa (Oszczypko et al., 2005a) and Szczawnica (Oszczypko and Oszczypko-Clowes, 2010, in press), of the Oligocene/Miocene lower Kremná Formation made it necessary to revise the lithostratigrapy and ages of the flysch deposits on the southern slops of the Prehyba-Radziejowa gorge.

Szczawnica Formation. In the Szczawnica-Krościenko area the Szczawnica and Zarzecze formations (Figs. 2 and 4) are composed of sandstone-dominated turbidites, up to 400 m thick (Alexandrowicz et al., 1984; Kulka et al., 1985; Birkenmajer and Oszczypko, 1989). The age of the Szczawnica Fm. was determined, on the basis of calcareous nannoplanton, as the upper part of the Middle Paleocene/middle part of Early Eocene (Birkenmajer and Dudziak, 1981; Oszczypko-Clowes, 2001). However, taking into account the discovery of the Kremná Formation, directly east of Szczawnica, a younger than Early Eocene age of the Szczawnica Formation cannot be excluded.

Magura Formation. The axial part of the Radziejowa Syncline is composed of the Magura Sandstone Formation (Fig. 2), which makes up the highest peaks of the Radziejowa Range (Golonka and Rączkowski, 1983, 1984). This formation, 1200–1600 m thick (Fig. 4), is composed of thick-bedded (0.5–5.0 m) muscovite sandstones (Fig. 9A, B), locally up to 10 m thick. The sandstones are intercalated with thin layers (1–15 cm) of grey shales or mudstone. In the uppermost part of the formation there appear debris flows deposits with exotic conglomerates (Jaksa-Bykowski, 1925; Golonka and Rączkowski, 1984). The base of the Magura Formation is composed of a 10 metre thick sandstone bed of the Sewerenówka Waterfall in the Sopotnicki Stream, NW of Szczawnica (Fig. 8A). The age of these formation is not older than the Middle Eocene. It should be stressed that biostratigraphic studies of the Magura Sandstone in the "type locality" of the Magura Sandstone Formation in the quarry at Oravská Jasenica (Horná Orava Region, Slovakia) indicated an earliest Miocene age (Soták et al., 2012).

Kremná Formation. This formation is distributed on the southern slops of the Beskid Sądecki Range from the Polish Slovak state boundary in the east, up to the town of Szczawnica in the west (Fig. 2). The outcrop width ranges from about 1 km

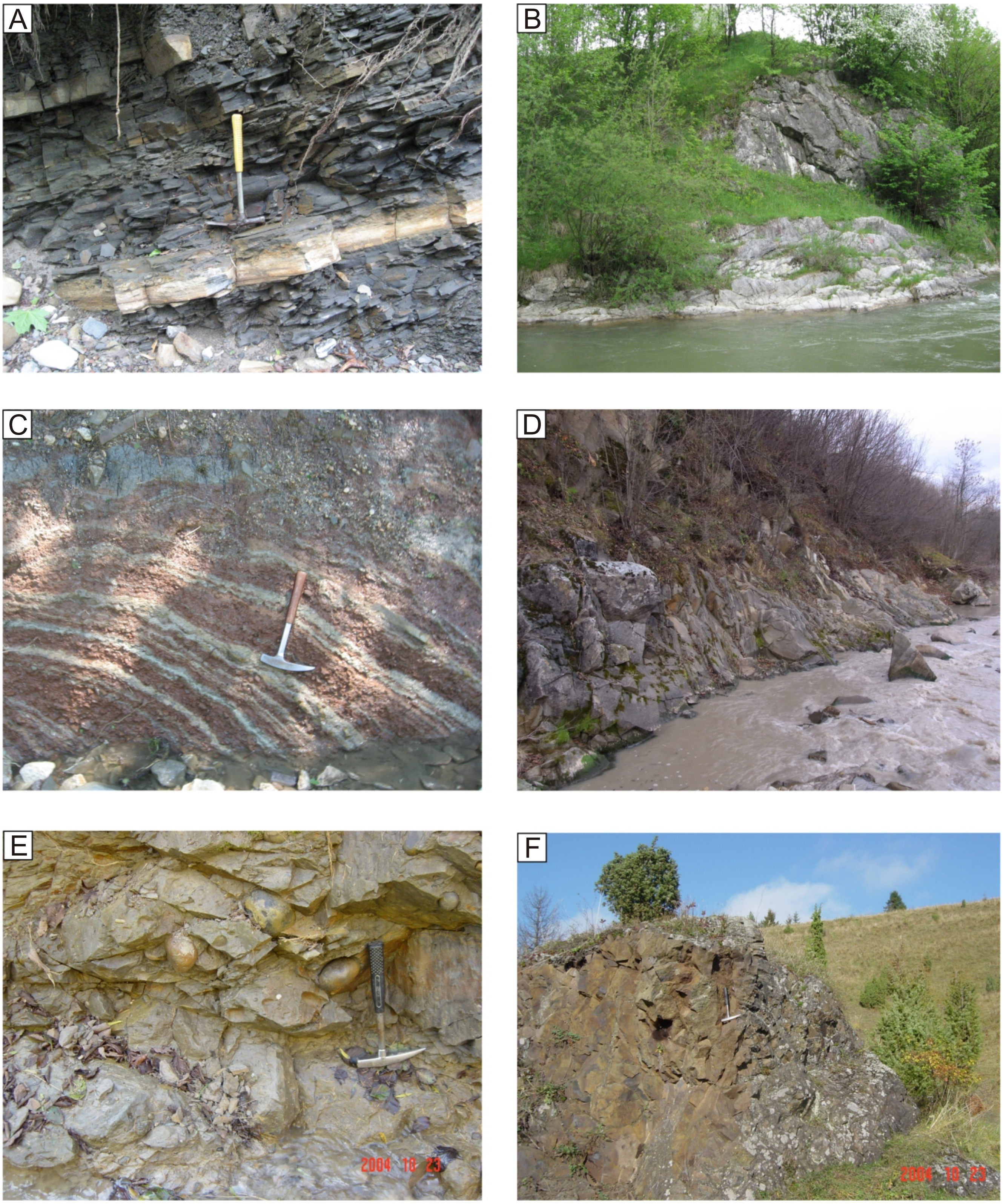

Fig. 8. Typical lithofacies unit of the Grajcarek thrust-sheets

A – "black flysch" of lower part of the Szlachtowa Formation, lower run of the Sztolnia Creek; **B** – spotted limestones of the CKH, Grajcarek Creek at Szlachtowa; **C** – variegated shales of the Malinowa Sh. Fm., Pod Jarmutą Creek, Szlachtowa; **D** – thick-bedded sandstones of the Jarmuta Fm., left bank of the Grajcarek Creek, Szlachtowa-Malinów; **E** – exotic pebbly mudstones of the Jarmuta Formation, middle section of the Czarna Woda Creek; **F** – block of Middle Cetaceous basalt at right slope of the Biała Woda Creek

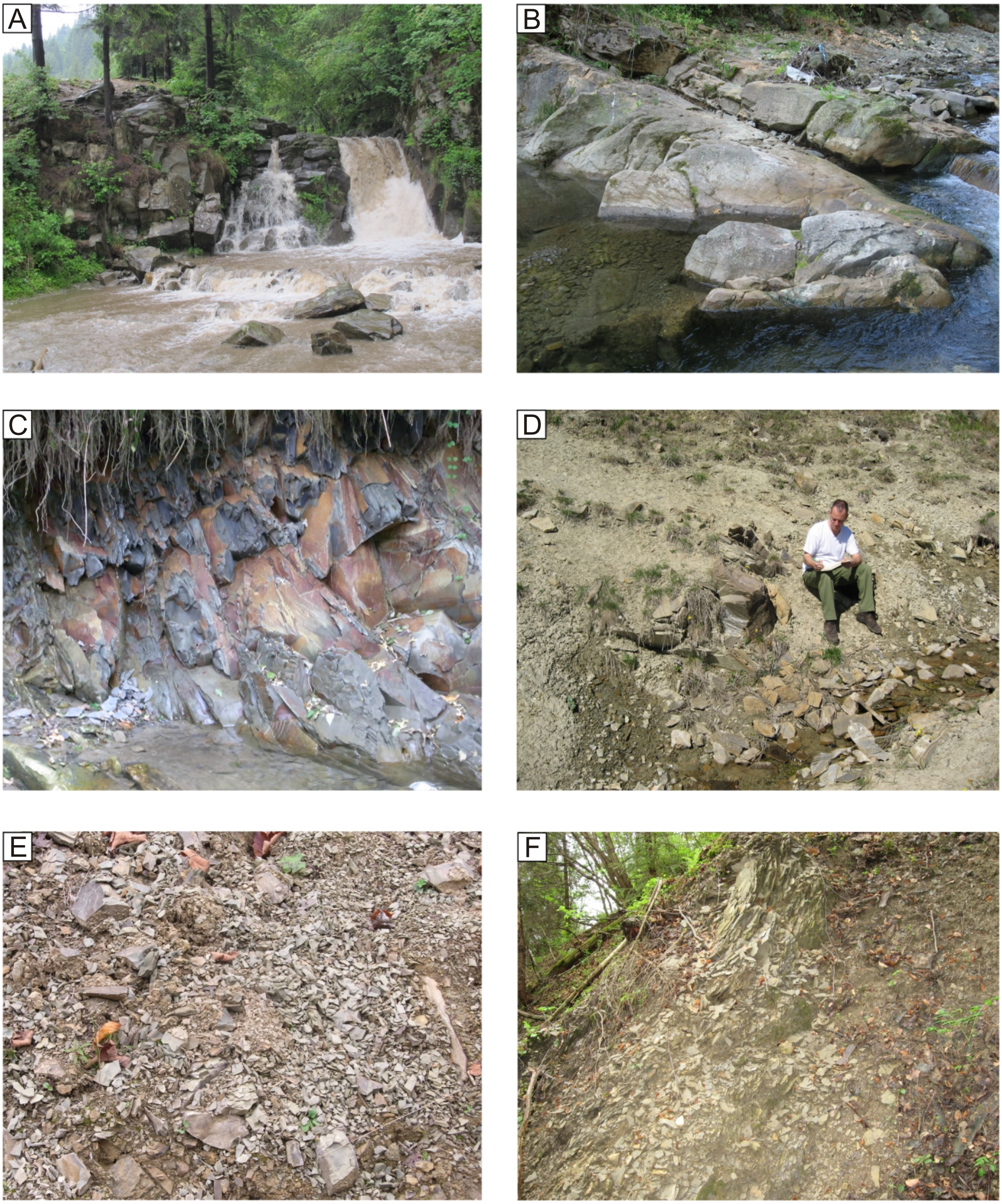

Fig. 9. Typical lithofacies of the Magura succesion of the Krynica Zone and the "autochthonous Magura Paleogene" of PKB

A – thick-bedded sandstone of the Magura Fm., Poprad Ss. Mb., Szczawnica, Sewerynówka Waterfall at the Sopotnicki Stream; **B** – thick-bedded Magura sandstone at Sopotnicki Stream, Szczawnica, **C** – massive, Łącko-type marls of the Kremná Fm., Sielski Stream at Szlachtowa, **D** – dark marly shales with intercalations of laminated detrital limestone of the Kremná Fm., Jasielnik Creek, WP 104; **E** – dark marly shales with intercalations of laminated marly mudstones with *Dendritus* ichnofacies, Kremná Fm., Biała Woda Creek, WP 80, **F** – laminated marls of the Kremná Fm., upper section of the Sztolnia Creek in the east to 1.5 km in the west. The southern border with the Grajcarek thrust-sheet is as a rule tectonic, while the northern boundary (with the Magura Formation) is difficult to define, given the present state of exposures. Lithologically the Kremná Formation is characterized by the presence of thin to medium-bedded carbonate flysch with intercalations of thick to very thick-bedded sandstones and conglomerates, as well as exotic paraconglomerates. The poorly cemented conglomerates locally including pebbles up to 20 cm across, are distributed mainly along the contact with the Grajcarek thrust-sheet. The conglomerates of the Kremná Formation are dominated by carbonate pebbles, with admixtures of milky quartz and metamorphic rocks.

A characteristic feature of this formation is the presence of thick marly beds and laminated sandy limestones and dark grey marl mudstones with Chondrites ichnofacies (Figs. 4 and 9C–E). A thin section of detrital coarse-grained limestone from Biała Woda (WP 77 – GPS N49°23.826'; E20°35.309') revealed a characteristic microfacies. According to B. Olszewska (pers. comm., 2012) this grainstone contains strongly recrystallized foraminifera indicating a Middle-Late Eocene age of the clasts: *Dorothia traubi* Hagn, *Clavulina* cf. *parisiensis* d'Orbigny, *Textularia* cf. *minuta* Terquem, *Cibicides*, *Pararotalia lithothamnica* (Uhlig), *Acarinina* cf. *rotundimarginata* Subbotina, *Turborotalia* cf. *cerroazulensis* (Cole), *Subbotina linaperta* (Finlay), *Tenuitellinata* sp., *Globanomalina* sp. and abundant *Miliolides*, as well as broken pieces and fragments of *Lithothamnium*. The approximate thickness of the Kremná Formation can be up to 750 m (Fig. 4), and palaeotransport directions indicate the basin was supplied from the SE.

"INTRA-KLIPPEN FLYSCH"

In the PKB, flysch deposits defined by Horwitz (1935) as "Intra-klippen flysch" have been known for a long time. These deposits were termed by Birkenmajer (1970), south of the Homole Block, as the "autochthonous Magura Paleogene". These deposits appear between the Czorsztyn-Niedzica and Branisko–Pieniny nappes in a wide zone (up to 1 km), and were regarded as the youngest members of the "PKB mantle" (Birkenmajer and Pazdro, 1968). Later, these deposits were included in the Szczawnica, Zarzecze and Magura formations of latest Paleocene–Early Eocene age (see Birkenmajer and Oszczypko, 1989). The same deposits that occur within the PKB (Fig. 2), between the Biała Woda Creek and Wierchliczka Mountain, as well in the middle reaches of the Krupianka and Sztolnia creeks, were described by Golonka and Rączkowski (1983, 1984) as sandstone and shales of the Magura beds of the Hulina (Grajcarek) succession. At the same time, these authors distinguished, near Durbaszka and Wysoki Wierch, the Zlatne sandstones and conglomerates, which they considered as equivalent Eocene/Oligocene sandstones to the succession of the Złatna–Cisówka Belt near Niedzica (Sikora, 1970; Morgiel and Sikora, 1975).

These beds are relatively poorly exposed, making it difficult for lithological identification and tectonic interpretation. In a few exposures, sandstones are pebble-dominated. Thicker intercalations of grey marlstones were found only in the spring of the Sztolnia Creek (Fig. 9F). They were accompanied by a thick laminated limestone. Marly shales are also found along the green tourist path (WP 138,141), above Homole Gorge. The above-mentioned exposures have been sampled for micropalaeontological content (Fig. 2; WP 2006).

TECTONICS OF THE MAŁE PIENINY MTS. AND THE ADJACENT PART OF THE MAGURA NAPPE

Previous views on the tectonics and structural evolution of PKB are based mainly on studies conducted in the classic areas: the Pieniny Mts. (Poland), and in the valley of the Váh River (Western Slovakia). To the east of the valley of the Dunajec River (Małe Pieniny Mts.) the tectonics of PKB significantly differ from these of the areas mentioned above. This is manifested by the disappearance of the large blocks of Mesozoic rock, which are replaced by numerous small individual klippen. At the same time a significant role is played by "Intra-klippen flysch".

PIENINY KLIPPEN BELT

Within the PKB, traditionally two nappes s.l. are defined: the Pieniny in the south and Czorsztyn in the north (e.g., Uhlig, 1890; Książkiewicz, 1977; Froitzheim et al., 2008). The Pieniny Nappe is composed of the Jurassic–Late Cretaceous Pieniny and Branisko facies, while the Czorsztyn Nappe is composed of the Czorsztyn, Czertezik and Niedzica facies (Birkenmajer, 1986). Due to the block tectonic structure of the Małe Pieniny Mts., it is very difficult to define this area in terms of nappe structure. It is much more convenient to use the term "facies-tectonic units of the PKB", applied by Birkenmajer (1970, 1979, 1986) as the Pieniny, Branisko, Niedzica, Czertezik and Czorsztyn units. To the south the PKB contacts with the Central Carpathian Paleogene deposits along a steep, north-dipping fault.

In the area studied, the Pieniny Unit occurs only locally west of Szafranówka and gradually expands toward the Dunajec valley (Figs. 1 and 2). To the east of Szfranówka its position is occupied by the Branisko Unit which extends along the Polish-Slovak state border. Its eastern part creates a synclinal lobe 3 km long and 1.5 km wide, extending west from Watrisko Mt. to Wysokie Skałki Mt. Between Wysokie Skałki Mt. and Durbaszka Mt. this unit is cut by a NWN–SES transverse fault. Further west, a prolongation of the unit builds up a narrow synclinal zone in the upper run of the Sztolnia Creek, *via* Huściawa to Cyrhla at the Slovak–Polish border zone.

The Branisko Unit (Figs. 2 and 10) is overthrust onto the Oligo-Miocene Kremná Formation (Oszczypko and Oszczypko-Clowes, in press), i.e. "Intra-klippen flysch" ("autochthonous Magura Paleogene", see Birkenmajer, 1979, 1986), which appears in tectonic window within the PKB (Oszczypko et al., 2010; Oszczypko and Oszczypko-Clowes, in press). In a synclinal lobe of the Huściawa–Cyrhla and west of Szafranówka Mt. the Pieniny Unit is thrust onto the Grajcarek thrust-sheet.

The Niedzica Unit appears to the east of the Homole Block, where it occurs in a synclinal block up to 2 km across (Figs. 2 and 10), that gradually narrows towards the east (down to 200 m in the Brysztan Creek). In this zone the axial part of the block is filled with Upper Cretaceous deposits of the Jaworki and Sromowce formations. The southern limb of the block, with width of 100–200 m, is composed of Jurassic and Lower Creta-

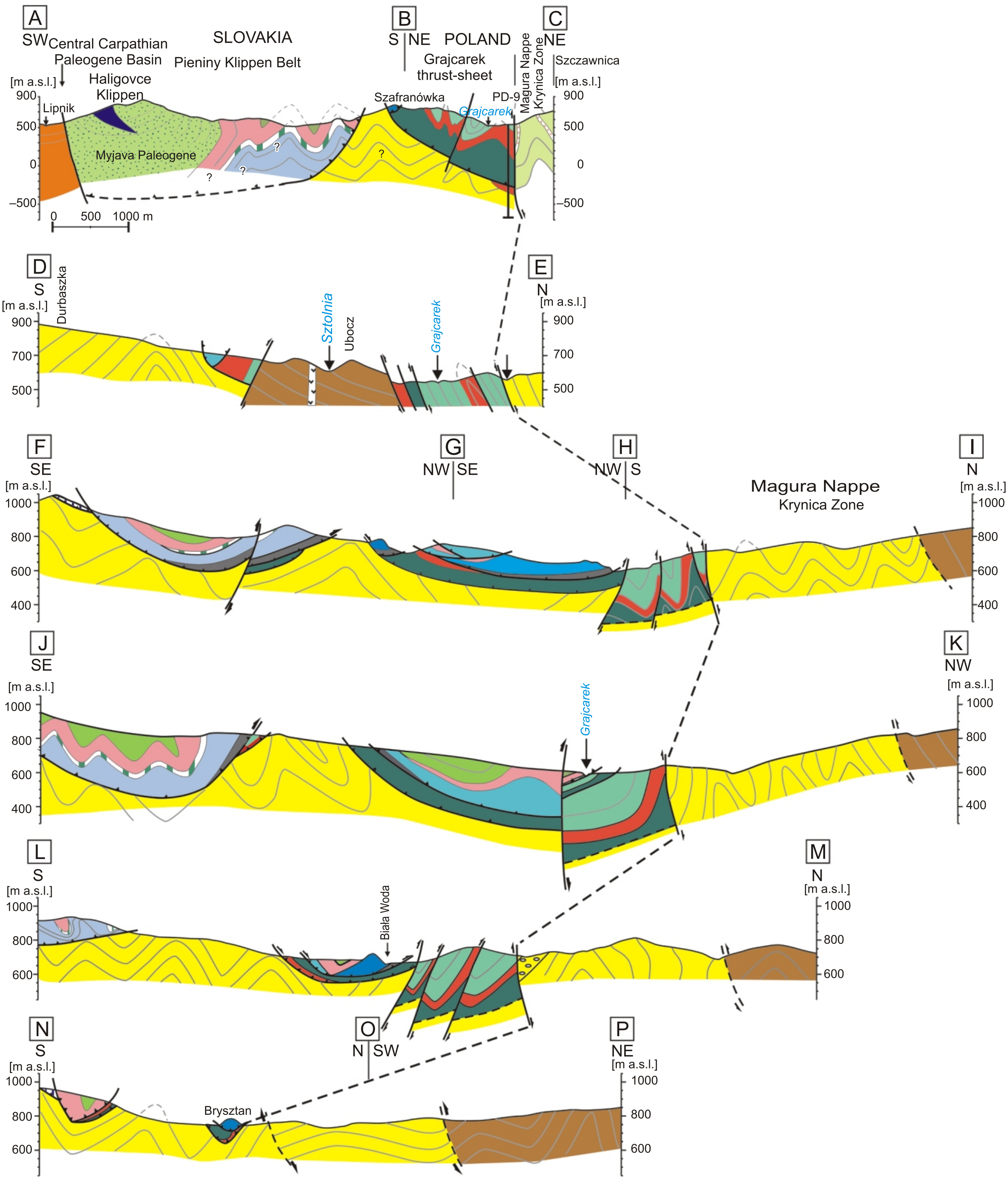

Fig. 10. Geological cross-section through the Małe Pieniny Mts. (after Oszczypko and Oszczypko-Clowes, in press)

Explanations as in Figure 2

ceous limestones, while on the northern wing, the Kapuśnica and Jaworki formations contact directly with the Czorsztyn, Dursztyn and Łysa crinoidal limestones of the Czorsztyn succession, along a small fault. Between Jaworki and Smolegowa Klippe frontal part of the Niedzica Unit is composed of Upper Cretaceous variegated marls thrust over the Grajcarek thrust-sheet.

The best natural outcrop of the Czorsztyn succession is the Homole Block (Birkenmajer, 1970, 1979), composed mainly of Jurassic to Cretaceous carbonate rocks (Figs. 2 and 10). This block is surrounded to the south, west and north by the Lower Cretaceous "black flysch" belonging to the Grajcarek thrust-sheet. The geological map (Fig. 2, see also Oszczypko and Oszczypko-Clowes, in press) clearly indicates that the Homole Block "floats" on the deposits of the Grajcarek thrust-sheet (see also Książkiewicz, 1972, 1977; Golonka and Rączkowski, 1983, 1984; Jurewicz, 1997).

Towards the east the Czorsztyn "imbricate unit" (Książkiewicz, 1977) appears in the Biała Woda valley, where it forms a picturesque range (1.5 km long and 150–200 m wide). Further east lies the isolated Brysztan Rock with a length of 300 m and a width of several tens of metres. It consists almost entirely of crinoidal limestones. Only at the eastern termination of the rock, small blocks of the Czorsztyn limestone are visible. The base of the Brysztan limestone rock forms a narrow strip of Cretaceous rocks the Szlachtowa and Malinowa formations of the Grajcarek thrust-sheet, flatly overthrust onto the Kremná Formation of the Magura Nappe.

The Homole Block includes two tectonic caps (outlayers) of the Niedzica Unit belonging of the Pokwitowska Homola and Czajakowa Skała hills (Birkenmajer, 1970, 1979; Jurewicz, 1994, 1997). The tectonically duplicated Pokwitowska Homola slice, measuring up to several hundred metres across, is made up of deposits from the Middle Jurassic Skrzypny Formation up to the Upper Cretaceous Jaworki Formation. The lower slice is flatly overthrust upon the mid-Cretaceous succession of the Czorsztyn Unit. Rocks of the Czajakowa slice, 100 400 m across, are stratigraphically similar to these of Pokwitowska Homola, and is overthrust onto the Czorsztyn succession of different age, including the Upper Cretaceous variegated marls of the Jaworki Marls Formation.

GRAJCAREK UNIT

A characteristic feature of the Małe Pieniny Mts. is the presence of the Grajcarek Unit, located in the contact zone between the PKB and the Magura Nappe to the north (Figs. 2, 10 and 11). This unit was previously known as the Jarmuta Digitation (Horwitz, 1935), the Hulina Unit (Sikora, 1971a, b) and most fully defined as the Grajcarek Unit by Birkenmajer (1970, 1977, 1979, 1986). The Grajcarek Unit occurs in a belt 0.5 km wide in the Dunajec valley, of 1.7 km in the Palenica Hill Block, of 2 km in Jarmuta and Krupianka hills and of to about 100 m east of Brysztan. The tectonic position of this unit is best visible on the geological cross-section (Figs. 10 and 11). In this interpretation, the Grajcarek Unit, composed of several tectonic slices, is an allochthonous tectonic element, secondary refolded and overthrust upon the southern part of the Magura Nappe. The east of the Homole Block this unit is accompanied by a tectonic window of the Magura Nappe (Figs. 2 and 10D–E). In previous interpretations (Birkenmajer, 1970, 1977; Golonka and Rączkowski, 1983), the structure was considered as a lobe of the Magura sandstones within the Grajcarek (Hulina) Unit.

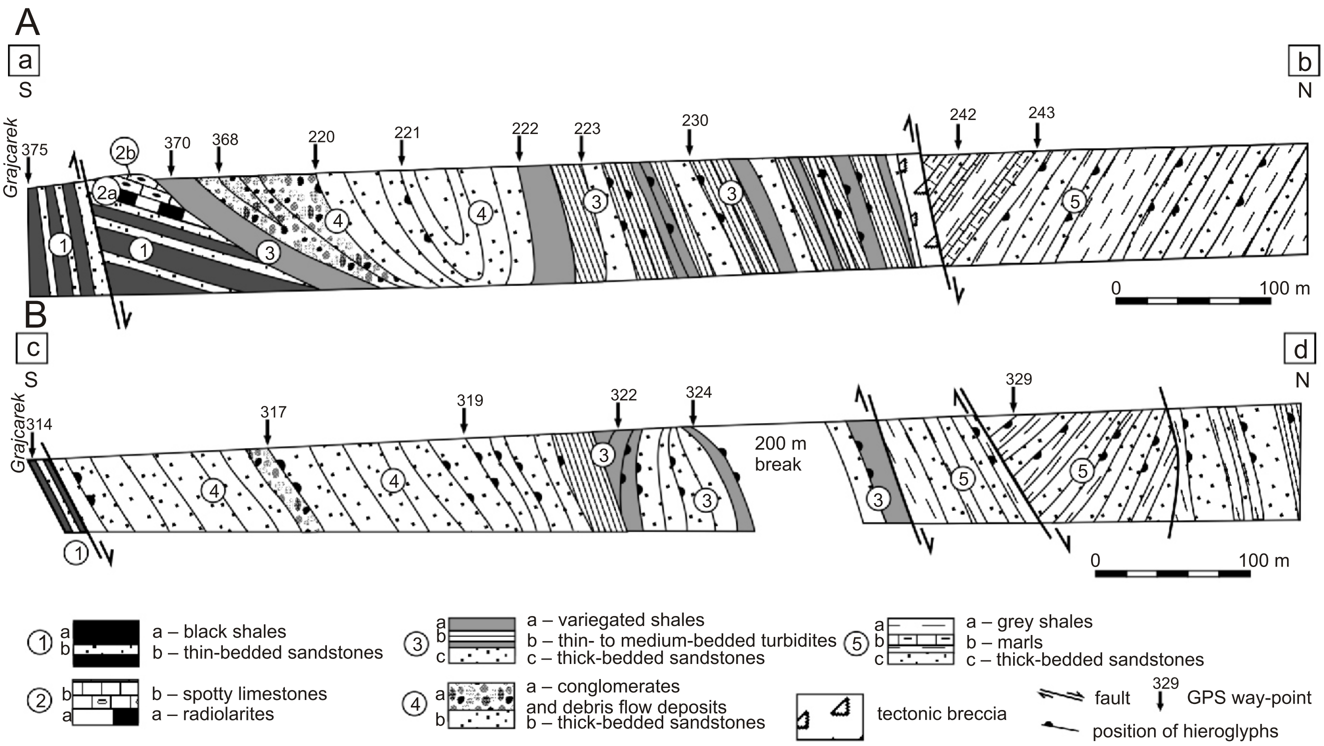

Fig. 11. Cross-section through the northern boundary zone (contact zone of the Grajcarek thrust-sheets and the Magura Nappe)

A – Sielski Steam at Szlachtowa, **B** – Stary Stream at Jaworki; Grajcarek thrust-sheet: 1 – "black flysch" (Szlachtowa and Opaleniec fms. undivided, Albian–Cenomanian), 2 – Cenomanian Key Horizon, 3 – Malinowa Sh. Fm. (Turonian–Campanian), 4 – Jarmuta Fm. (Maastrichtian–?Paleocene), Magura Nappe: 5 – Kremná Fm. (Early Burdigalian)

To the north, the Grajcarek Unit contacts with the Magura Nappe (Figs. 10 and 11) along the subvertical deep-seated North Boundary Fault (Birkenmajer et al., 1979).

To the west of Szafranówka Hill, the Grajcarek Unit is overlapped by the Pieniny Nappe (Figs. 2 and 10). Further to the east, up to the Krupianka tranverse fault, front of the Pieniny Nappe bends back to the south. As the result, along the Polish-Slovak border, the Upper Oligocene/Lower Miocene Kremná Formation of the Magura Nappe is exposed in the Durbaszka tectonic window. On the east of the Krupianka Fault tectonic situation changes drastically, and the front Klippen units of the PKB expand more than 2.5 km to the north, flatly sliding on the Grajcarek Unit. At the same time the axial zone of the Magura Nappe tectonic window is moved 1.5 km to the north (Figs. 2 and 10). The tectonic window of the Pawłowska and Repowa Mts. is limited by the Branisko and Niedzica overthrusts to the south and north, respectively.

MAGURA NAPPE

To the north of the boundary fault there are formations belonging to the Krynica Zone of the Magura Nappe. To the west of the Szczawnica transversal Fault, this zone is composed of the Szczawnica and Magura formations, and to the east of the Magura and Kremná formations. At the front of the Grajcarek Unit the formations belonging to the Magura Nappe are strongly deformed and often overturned. To the east of the Biała Woda Fault, the Grajcarek Unit is reduced to 150–200 m. As the result, the folded strata of the Kremná Formation of the Magura Nappe and the Pawłowska Góra–Repowa Tectonic Window are in close contact.

STAGES IN THE TECTONIC EVOLUTION OF THE PKB IN THE MAŁE PIENINY MTS.

This section is based both on previous works (Książkiewicz, 1972, 1977; Birkenmajer, 1986, 1988, 2001; Plašienka, 2012a, b; Plašienka et al., 2012) and the authors studies, in particular those on the age and position of the Magura flysch at the front of the PKB and "Intra-klippen flysch" within the PKB.

OPENING OF THE BASIN

According to Birkenmajer (1977, 1986, 1988, 2001) the opening of the Klippen Basin took place during the Middle Triassic, in course of rifting and sea-floor spreading. This basin was situated between the Outer and Central Carpathian domains, and was composed of the following sedimentary areas (Fig. 12): the northern ridge and slope of the basin (the Czorsztyn, Czertezik and Niedzica successions), the central furrow (the Branisko, Pieniny and "Ultra-Pieniny" successions) and the Andrusov Exotic Ridge (Birkenmajer, 1977, 1986, 1988, 2001). According to Plašienka's (2012a, b) interpretation, the Klippen Basin, was composed of the Czorsztyn–Niedzica and Kysuca–Pieniny successions (Oravic Basin Middle Penninicum), which developed on continental basement. This basin, opened during the Middle Jurassic, passed southwards into deep-water sediments of the Belice succession, developed on the oceanic crust of the Vahic Ocean (South Penincum).

In the Czorsztyn sub-basin the post-rift sedimentation was characterized mainly by shallow-water platform carbonate sedimentation, as well as by slope and swell deposition, upon the continental crust. During the Barremian–Aptian, the Czorsztyn

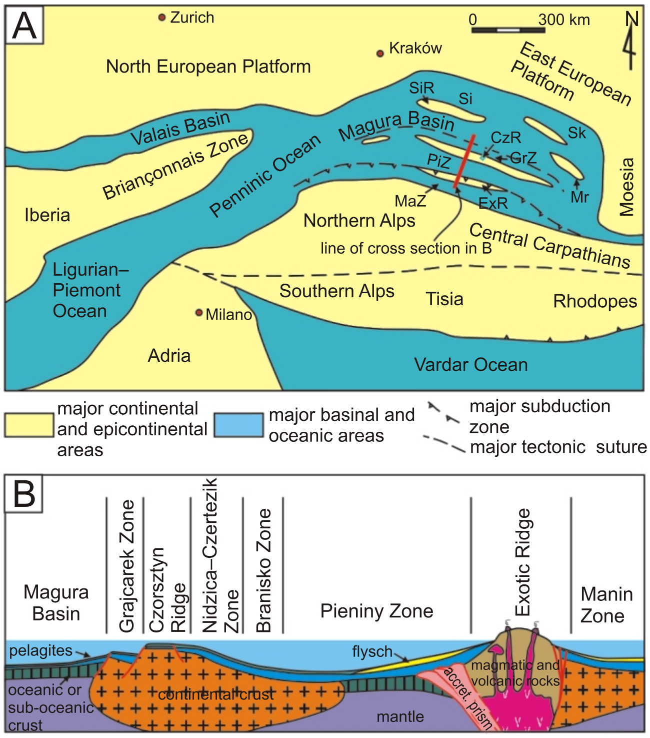

Fig. 12A – palaeogeographic map of the European part of the Tethys during the Middle Cretaceous (based on Uchman et al., 2013); B – Middle Cretaceous palaeogeographic position of the Magura/PKB basins (based on Uchman et al., 2013)

CzR – Czorsztyn Ridge; ExR – Exotic Ridge; GrZ – Grajcarek Zone; MaZ – Manín Zone; Mr – Marmarosh Massif; PiZ – Pieniny Zone; Si – Silesian Basin; SiR – Silesian Ridge; Sk – Skole Basin

Ridge was uplifted and dominated by erosion and karst development (Birkenmajer, 1977; Aubrecht et al., 2006). This period was followed by Albian marine transgression and Cenomanian–Campanian pelagic sedimentation. The Niedzica/Czertezik sub-basin located on the continental slope is regarded as a transitional facies between the Czorsztyn and Branisko/Pieniny development. The Jurassic–Early Cretaceous carbonate sedimentation of this succession was followed by Cenomanian–Turonian pelagic marls and Coniacian–Campanian flysch with horizon of synorogenic exotic conglomerates at the top. To the north of the Czorsztyn Ridge, the Magura Basin was located. The timing of opening of the Magura Basin is rather speculative, because the Magura Nappe was detached from its substrate roughly at the base of the Upper Cretaceous sequence (Oszczypko, 2006; Oszczypko and Oszczypko-Clowes, 2009). Frequently, an Early/Middle Jurassic age of opening of this basin is accepted (Birkenmajer, 1986; Oszczypko, 1992; Golonka et al., 2000; Oszczypko and Oszczypko-Clowes, 2009), probably as the eastern prolongation of the oceanic Valais–Rhenodanubian (North Penninic) Basin (Schmid et al., 2008). The southern part of the Magura Basin was occupied by the Grajcarek sub-basin (Fig. 12) with its Jurassic-Paleocene succession (Birkenmajer 1977, 1986; Oszczypko et al., 2012a). The Albian global rising of sea level was marked by deepening of the southern part of the Magura Basin, followed by the Upper Cenomanian Bonarelli Level/OAE-2 Event (Uchman et al., 2013). Further deepening of the basin, below the local CCD, resulted in sedimentation of hemipelagic red shales with intercalations of thin-bedded turbidites of the Malinowa Fm. (Turonian–Campanian). This succession is followed by normal flysch deposition in the Magura Basin (Oszczypko et al., 2005b) and the Jarmuta conglomerates (Maastrichtian–Middle Paleocene, Birkenmajer et al., 1987) in the Grajcarek sub-basin.

OROGENIC PHASE

The begining of collision in the outer zones of the Alpine–Carpathian system is associated with Late Cretaceous (Santonian) subduction of the Piemontese-Ligurian oceanic basins (ALCAPA and TISZA–DACIA microplates) beneath the Adriatic micro-plate (Golonka et al., 2000; Schmid et al., 2008; Márton et al., 2013). At the end of the Late Cretaceous the subduction zone was probably relocated to the northern margin of the Czorsztyn Ridge. This resulted in thrusting of the accretionary prism over the destroyed Czorsztyn Ridge and the development of submarine slumps and a large olistolith (Cieszkowski et al., 2009).

In the Grajcarek sub-basin, the Maastrichtian began the sedimentation of coarse clastic material of the Jarmuta Fm., derived from the erosion of the uplifted Czorsztyn Ridge. In the basal portion of this formation conglomerates contain large clasts of red shales (Malinowa Fm.) of the Grajcarek succession as well boulders and pebbles of Jurassic–Lower Cretaceous limestone (see also Birkenmajer, 1970) and exotic pebbles derived from newly developed nappes of the PKB (Birkenmajer and Wieser, 1990; Krobicki and Olszewska, 2005). In the Biała Woda section the Jarmuta conglomerates contain olistolith a few metres across of Lower Cretaceous basalts (Birkenmajer and Pécskay, 2000) which was derived from the Czorsztyn Ridge (Oszczypko et al., 2012b). In the Polish sector of the Grajcarek Unit, deposits younger than Paleocene are unknown.

In the Małe Pieniny Mts. the imbricated slices of Klippen successions are overthrust upon the Grajcarek successions. This is documented both from the intersection of the frontal thrust of the PKB, as well as from presence of the Grajcarek deposits in tectonic windows of the PKB (Figs. 2 and 10, see also Oszczypko and Oszczypko-Clowes, in press). These observations clearly exclude the Laramian back-thrusting of the Grajcarek Unit upon the Klippen units (Birkenmajer, 1986, 2001). In this way the new orogenic belt, now represented by the PKB, was formed. At the same time connection of the Grajcarek sub-basin with the Magura Basin was interrupted.

During the Middle/Late Eocene, an extensive marine transgression invaded the Central Carpathians and partly covered the PKB/Magura Nappe boundary. It is well documented in the Leluchów–Orlov–Udol area in the Poprad valley (Nemčok, 1990a, b; Oszczypko-Clowes, 2001; Plašenka et al., 2012).

Our results in the Małe Pieniny Mts. did not confirm that the Eocene marine transgression was followed by deposition of the “autochthonous Magura Paleogene” as was suggested by Birkenmajer (1986). According to our geological mapping these deposits occur in tectonic windows inside the PKB (Figs. 2, 10 and 11). Taking these data into account we conclude that during the Middle Eocene to Oligocene interval, the northern part of PKB evolved into a narrow island arc that separated the Central Carpathian and the Magura basins. At the same time, in the Magura Basin, continual deep-water sedimentation of flysch continued (cf. Oszczypko et al., 2005b). During the Early/Middle Eocene, re-deepening of the Magura Basin resulted in sedimentation, below the local CCD, of the variegated shales of the Łabowa Fm. From the Middle Eocene to the Early Oligocene, uplift of the source areas of the Magura Basin resulted in deposition of coarsening and thickening upwards sequences, typical of deep-water sub-marine cones (e.g., Beloveža, Zarzecze and Magura formations, Oszczypko and Oszczypko-Clowes, 2006, 2010). The presence of the Oligocene Malcov Fm. in the East Slovakia sector of the Magura Nappe indicates that the Magura and Central Carpathian Paleogene Basin (CCPB) basins were periodically connected (Książkiewicz and Leško, 1959).

At begining of this century there was a widely accepted viewpoint that closing of the Outer Carpathian sedimentary basins took place, according to traditional classic Alpine models, gradually from the Internides to the Externides (i.e., from the south to the north; Książkiewicz, 1977; Birkenmajer, 1986, 1988; Oszczypko, 1992, 2006; Golonka et al., 2000). However, the discovery of Lower Miocene deposits of the Zawada and Kremná formations in the Magura Nappe as well as in front of the PKB indicates that substantial revision of this view is required. At the same time, there is no evidence for deposits of Early Miocene age in the Rača and Siary sub-units of the Magura Nappe (Oszczypko-Clowes, 2001), either in the Grybów or in the Dukla units (Oszczypko-Clowes and Oszczypko, 2004; Oszczypko-Clowes, 2008; Oszczypko and Oszczypko-Clowes, 2011). This implies that the flexural foreland basin at the front of the Outer Carpathian accretionary wedge and the remnant (piggy-back basin) at the front of the PKB were separated by the partially uplifted Outer Carpathians (Fig. 13, see Oszczypko and Oszczypko-Clowes, 2009).

Our research in the Małe Pieniny Mts. and Radziejowa Range documented that the Kremná Formation (Oligocene/Lower Miocene) of the Magura Nappe is distributed along the front of the PKB, as well as in tectonic windows beneath the Grajcarek Unit and Klippen nappes. Thus it is possible to conclude that at the end of the Early Miocene, after deposition of the Kremná Formation, the PKB tectonic units together with the Grajcarek Unit overthrust folded and ?partly eroded the Magura Nappe. The amplitude of this overlap was probably less than 5 km, i.e. up to the fault zone between the PKB and the Central Carpathian Block. Overlap of the PKB over the Magura Nappe was also confirmed by data from the deep boreholes which penetrated the PKB (i.e., Lubina-1 near Myjava, Hanušovce-1 in Eastern Slovakia and Svalava 1 and Drahovo-1 in the Ukrainian Carpathians; fide Leško et al., 1985). These boreholes pierced the youngest deposits of the Magura succession beneath the PKB.

Overthrust of the PKB onto the Magura Nappe was probably approximately synchronous (17–18 Ma, i.e. Ottnangian/Karpatian), with the beginning of folding and overthrusting in the Outer Carpathians. At that time, the edge of the subduction zone was located directly south of the PKB (Ustaszewski et al., 2008).

In course of the Middle Miocene overthrusting of the Outer Carpathian accretionary wedge its internal shortening was hampered by the backstop at the boundary between the PKB and the Central Carpathian Block. This caused strong compression at the Central Carpathian/PKB boundary. Initially, this caused back-thrusting and formation of zones of overturned beds, observed along the northern boundary of the PKB (Figs. 11 and 12), and then was followed by lateral, probably convergent, strike-slip movements along the southern and northern boundaries of PKB. This tectonic displacement dismembered the initial geometry of the PKB, and allowed opening of tectonic windows and development of its present-day flower structure. The relaxation of tectonic stress enabled andesite intrusion followed by formation of the transverse faults. Post - orogenic erosional uplift resulted in the opening of tectonic windows in the axial part of the Małe Pieniny Mts., and migration of carbon dioxide-saturated mineral waters along the faults (e.g., in the Krościenko-Szczawnica Spa area).

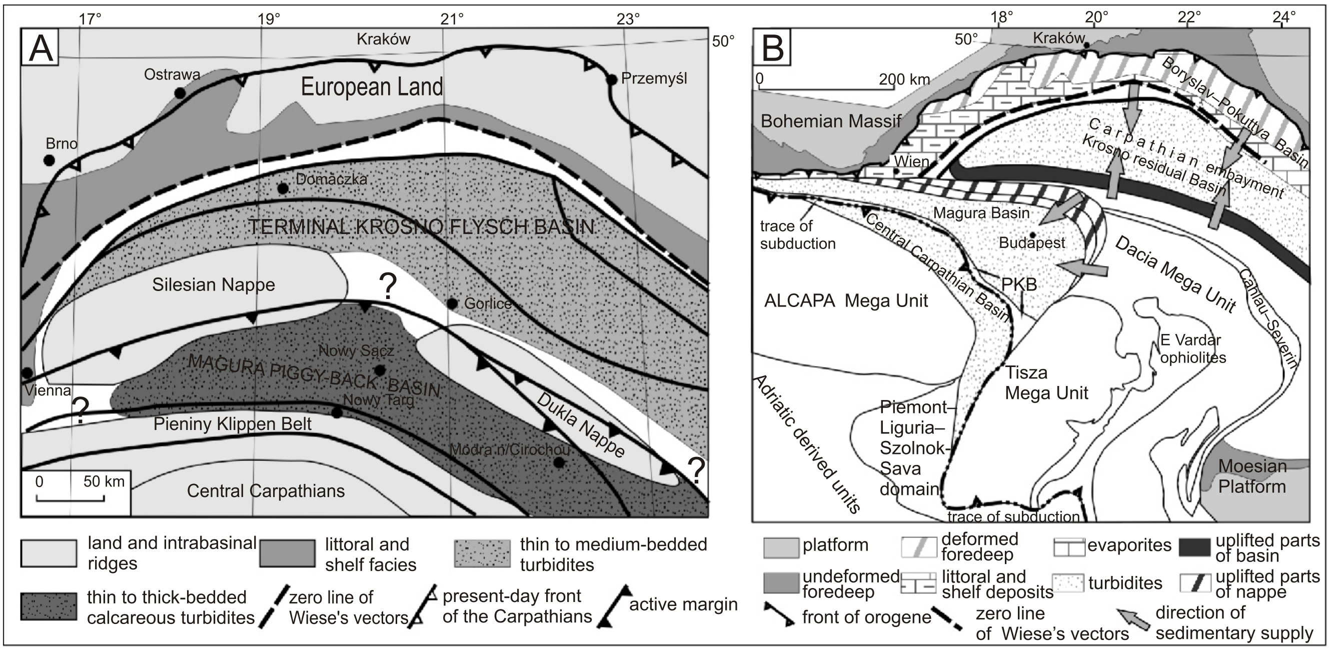

Fig. 13A – Early Burdigalian palinspastic palaeogeogegraphic map of the northern sector of the Western Carpathian basins system (after Oszczypko and Oszczypko-Clowes, 2009, modified); B – a map-view restoration of the Alpine–Carpathian–Dinaridic system for the Early Miocene after Ustaszewski et al. (2008), simplified

CONCLUSIONS

1. Along the northern border of the Małe Pieniny Mts. the PKB is separated from the Magura Nappe by a narrow, strongly tectonically deformed zone belonging to the Grajcarek Unit.

2. The Magura Nappe situated on the southern slope of the Beskid Sądecki Range is composed of Paleogene to Early Miocene deposits of the Krynica facies Zone.

3. The youngest deposits of the Magura succession belong to the Kremná Fm. (NN2 zone, Burdigalian).

4. This formation is distributed both at the front of as well as in tectonic windows inside the PKB.

5. The Kremná Fm. can be correlated with other Lower Miocene deposits known from the contact zone between the Magura Nappe and the PKB in the Nowy Targ area, as well as in the Horná Orava Region of Slovakia.

6. These deposits developed in the Early Miocene remnant Magura (piggy-back basin) at the front of the PKB.

7. The present-day structure of the Małe Pieniny Mts. developed in the course of the Late Cretaceous/Paleocene and Early Miocene folding and thrusting as well as Middle/Late Miocene compression and strike-faulting.

8. The strike-slip boundaries of the Magura Nappe/PKB and PKB/Central Carpathian Paleogene Basin define the PKB as the Middle Miocene flower structure.

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