

## The Early Miocene residual flysch basin at the front of the Central Western Carpathians and its palaeogeographic implications (Magura Nappe, Poland)

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In the Polish sector of the Magura Nappe, along the front of the Pieniny Klippen Belt, strongly tectonized calcareous flysch up to 1000 m thick is exposed. Previously these deposits, composed of thin- to thick-bedded flysch, with a packet of Łącko-type marls, have been included into several Paleocene/Eocene formations, e.g., the Szczawnica Formation. This formation contains a poor assemblage of agglutinated foraminifera and a relatively rich assemblage of calcareous nannoplankton, with abundant reworked species. The youngest species give evidence of the NN2 Zone (Lower Miocene). Additionally, in three profiles (Szlachtowa, Knurów and Waksmund) of the Kremna Fm., Early Miocene foraminifera have been recognized. This research documented that during the Burdigalian, at the front of Central Western Carpathians, there still existed a residual marine basin probably up to 100 km wide. These deposits also contain thick packages of exotic carbonate conglomerates derived from the SE, previously regarded as the Jarmuta Formation.

Key words: Outer Carpathians, Magura Nappe, residual flysch basin, Early Miocene, calcareous nannoplankton, palaeogeography.

### INTRODUCTION

Since the second half of the last century, there has been a dominant view that the closure of sedimentation in the Magura Paleogene Basin progressed gradually from the Middle Eocene in the Krynica facies zone, in the south, to the Early Oligocene in the Siary facies zone in the north (Sikora and Żyto, 1960; Węclawik, 1969; Sikora, 1970; Książkiewicz, 1972, 1977; Birkenmajer and Oszczypko, 1989). This point of the view has been partially modified following the discovery of the Oligocene Malcov Formation (Fm.) above the Magura Sandstone Fm. in the Nowy Sącz and Nowy Targ areas by Oszczypko (1973) and Cieszkowski and Olszewska (1986), respectively. Later, some of these strata were considered by Cieszkowski (1992, 1995) as younger marine “molasse” formations of Badenian/Sarmatian age.

At the turn of the last century Oligocene/Miocene flysch deposits were discovered in several places within the Magura Nappe of the Polish and Slovak sectors of the Outer Western

Carpathians (Oszczypko et al., 1999, 2005a; Oszczypko and Oszczypko-Clowes, 2002; Matašovský and Andreyeva-Grigorovich, 2002). In subsequent publications (Oszczypko and Oszczypko-Clowes, 2010, 2014) these Oligocene/Miocene deposits have been described as the Kremna Fm. at Stara Ľubovňa (Slovakia) and in the Małe (Little) Pieniny Mts. (Poland). Farther to the east these deposits were recognized by us at the front of the Pieniny Klippen Belt (PKB), at the Obručné and Dubné localities (Smreczek Stream, right tributary of the Poprad River). This study focuses on the area between Jaworki (E) and Nowy Targ (W), as crucial the understanding the relationship between the Magura Nappe, the PKB and the Central Western Carpathians (CWC). Keeping this in mind we re-evaluate existing as well as new geological and biostratigraphical data of the Oligocene/Miocene deposits at the front of the PKB. This is important for better understanding of the palaeogeography and relationships between the CWC, PKB and Magura Nappe before the Early/Middle Miocene shortening of the Outer Western Carpathians (OWC).

### PREVIOUS WORK

In the Polish Outer Carpathians the Upper Eocene/Oligocene deposits of the Magura Succession were first recognized by Oszczypko (1973), at the southern margin of the Nowy Sącz

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Basin (Nowy Sącz 1 borehole), and in the Zawada and Biegonice sections of the Rača facies zone (Figs. 1, 2 and 3). These deposits, located at the top of the Upper Eocene Magura Sandstone Fm., were regarded as the Malcov Formation (Książkiewicz and Leško, 1959; Leško and Samuel, 1968). In samples from the Malcov Formation, Blaicher (in Oszczypko, 1973) recognized three different age assemblages (benthic and planktonic), albeit intermixed, containing Early/Middle Eocene; Late Eocene/Oligocene and Oligocene species. The youngest Oligocene foraminifera were considered as autochthonous, and the two other assemblages as reworked.

The Biegonice and Zawada sections have been re-examined by Oszczypko et al. (1999). These studies documented the presence of Early Miocene foraminifera (N5) and calcareous nannoplankton (NN1-3) in deposits assigned to the Middle Eocene, as the Łącko Marls. Finally all these marly deposits were included into the Zawada Formation (Oszczypko et al., 1999; Oszczypko and Oszczypko-Clowes, 2002).

Other young deposits (Upper Eocene/Oligocene) of the Magura Succession have been recognized as the Malcov Formation (Cieszkowski and Olszewska, 1986), in several sections near Nowy Targ and close to the PKB (Figs. 1 and 2). In these sections, the thick-bedded Magura-type sandstones with intercalations of grey marly claystones, were previously regarded as the Inoceraman beds (Cenomanian–Turonian – Halicki, 1959; Turonian–Maastrichtian–Danian – Watycha, 1963).

A few years later, the Early Miocene flysch of the Magura Succession was recognized, in the Nowy Targ 1 borehole (Paul and Poprawa, 1992), close to northern boundary of the PKB. More or less simultaneously, in similar deposits (thick-bedded sandstones) Cieszkowski (1992, 1995) and Cieszkowski et al. (1993) described the flysch deposits of the Stare Bystre and Rogoźnik sections (Podhale region) which were considered to be the youngest Middle Miocene (Langhian–Serravalian) deposits of the Magura Succession. Recently the age of the Stare Bystre deposits was re-evaluated to be of Early Miocene age (see the discussion in Kaczmarek et al., 2016).

There has been an interesting evolution of views on the age of the youngest deposits of the Magura Nappe in Eastern Slovakia. This began with the discovery by Matašovský and Andreyeva-Grigorovich (2002) of the Upper Oligocene/Lower Miocene deposits of the Magura Nappe in the Peri-PKB zone near Humenné. Previously these deposits were regarded as of Eocene age. Towards the west, near Stara Ľubovňa, in a similar tectonic position (Peri-PKB zone), there are deposits described by Uhlig (1890a, b, 1903) as the “Nördliche Grenze Flysch Zone”. Horwitz (1935) described these strata as the “Peri- or Inter-Klippen Flysch”, later distinguished by Matějka (1959) as the Kremna facies. These beds have also been studied by Stranik and Hanzlíková (1968) as the Paleocene/Eocene sandy-conglomeratic calcareous flysch, 1200–1600 m thick, with intercalations of grey-greenish claystones and siltstones.

Many years later these deposits were defined by Oszczypko et al. (2005a) as the Kremna Formation, being the youngest Oligocene–Lower Miocene member of the Magura Succession in the Peri-PKB zone, different from the Malcov Fm. Calcareous nannoplankton studies of the Kremna Fm. showed a predominance (50%) of redeposited species, mainly Middle–Late Eocene, while the youngest species identified belong to the Early Miocene (NN1 and NN2 zones, Oszczypko et al., 2005a). The Kremna Fm. is regarded as an equivalent of the Zawada and Stare Bystre formations in the Nowy Sącz and Podhale areas. Recently the Kremna Fm. has been recognized in the Krynica facies zone of the Muszyna and Jaworki areas (Oszczypko and Oszczypko-Clowes, 2010) as well in the “Magura Autochthonous Paleogene” in tectonic windows in the

PKB (Oszczypko and Oszczypko-Clowes, 2010, 2014). Oligocene–Lower Miocene flysch deposits have also been documented in the Horná Orava region of Western Slovakia (Oszczypko-Clowes et al., 2013).

## GEOLOGICAL SETTING

Our studies mainly focus on the Paleogene deposits of the Magura Nappe (Krynica sub-unit), along the northern margin of the Polish sector of the PKB (Figs. 1, 2 and 3). This area is a morphological depression, several kilometres wide, situated between the Pieniny and Małe (Little) Pieniny Mts. to the south and the Gorce/Beskid Sądecki ranges in the north. The “Nördliche Flysch Zone” (Uhlig, 1890a, b, 1903, 1907) or “Magura flysch (Paleocene/Lower Eocene)” (Horwitz, 1935, 1963), placed beneath the Middle/Upper Eocene (sub-Magura and Magura beds), have been regarded as the oldest deposits of the Magura Succession in the the Gorce and Beskid Sądecki ranges. Based on poorly preserved foraminifera, these are regarded as the oldest deposits in this area, and have been classified into the Ropianka beds (Watycha, 1975; Burtan et al., 1981), an equivalent of the Inoceraman beds (Upper Cretaceous/Paleocene) of the more external units of the Polish Outer Carpathians. Further studies based on small numbers of agglutinated foraminifera and poorly preserved calcareous nannoplankton (Birkenmajer and Dudziak, 1981; Golonka and Rączkowski, 1981, 1984; Alexandrowicz et al., 1984; Kulka et al., 1987, 1991) led to units of Upper Paleocene–Middle Eocene age being distinguished. The following Paleocene/Eocene formal lithostratigraphy of the Krynica sub-unit has been proposed by Birkenmajer and Oszczypko (1989): the Szczawnica Formation (Middle/Upper Paleocene), up to 400 m thick, with the level of the Łącko Marls (up to 50 m), followed by the Frydman Fm. (Lower Eocene), up 400 m thick, and the Magura Sandstone Fm. (Lower/Upper Eocene), overlain by the uppermost Eocene/Lower Oligocene Malcov Fm.

The Magura Fm. is the youngest deposit of the Krynica sub-unit, with the exception of the Malcov Fm., locally occurring near Nowy Sącz (Oszczypko, 1973) and Nowy Targ (Cieszkowski and Olszewska, 1986). The Magura Fm., up to 2000 m thick (Birkenmajer and Oszczypko, 1989; Kulka et al., 1991) is dominated by massive, thick-bedded sandstones, with sporadic intercalations of thin-bedded turbidites. The Magura Fm. is subdivided into three members: the Piwniczna Sandstone Member (PSM), the Mniszek Shale Member (MSM) and the Poprad Sandstone Member (PoSM). This formation is dominated by coarse clastic turbidites, resulting in a scarcity of agglutinated foraminifera and a dominance of reworked calcareous nannoplankton.

In the PSM, there are calcareous nannoplankton belonging to NP15/17 in the Piwniczna area (Oszczypko-Clowes, 2001; Oszczypko and Oszczypko-Clowes, 2010) and NP18–20 in the Muszyna area (Dudziak in Oszczypko et al., 1990). The MSM is represented by variegated shales with *Reticulophragmium amplexans* which was traditionally regarded as a Middle Eocene form, while now it indicates the Late Eocene (Bindu et al., 2015).

West of the Poprad River, the MSM has not been confirmed. In this part of the Krynica sub-unit, the position of the MSM is possibly occupied by the Kowaniec beds. These beds, up to 100 m thick, are composed of thin to medium-bedded turbidites.

In the Polish sector of the Krynica sub-unit, the PoSM has not been precisely dated. By contrast, samples collected from the Ruska Vola section on the Poprad River (Eastern Slovakia), con-

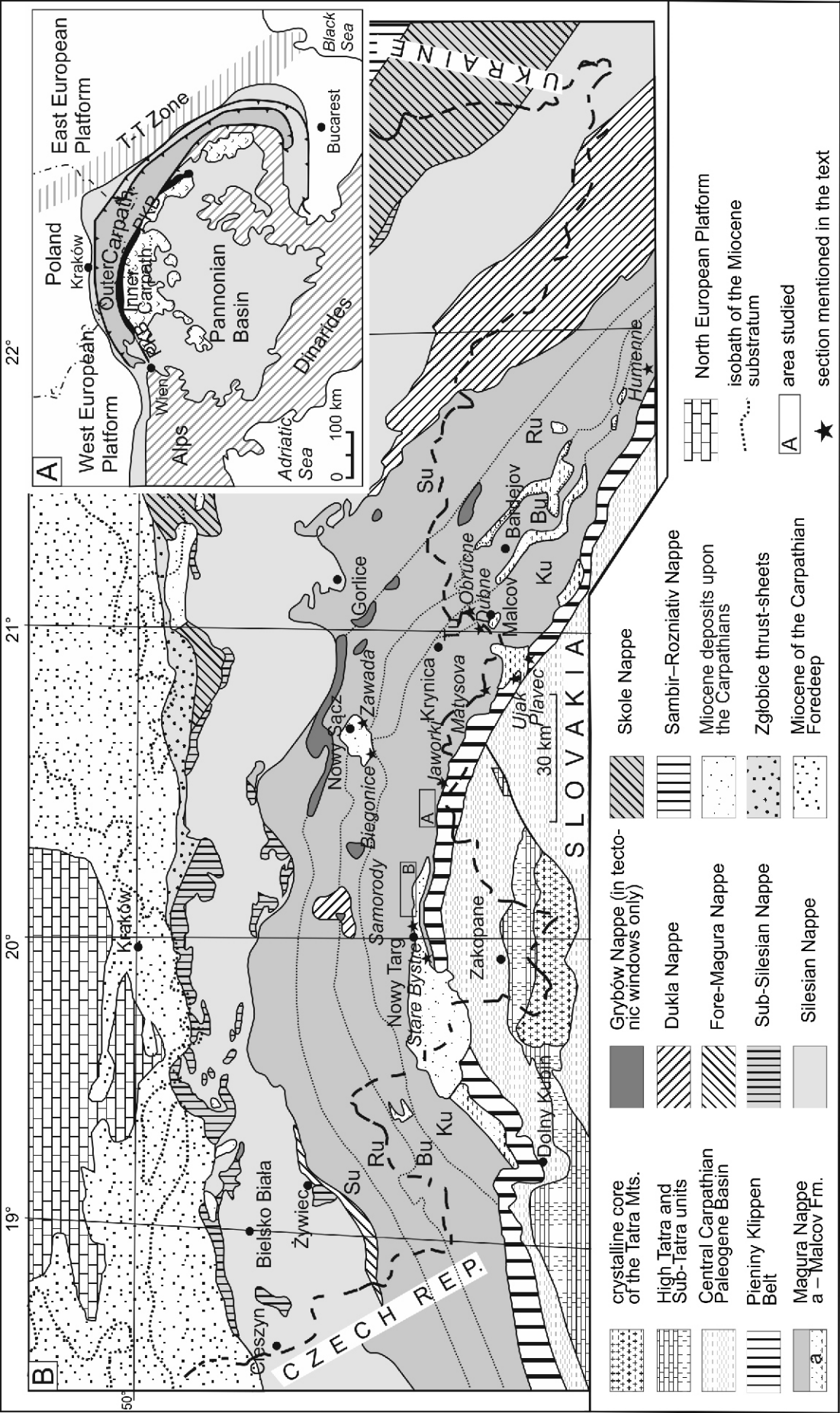


Fig. 1A – tectonic map of the Alpine-Panonian-Carpathian System (after Schmid et al., 2008); B – geological sketch-map of the Polish Carpathians (after Żyto et al., 1989, modified)

Bu – Bystrica, Ku – Krynica sub-units, Ru – Rača, Su – Siary



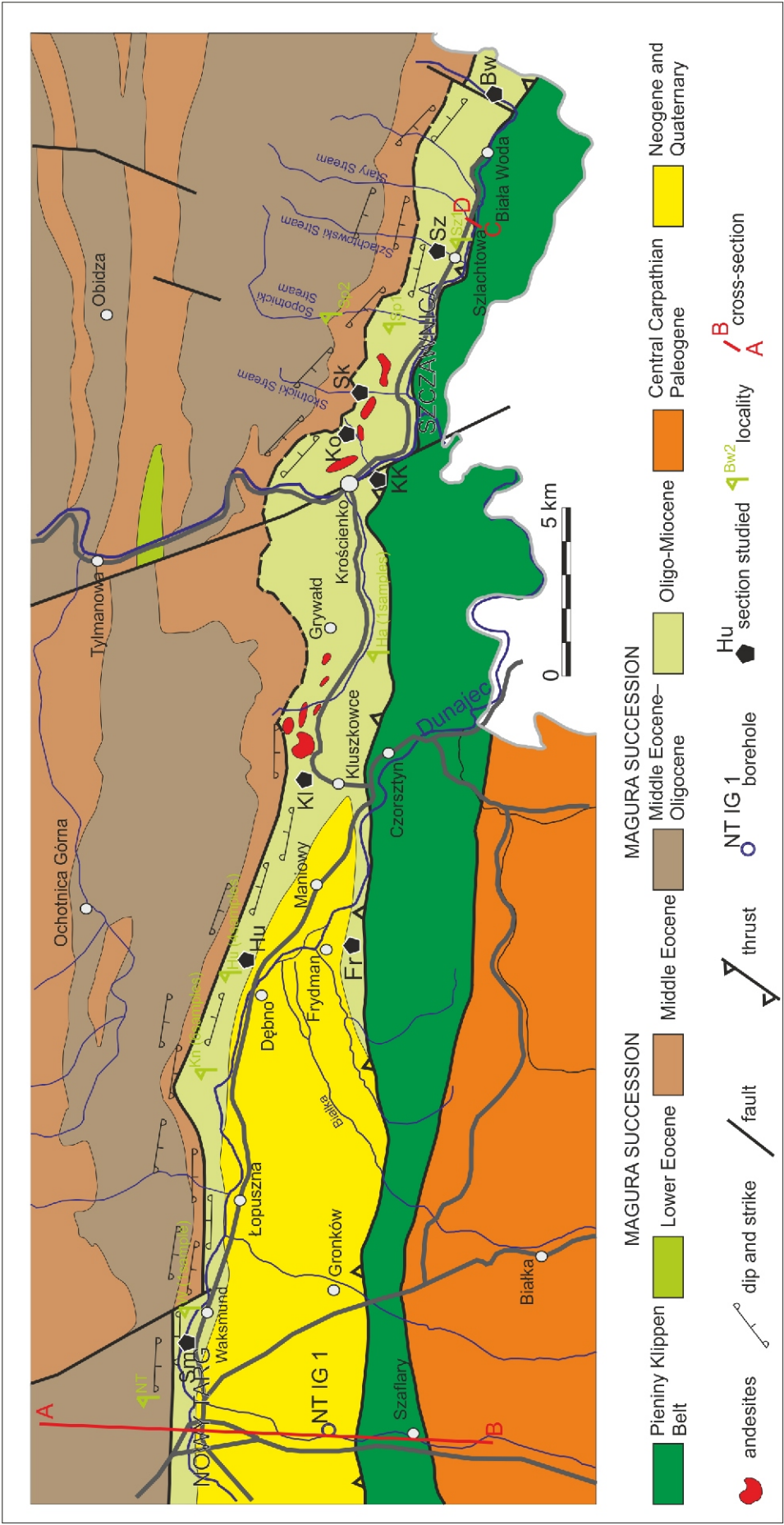


Fig. 2. Geological sketch map of the Mate Pieniny Mts. and adjacent part of Beskid Sądecki Range (based on Burtan et al., 1981; Golonka and Rączkowski, 1981; Kulka et al., 1987; Oszczytko and Oszczytko-Clowes, 2014)

Bw – Biała Woda, Ha – Hatuszowa, Hu – Huba, KK – St. Kinga Chapel, Kl – Kluszkowce, Ko – Kozłeki, NT – Nowy Targ, Sk – Skotnicki, Sm – Samorodny, Sp – Sopotnicki, Sz – Szlachtowna, W – Wąskmurd



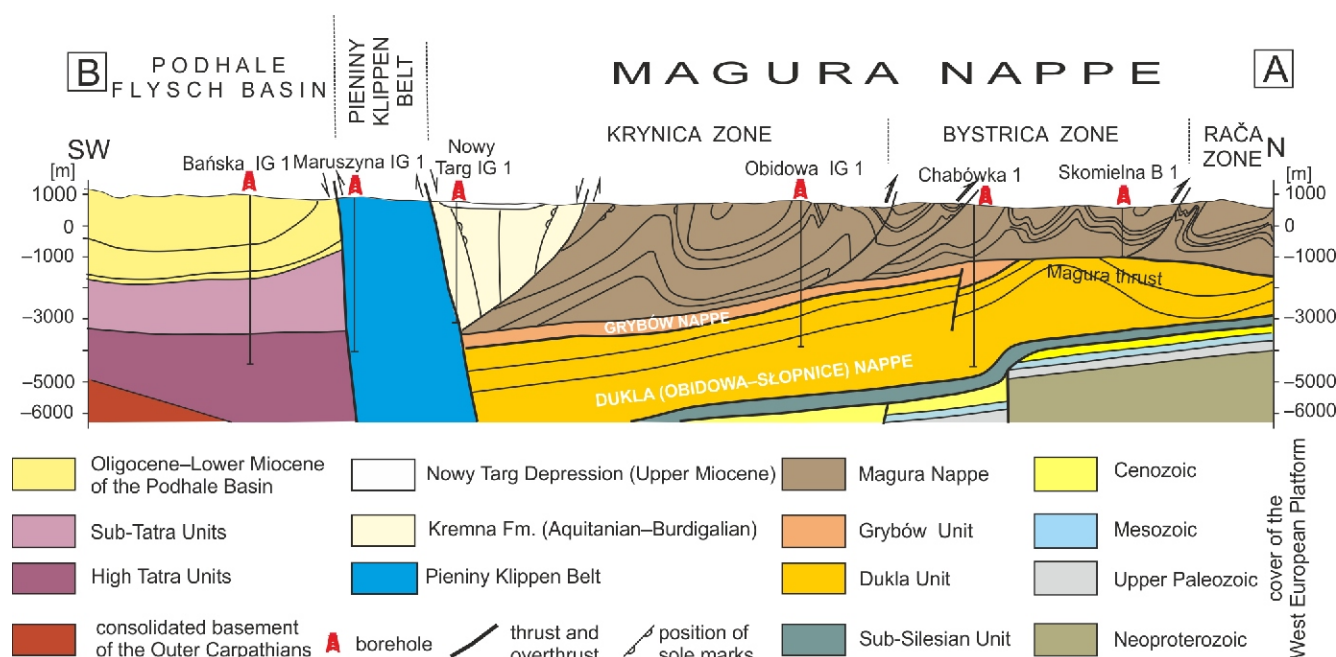


Fig. 3. Geological cross-section Obidowa IG 1–Bańska IG 1 (based on [Oszczypko, 1997](#)), modified

tain a well-preserved and moderately abundant nannofossil assemblage belonging to the NP25 and NN1 zones, followed by the Kremna Fm. (NN1-2; [Oszczypko-Clowes in Oszczypko et al., 2005a](#)). The same age was determined in samples collected in the upper part of the Homole Gorge and Biała Woda sections of the PKB ([Oszczypko and Oszczypko-Clowes, 2010, 2014](#)).

## METHODOLOGY

Our current research has been focused on the Polish sector of the Peri-PKB zone, between the Biała Woda Stream in the east (Małe Pieniny Mts.) and the Nowy Targ–Orava Neogene Depression in the west (Figs. 1 and 2). This area linked the already known occurrences of Oligocene/Miocene deposits in the valley of the Poprad River ([Oszczypko et al., 2005a; Oszczypko and Oszczypko-Clowes, 2010](#)), the Małe Pieniny Mts. ([Oszczypko and Oszczypko-Clowes, 2010, 2014](#)), and near the Nowy Targ area ([Cieszkowski and Olszewska, 1986; Cieszkowski, 1992; Paul and Poprawa, 1992; Kaczmarek et al., 2016](#)). Taking into account the poor condition of exposures in this area it has been necessary to use all available natural exposures.

Geological profiling was conducted using traditional methods, but fully linked to satellite navigation (GPS way points – WP). The profiling allowed us to establish the stratigraphic succession of beds as well as their lithological and sedimentological character.

In order to establish the age and variability of assemblages in the samples, species of nannoplankton and planktonic foraminifera were determined. Slides for nannofossil determination were prepared using a simple smear slide technique according to Bown and Young (in: [Bown, 1998](#)). All samples were analysed with a Nikon-Eclipse E 600 POL, at 1000x magnification using both parallel and crossed polars. Qualitative analyses allowed the age determination. The taxonomic framework applied is based upon [Aubry \(1984, 1988, 1989, 1990, 1999\)](#), [Perch-Nielsen \(1985\)](#) and [Bown \(1998\)](#) and references therein). Biostratigraphy is based on the standard zonation of Martini and

[Worsley \(1970\)](#). However, the marker species for the Lower 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.

In addition, a quantitative analysis was performed for samples from the Huba section. Quantitative analyses involved using counts of 300 specimens in random fields of view for selected samples, in order to ascertain the percentage content of reworked and autochthonous species. According to [Thierstein et al. \(1977\)](#), at the 95% confidence level, 300-specimen counts ensure the presence of a taxon whose relative abundance was 1% in the total population. The palaeoecological analyses were performed on autochthonous assemblages. The percentages were taken literally.

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 in fragments; P – poor, severe dissolution, fragmentation and/or overgrowth; the specific identification of specimens is difficult; M – moderate, etching or mechanical damage is apparent but most specimens are easily identifiable; G – good, little dissolution and/or overgrowth; diagnostic characteristics are preserved, the specimens could be identified to species level without any 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).

Additionally, in the Stary Stream in Szlachtowa and Waksmund sections, the determination of calcareous nannoplankton was supplemented by the analysis of small foraminifera (Figs. 1 and 2).

## RESULTS

## SECTIONS STUDIED

Studies carried out in Eastern Slovakia near Stara Ľubovňa (Oszczypko et al., 2005a) have clearly demonstrated that the Poprad Sandstone Mb. of the Magura Fm. (NP25/NN1) is overlain by flysch of the Kremna Fm. (NN1/NN2). This sequence has been documented in the Matyšova section (N49°18.864' E20°46.513', 542 m a.s.l.) and at Sedlo Vabec (N49°20.585' E20°40.513.658', 750 m a.s.l.). On the Polish side, the stratigraphic succession of the Kremna Fm. above the Poprad Sandstone Mb. has only been documented in the Biała Woda Valley. Farther to the west, in the vicinity of Nowy Targ, this contact is not visible. The interpretation of existing geological maps (Watycha, 1975; Burtan et al., 1981; Kulka et al., 1991) and our field observations suggest a tectonic contact. Unfortunately, these maps dating back to the last century are largely outdated.

The discovery of the Kremna Fm. (Oligocene/Lower Miocene), previously described and assigned to the Szczawnica Fm. (Paleocene/Lower Eocene), is of paramount importance.

**Biała Woda Stream section (WP 77 and 506; N49°23.826' E20°35.307').** The profile studied, 2 km long (Fig. 4), is located in the upper section of Biała Woda Creek. The results from this section have already been published (Oszczypko and Oszczypko-Clowes, 2010, 2014). However, in the area studied, on the Polish side, this is the only profile documenting the stratigraphic succession of the Kremna Fm. above the PoSM. The profile displays SW-dipping (Fig. 4), deposits, in normal position, of the Lower Miocene Kremna Fm. (Oszczypko and Oszczypko-Clowes, 2010, 2014), composed of dark grey laminated marly mudstones with the *Dendritus* ichnofacies, with sporadic intercalations of thin-bedded, turbiditic sandstones. These beds were previously regarded (Birkenmajer, 1979; Golonka and Rączkowski, 1984) as the Szczawnica Fm. (Paleocene/Lower Eocene). Towards the south, the Kremna Fm. has tectonic contact with the PKB (Fig. 4B).

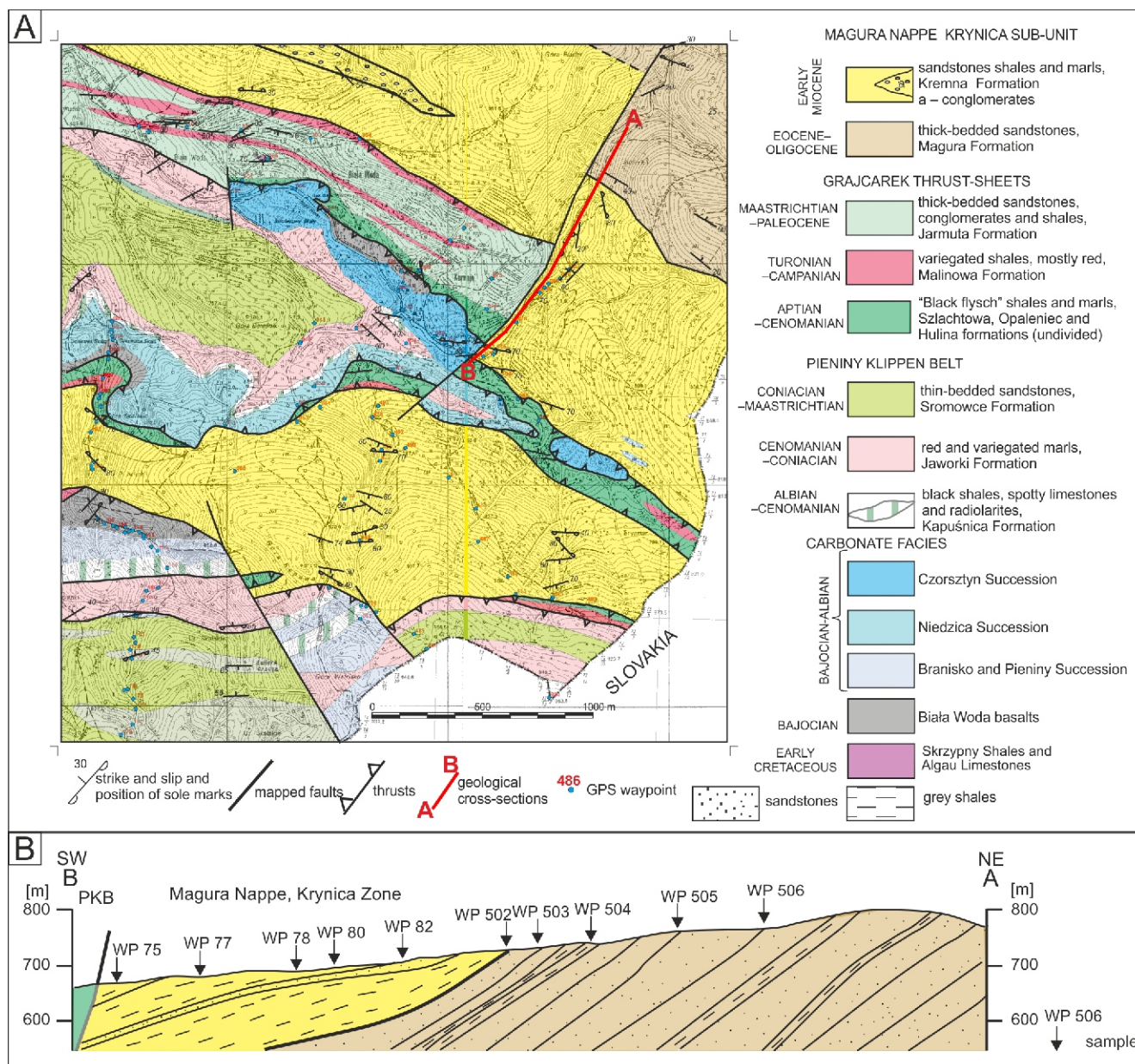


Fig. 4A – geological map of the Biała Woda area (after Oszczypko and Oszczypko-Clowes, 2014); B – cross-section



**Słoty Stream in Szlachtowa; (WP 329–337: N49°24.757' E20°32.952' to WP 279: N49°24.950' E20°33.169').** This section displays the tectonic contact of the Grajcarek Unit (Fig. 5) with the Kremna Fm. of the Magura Nappe. Here, variegated shales of the Malinowa Fm. (Turonian–Campanian) of the Grajcarek Unit are thrust, in overturned position, on the SSW-dipping, in normal position, deposits of the Kremna Formation. This formation is composed of dark grey marly mudstones and thick-bedded (1–3 m), Łącko-type marls, with intercalations of thick-bedded (0.4–1.0 m) sandstones (Fig. 6). The marls are massive with delicate horizontal lamination.

**Skotnicki Stream section near Szczawnica (WP 491: N49°23.594' E20°34.983' to WP 499: N49°24°041' E20°34.903').** The geological map of Kulka et al. (1987) shows the following interpretation of the geological structure of the Skotnicki Stream: the Szczawnica Beds (Paleocene/Eocene) with andesite dikes in the lower part of the creek pass upwards into the Eocene sequence of the Magura Fm., represented by the PSM followed by the Kowaniec Beds and the PoSM of the Magura Fm. Taking into account that the former Szczawnica Fm. (Paleocene/Eocene) now belongs to the Kremna Fm. (Oligocene–Miocene), our interpretation of this section is different.

The first exposures of the Kremna Fm., visible above the Pitoniakówka mineral water spring (Fig. 7A), are represented by thin- to medium-bedded fine-grained calcareous sandstones, accompanied by dark grey marly mudstones and shales. These strongly brecciated beds, dipping sub-vertically to the north, are in overturned position. Going up the stream, after ~150 m, the right inlet shows large blocks of Neogene andesites (Fig. 7A). After a few tens of metres, exposure disappears, and over a distance of ~150 m there are coluvia of an active landslide on the right slope of the valley. This landslide covers the contact between the Kremna and the Magura formations.

After the break in exposure, above a bifurcation in the stream, we found in the right inflow (Biały) the first exposure (WP 491, Fig. 7A, B), represented by 5 m thick grey shales with an intercalation of thick-bedded sandstone (1.5 m). Uphill, these strata dip to the south (190/60), in overturned position. This type of deposit, up 50 m thick, can be correlated with the Kowaniec beds the Magura Fm. Higher up in the section, dark-grey thin bedded turbidites are exposed, with a dominance of marly mudstones, at least 25 m thick (Figs. 7C and 8). These

thin-bedded turbidites continue to be south-dipping and overturned. This succession can probably be correlated with the Kowaniec Member (Middle to Upper Eocene, see Kulka et al., 1987, 1991). Above WP 495 to WP 496 the Kowaniec Mb. is followed by thick- to very thick-bedded sandstones of the PoSM of the Magura Fm. (Figs. 7 and 8). The Kowaniec Beds in the Skotnicki Stream are well-known as a correlative horizon (formerly the sub-Magura Beds, see Burtan et al., 1981; Birkenmajer and Oszczypko, 1989). On the southern slope of the Gorze and Besid Sądecki ranges, the Kowaniec Member marks the boundary between the PSM and PoSM of the Magura Fm. In the Skotnicki Stream the north-dipping (in overturned position) Kremna Fm. (Oligocene/Miocene) contacts with the south-dipping (in overturned position) Magura Fm. (Middle/Upper Eocene), along a reverse fault. A similar boundary between the Magura Fm. and Kremna Fm. was documented (Figs. 2 and 3) on the right slope of the Grajcarek Valley, between Szczawnica and Biała Woda (see Oszczypko and Oszczypko-Clowes, 2014).

#### KROŚCIENKO ON THE DUNAJEC RIVER

**Kozłeki Stream section (WP501–504; N49°26.453' E20°26.753'; Fig. 9).** The section studied is located in the lower run of the Kozłeki Stream, at the right confluence of the Dunajec River (Fig. 2). This ~100 m long section is composed of medium-bedded (20–30 cm), fine to very fine-grained sandstones with an intercalation of dark grey marly shales (Fig. 8). The flute marks display axes of palaeotransport of 20°(NNE)–200°(SWS). In previous studies these strata have been regarded as the Szczawnica Formation (Upper Paleocene/Lower Eocene: Birkenmajer and Dudziak, 1981; Alexandrowicz et al., 1984; Kulka et al., 1987, 1991; Golonka and Waśkowska, 2014). Higher up in the section (WP 503–504), on the left bank of the creek, grey shales with a thick bed of exotic conglomerate are exposed. The deposits from Kozłeki Stream can be regarded as the NW prolongation (in the same tectonic position) of the Kremna Formation from Sopotnicki Stream.

**Krościenko on the Dunajec River, Chapel St. Kinga section (WP523–528; N49°25.921' E20°26.322'; Figs. 10 and 11).** This section belongs to the Paleogene deposits of the

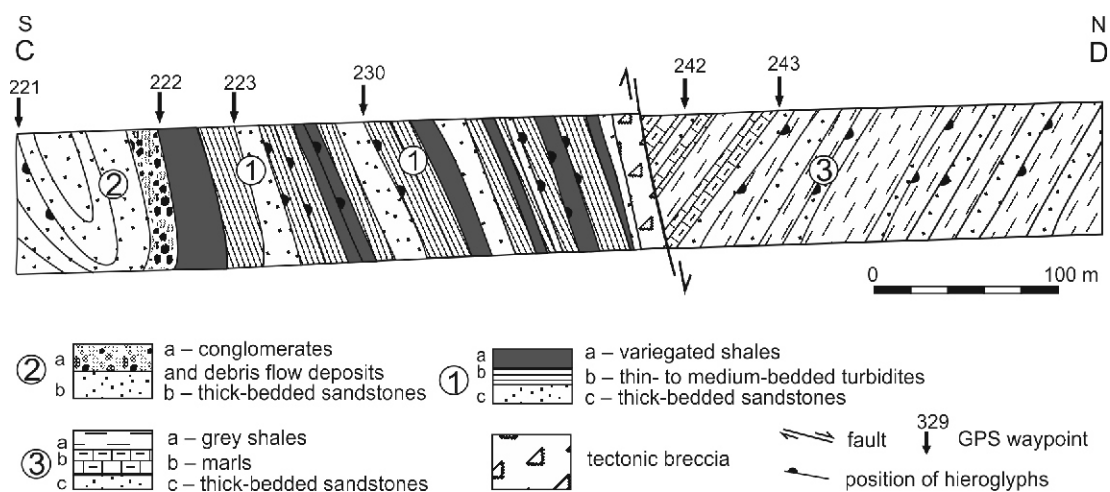


Fig. 5. Cross-section through the northern boundary contact zone of the Grajcarek thrust sheets and the Magura Nappe, Słoty Stream section (based on Oszczypko and Oszczypko-Clowes, 2014, supplemented)

1 – Malinowa Fm., 2 – Jarmuta Fm., 3 – Kremna Fm.





Fig. 6. Thick-bedded marls of the Kremna Fm. from the Stary Stream section at Szlachtowa

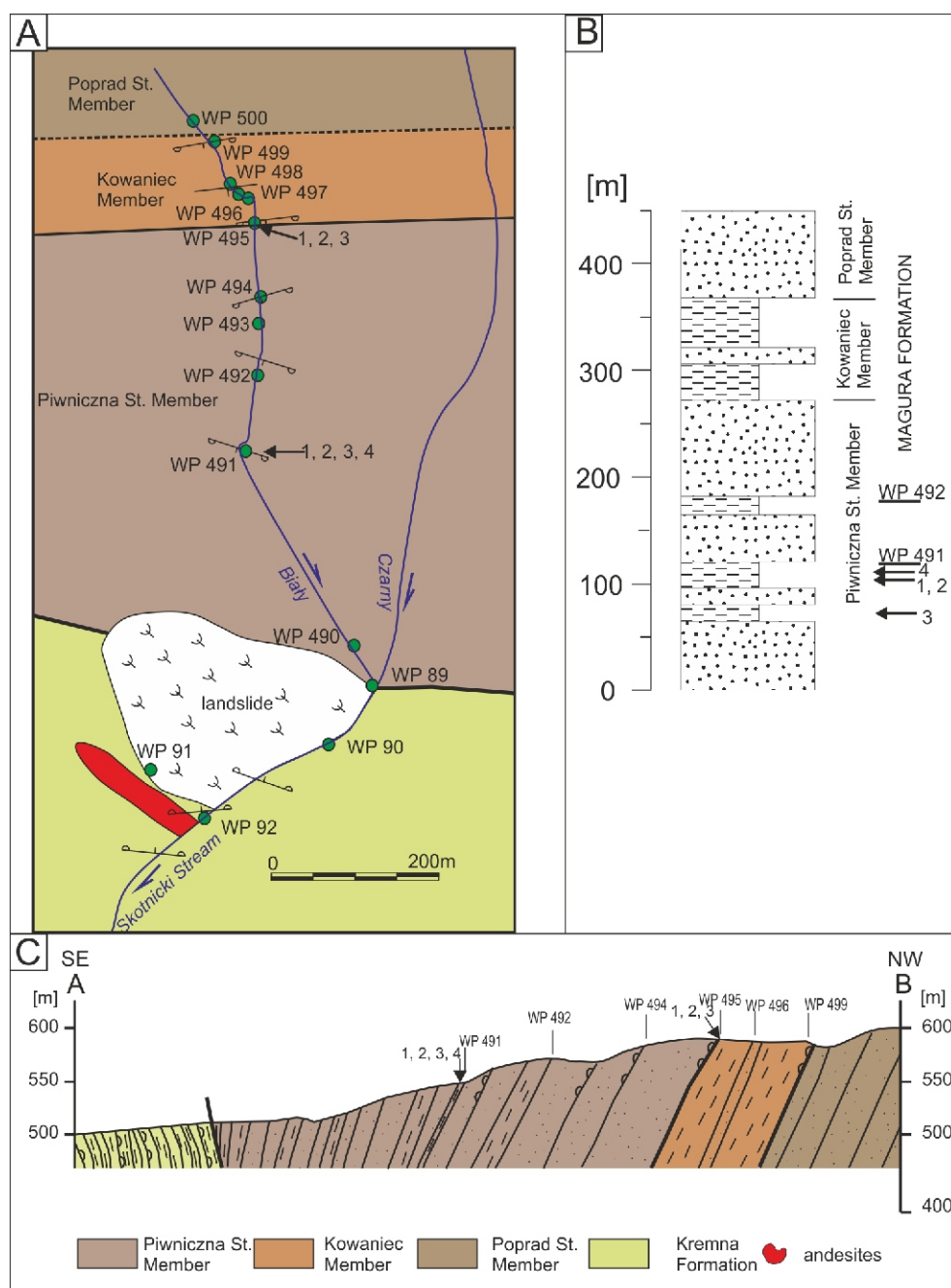


Fig. 7A – geological map, B – lithostratigraphic log of the Skotnicki Stream section, C – cross-section

For explanations see [Figure 4](#)





**Fig. 8. Typical lithofacies the Skotnicki Stream section at Szczawnica**

**A** – dark marly shales with intercalations of broken, thick-bedded, sandstone in overturned position; **B** – dark marly shales with intercalations of medium-grained thick-bedded sandstone; **C** – debris of fine-grained sandstones; **D** – vertical dipping, dark shales with intercalations of very fine-grained sandstones, in vertical position; **E** – sub-vertical dipping, dark shales with intercalations of medium-bedded sandstones; **F** – thick-bedded, laminated fine-grained sandstones with intercalations of dark shales





**Fig. 9. Typical lithofacies from Kozlecki Stream section**

**A** – vertical dipping, thick-bedded turbiditic sandstones; **B** – thin and very thin-bedded turbiditic sandstones with thin intercalations of shales, in overturned position; **C** – fragment of thick-bedded sandstone incorporated in dark shales; **D** – drag flute casts on the basal surface of the thick-bedded sandstone; **E** – dark shales with intercalations of the thin-bedded sandstones



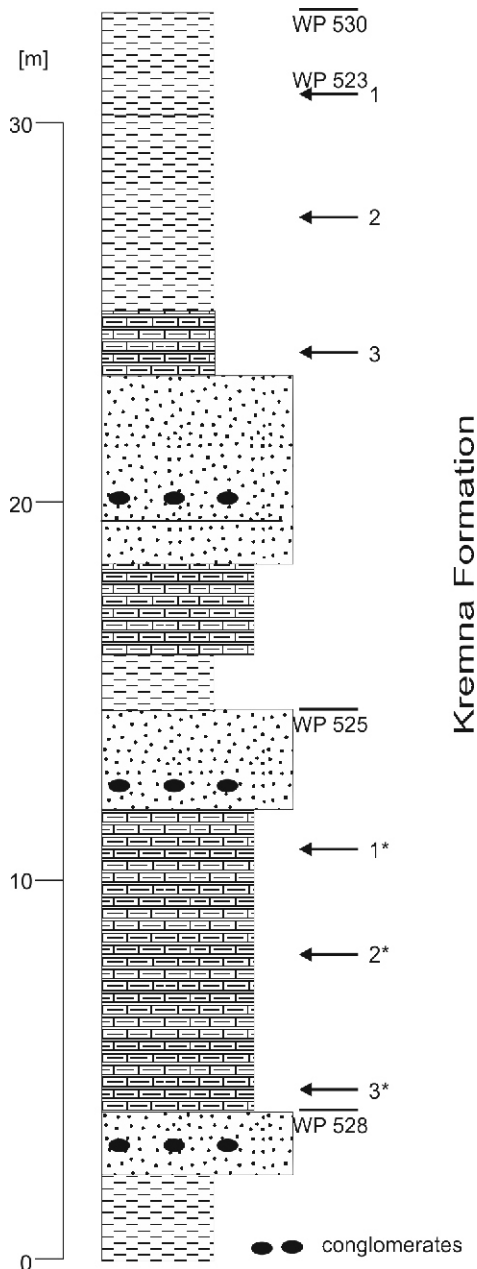


Fig. 10. Lithostratigraphic log of the St. Kinga section

For other explanations see Figure 5

Krynica succession of the Magura Nappe, close to the northern boundary of the PKB. This is a large exposure well-known as the Zawiasy section (Birkenmajer, 1979, 1986; Golonka et al., 2006). According to Birkenmajer (1979, 1986) the Zawiasy section belongs to the Jurassic–Lower Cretaceous succession of the Branisko Unit. Here, the PKB and the Magura Nappe contact along a longitudinal reverse fault. According to Golonka et al. (2006) this boundary developed as a major right-lateral strike-slip fault, between the Magura Nappe and the PKB. Recently, Golonka et al. (2015) considered the Zawiasy Klippen to be a big olistolith developed during the Paleocene. Birkenmajer (1986) interpreted that between the Branisko Unit and the Magura Nappe there are wedged fragments of the Grajcarek Unit (Malinowa and Jarmuta formations), now not exposed. The geological profile of the left bank of the Dunajec River, near the Chapel of St. Kinga, was first described by Alexandrowicz et al.

(1966). In this exposure, all deposits of the Magura succession are NW-dipping (Fig. 10), in overturned position ( $350\text{--}340^\circ/15\text{--}35^\circ$ ). This ~30 m thick profile is composed of shales and siltstones with intercalations of thin-bedded laminated sandstones as well as medium- to thick-bedded sandstones with convolutions and clasts of shale balls. The base and top of the profile is composed of Łącko-type marls, ~9 m and 2.2 m at the base and the top respectively. The profile studied displays coarsening- and thickening-upwards sequences (Figs. 10 and 11), composed of thick-bedded sandstones (1.8 up to 5.0 m). These sandstones are amalgamated and contain clast levels. The sandstone beds are overlain by hard grey-greenish Łącko-type marls, up to 3 m thick. The marls are followed by dark grey marly mudstones, up to 8 m thick (Fig. 10). For long, these deposits were regarded as the Szczawnica Fm. of Paleocene/Eocene age; their age was determined first by Alexandrowicz (1966), based on rare benthic and planktonic foraminifers such as *Globorotalia marginodentata* Sub., and *G. cf. crassata* Cushman, and subsequently Birkenmajer and Dudziak (1981) included these beds into the upper part of the Szczawnica Formation (Lower Eocene, NP-10/11 Zone). These beds have been regarded as the Zarzecze Formation (Chrustek et al., 2005). Recently, Golonka and Wałkowska (2014) studied foraminifera from this section and determined the age of these deposits as not older than late Ypresian–early Lutetian.

#### DUNAJEC RIVER WEST OF CZORSZTYN

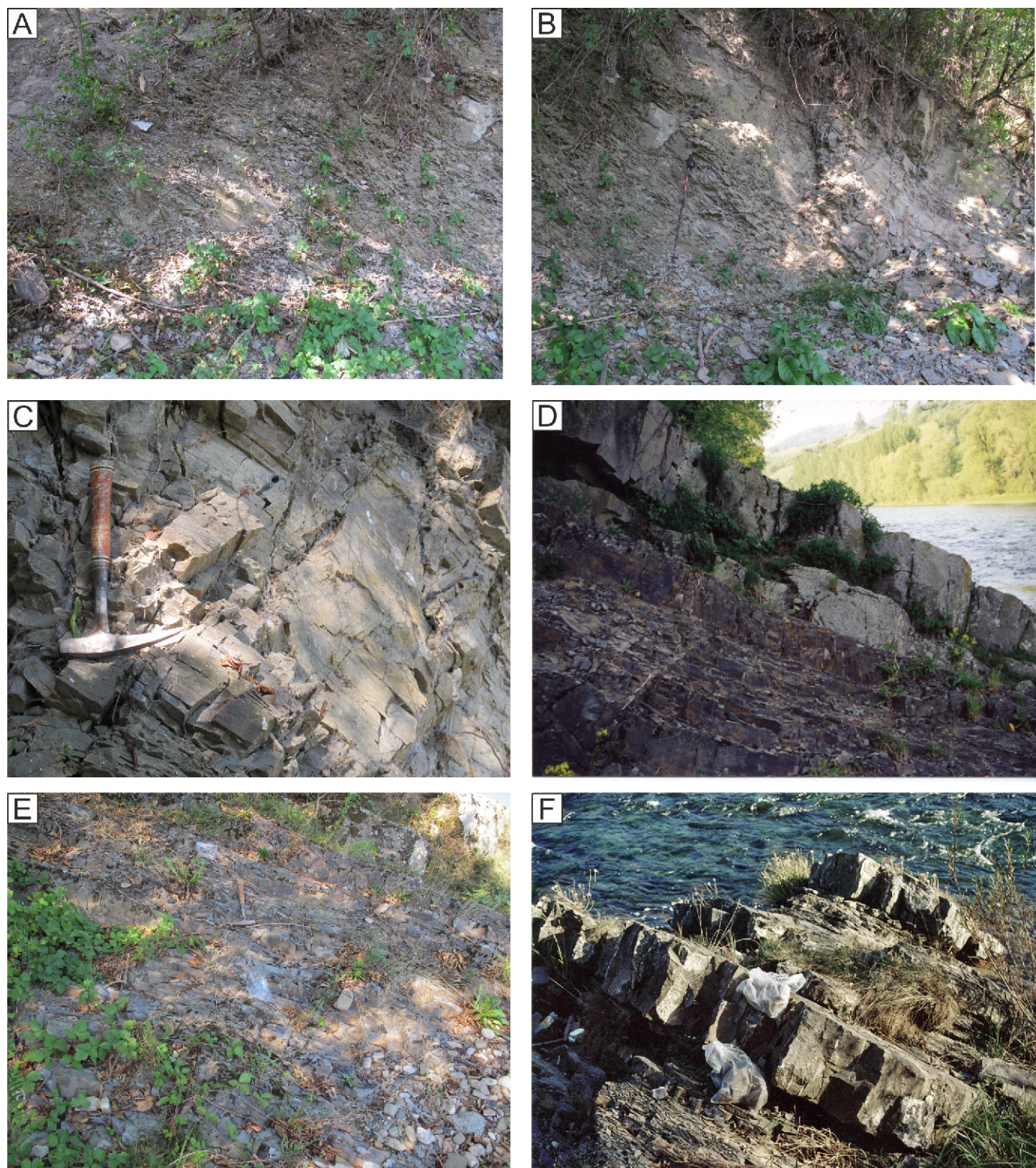
**Frydman (N49°26.413 E20°14.115).** The section studied is located along the road from Frydman to Czorsztyn (Fig. 2). In the abandoned quarry WP 657 are exposed thick-bedded sandstones (0.5–1.5 m) steeply dipping to the south ( $170/70^\circ$  in normal position), with an intercalation of thin-bedded, very fine sandstone and grey marly shales (Fig. 12). The thick-bedded sandstones contain muddy clasts and show palaeotransport direction from the east.

**Huba (N49°27.889 E20°14.599).** This profile is located below the Huba-Maniowy/Czorsztyn road, in a small left tributary of the Czorsztyn Lake (WP 27).

Over a distance of ~170 m, the profile exposes a shale/sandstone succession ~100 m thick. The succession is sub-vertically dipping to the N ( $360/70^\circ$ ), in overturned position. This succession is composed of medium- to thick-bedded sandstones with intercalations of dark grey marly shales (Fig. 13). The grey hard, medium to thick-bedded sandstones are mainly fine-grained. Locally, the basal parts of the beds are composed of chaotically dispersed quartz and lithoclastic grains, passing upwards into the fine, oblique-laminated sandstone. The laminate surfaces are rich in coalified plant and muscovite detritus. In some places, in the lower and the middle parts of the profile, occur intercalations of the Łącko type marls, up to 2 m thick. There is an exposure gap in the 80–155 m interval of the profile. This succession has been distinguished by Watycha (1976) as the Lower Eocene of the Turbacz Beds or the Lower Eocene sub-Magura Beds by Birkenmajer and Dudziak (1981) and Kulka et al. (1991).

**Knurów (N49°29.387' E20°10.460').** This profile is located ~4 km west of locality Huba (Fig. 2). In the left tributary of the Dunajec River Magura-type sandstones are exposed, with intercalations of marly shales. These deposits dip gently to the north and were classified by Burtan et al. (1981) as the Paleocene Ropianka Beds. Later Cieszkowski (1992) defined these strata as the Malcov Formation and Waksmund Beds (Uppermost Eocene–Lower Miocene).





**Fig. 11. Typical lithofacies in the St. Kinga section.**

**A, B** – packets of the thin-bedded flysch deposits; **C** – broken packets of the Łącko type marls; **D** – overturned, NE dipping sequence of the thick-bedded sandstones, “Łącko Marls” and thin-bedded turbidites; **E, F** – detail of the [Figure 11D](#)



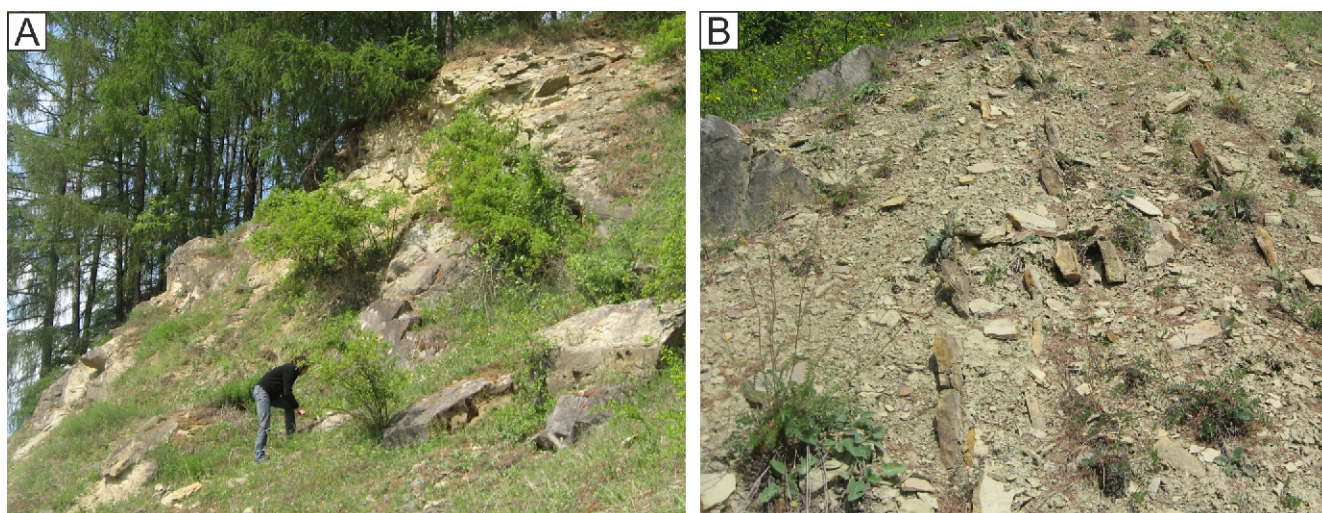


Fig. 12. Very thick-bedded sandstones and marly shales in the Frydman section

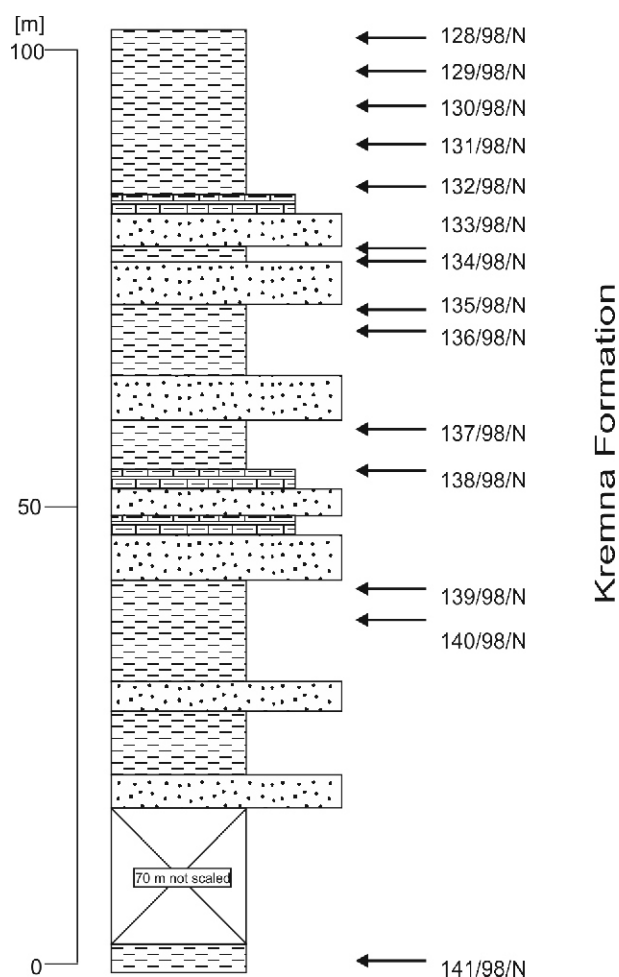


Fig. 13. Lithostratigraphic log of the Huba section

For lithology explanation see Figure 5

**Waksmund (N49°29.418' E20°04.520').** These exposures are located at Waksmund, ~1.5–2 km east of Nowy Targ (Fig. 2). Burtan et al. (1981) included these deposits into the Inoceranian–Ropianka Beds (Paleocene). Later (Cieszkowski and Olszewska, 1986) classified them as the Malcov Formation (uppermost Eocene–Oligocene), and Cieszkowski (1992) termed them the Waksmund Beds.

#### PRESERVATION, SPECIES DIVERSITY AND ABUNDANCE OF CALCAREOUS NANNOPLANKTON

Considering all the assemblages investigated, the preservation of calcareous nannofossils is moderate (M) or predominantly moderate-to-good (M–G) (Appendices 1 and 2\*). Nannofossils show minor etching and minor to moderate overgrowth. The good to moderate preservation of nannofossils indicates that little carbonate dissolution has occurred in these deposits (Fig. 14).

For each sample the ratio between autochthonous and reworked nannofossils 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.

A maximum of 66 species were identified during quantitative and qualitative analyses of the calcareous nannoplankton. However, the abundance pattern as well as the taxonomical diversity varies, not only between sections but also between samples from a particular section.

**Skotnicki Stream section.** The majority of samples were barren and only four samples contained determinable nannoplankton species. The assemblage is moderately diverse. The most characteristic species are *Cyclicargolithus floridanus*, *Ericsonia formosa*, *Zygrhabillithus bijugatus*, *Neococcolithes dubius*, *Chiasmolithus grandis*, *Coccolithus pelagicus*, *Sphenolithus radians*, *Discoaster deflandrei*, *D. binodosus* and *Chiasmolithus solitus*.

**Kozłecky Stream, Chapel St. Kinga, Huba, Frydman, Knurów and Waksmund sections.** The assemblage obtained is moderately diverse. The relative abundance of samples usu-

\* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1425



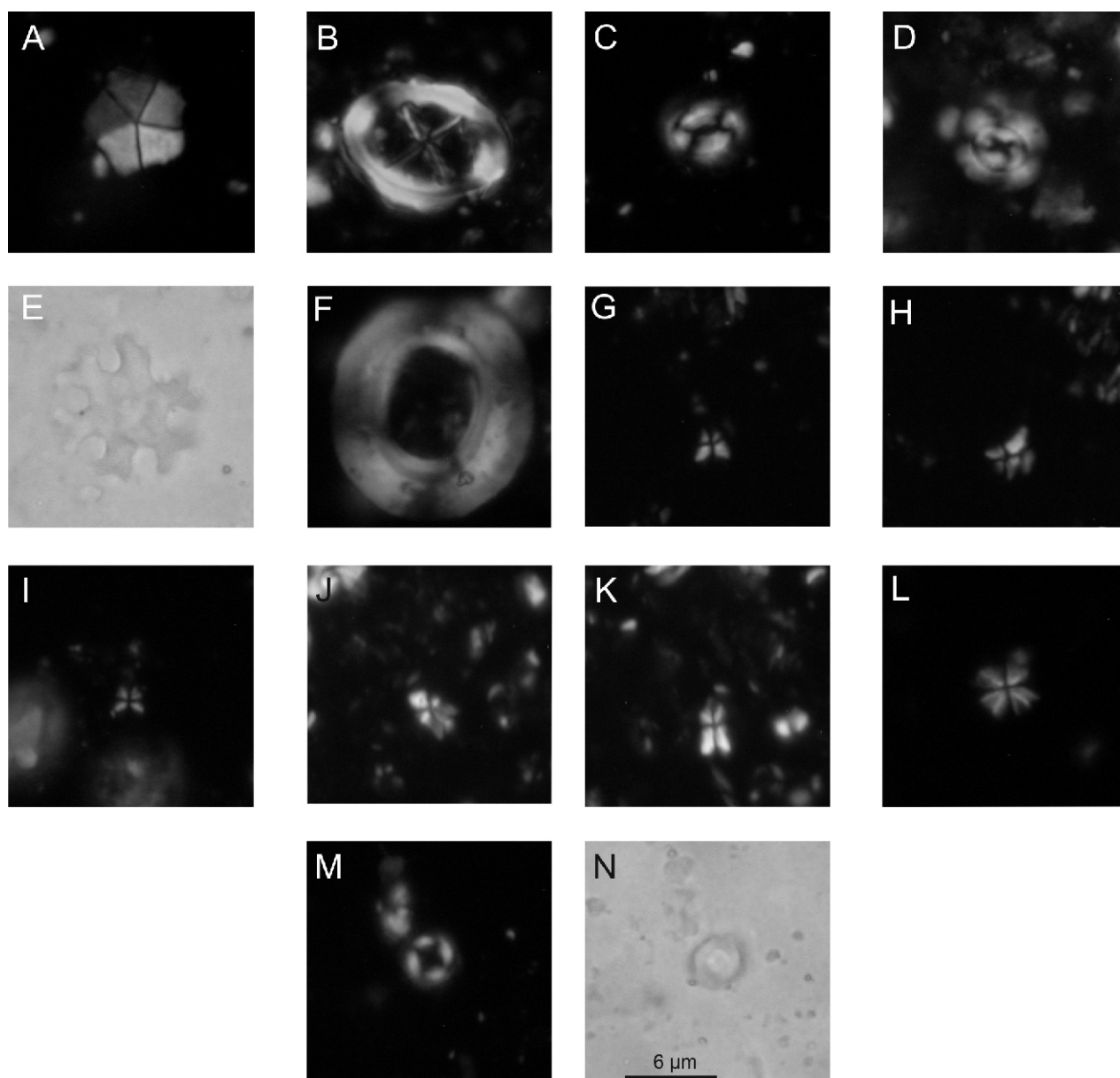


Fig. 14. LM microphotographs of typical nannofossil species

**A** – *Braarudosphaera bigelowii*, **B** – *Chiasmolithus modestus*, **C** – *Coccolithus pelagicus*, **D** – *Cyclicargolithus abisectus*, **E** – *Discoaster deflandrei*, **F** – *Reticulofenestra umbilica*, **G–I** – *Sphenolithus conicus*, **J, K** – *Sphenolithus disbelemnus*, **L** – *Sphenolithus moriformis*, **M, N** – *Umbilicosphaera rotula*; A–D, F–M – crossed polars; E, N – parallel polars; scale bar is the same for all photographs

ally ranges from 10 to 15 species per observation field. The difference between the assemblages from these sections is mostly quantitative; qualitatively, the assemblages are similar. They were divided into autochthonous and reworked species, then the percentage of both was calculated in each sample (Appendix 2). As it is highly probable that long-lived species are both autochthonous and reworked, the calculation should be considered as a “minimum reworked ratio”

The autochthonous species include *Braarudosphaera bigelowii*, *Coccolithus pelagicus*, *C. subpertusus*, *Coronocyclus nitescens*, *Cyclicargolithus floridanus*, *Pontosphaera discopora*, *P. multipora*, *Reticulofenestra haque*, *Sphenolithus calyculus*, *Sph. conicus*, *Sph. disbelemnus*, *Sph. dissimilis*, *Sph. moriformis*, *Tetralithoides symeonidesii*, *Umbilicosphaera rotula* and *Zygrhabillithus bijugatus*.

In most samples from the Huba section the percentage of autochthonous species (Appendix 2) varies from 26 to 34%. The most numerous autochthonous species present in each sample are *Coccolithus pelagicus* and *Sphenolithus moriformis*. The percentage variation in the Huba section is shown in Appendix 2.

The percentage of the species *Umbilicosphaera rotula* is in the range of 1–3%. The species *Umbilicosphaera rotula*, *Pontosphaera discopora* and *Sphenolithus conicus* show in most samples with a similarly fluctuating percentage. Other species such as *Braarudosphaera bigelowii*, *Pontosphaera multipora*, *Sph. disbelemnus* and *Sph. dissimilis* are irregularly present in the samples. The lowest abundance was noticed in the case of *Sph. calyculus* and *Sph. disbelemnus*.

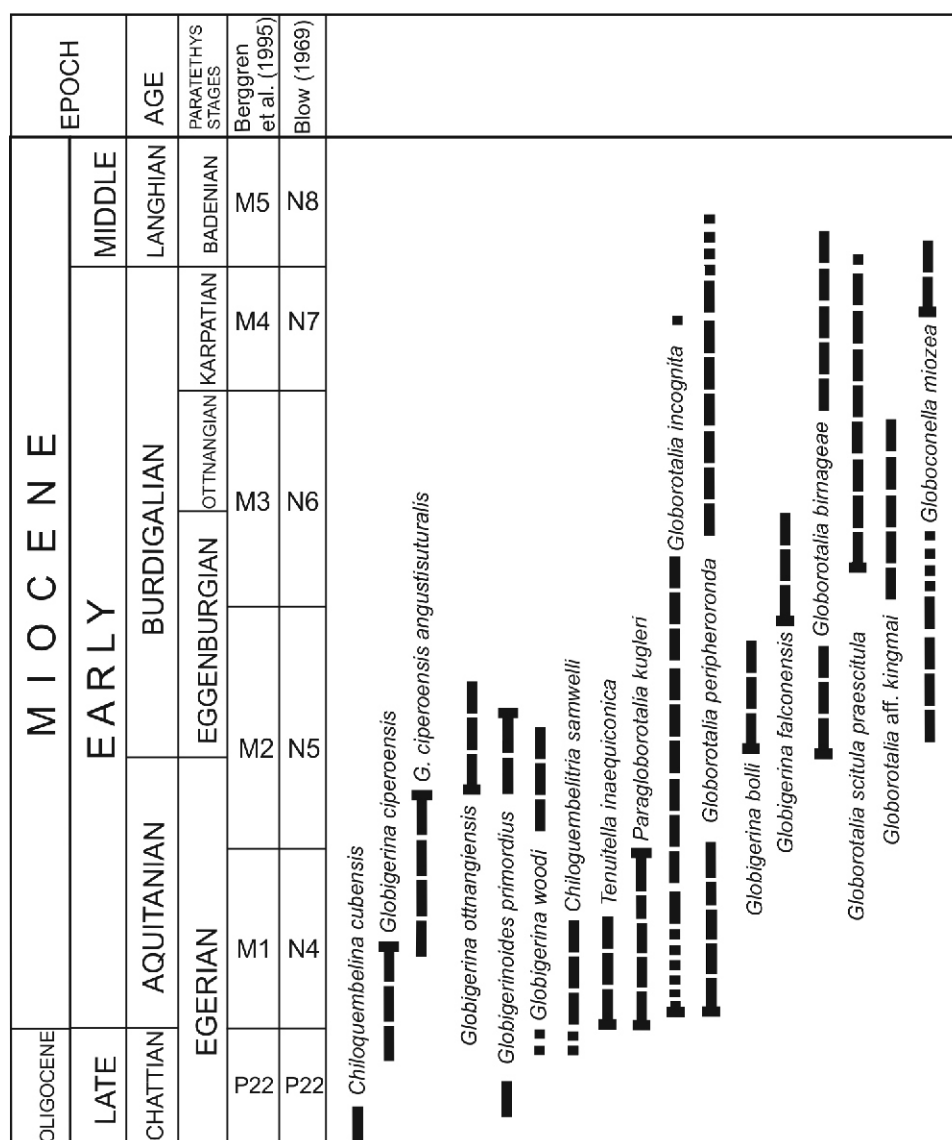


Fig. 15. Stratigraphic assessment of the Kremna Fm. using planktonic foraminifera

Age data are constrained by the biostratigraphic ranges of foraminiferal species, their first and last occurrences (FO, LO), bioevents and zonal markers (see [Berggren et al., 1995](#)); overlapping stratigraphical range of foraminiferal species is marked by grey field

The level of reworking is generally high. It varies from 54% to 68% for the samples collected from the Huba section ([Appendix 2](#)). The reworked assemblage consists of Paleogene and Cretaceous taxa.

The most abundant reworked species in the Huba section include *Ericsonia formosa*, *Toweius crassus*, *T. rotundus*, *T. selandianus* and undivided Cretaceous species (see [Appendix 2](#)).

**Preservation, species diversity and abundance of foraminiferal microfauna from Stary Stream, and the Szlachtowa and Waksmund sections.** Planktonic foraminifera from the Stary Stream section (WP 242-2, WP 242-3) and Waksmund 11 (Nowy Targ 11) sections are reduced in size and abundance. Their association consists of globigerinids, paragloborotaliids, globorotaliids, chiloquembeliniids and tenuitellinids ([Figs. 15–17](#)). Most common are five-chambered species of *Globigerina ciperoensis* and *G. ciperoensis angustisuturalis*, which are known mostly from Up-

per Oligocene formations. Nevertheless, the LO of *Globigerina ciperoensis* is marked in the Lower Miocene between the M1 and M2 zones (e.g., [Wade et al., 2011](#)), which is also the case for other species (*Globigerinoides primordius*, *Chiloguembelitra samwelli*, *Globigerina woodi*). These species ([Fig. 15](#)) are associated, and partly also reworked, with Early Miocene species such as *Globigerina ciperoensis ottnangiensis* (FO – Zone M2), *Paragloborotalia kugleri* (Zone M1), *Paragloborotalia incognita* (Zone M2), *Globorotalia mayeri*, *Globigerina falconensis* and *Tenuitella inaequiconica*. The species *Paragloborotalia kugleri* is known as an early member of the Neogene globorotaliids and a biostratigraphic marker of Zone M1 (e.g., [Keller, 1981](#); [Spezzaferri, 1991](#); [Berggren et al., 1995](#); [Rögl, 1996](#)).

Foraminiferal associations of the Kremna Fm. are specific by the presence and diversity of globorotaliids. Their rounded forms with arched apertures belong to the species *Globorotalia (Paragloborotalia) incognita* and *Glob. peripheroronda*. *Glob.*

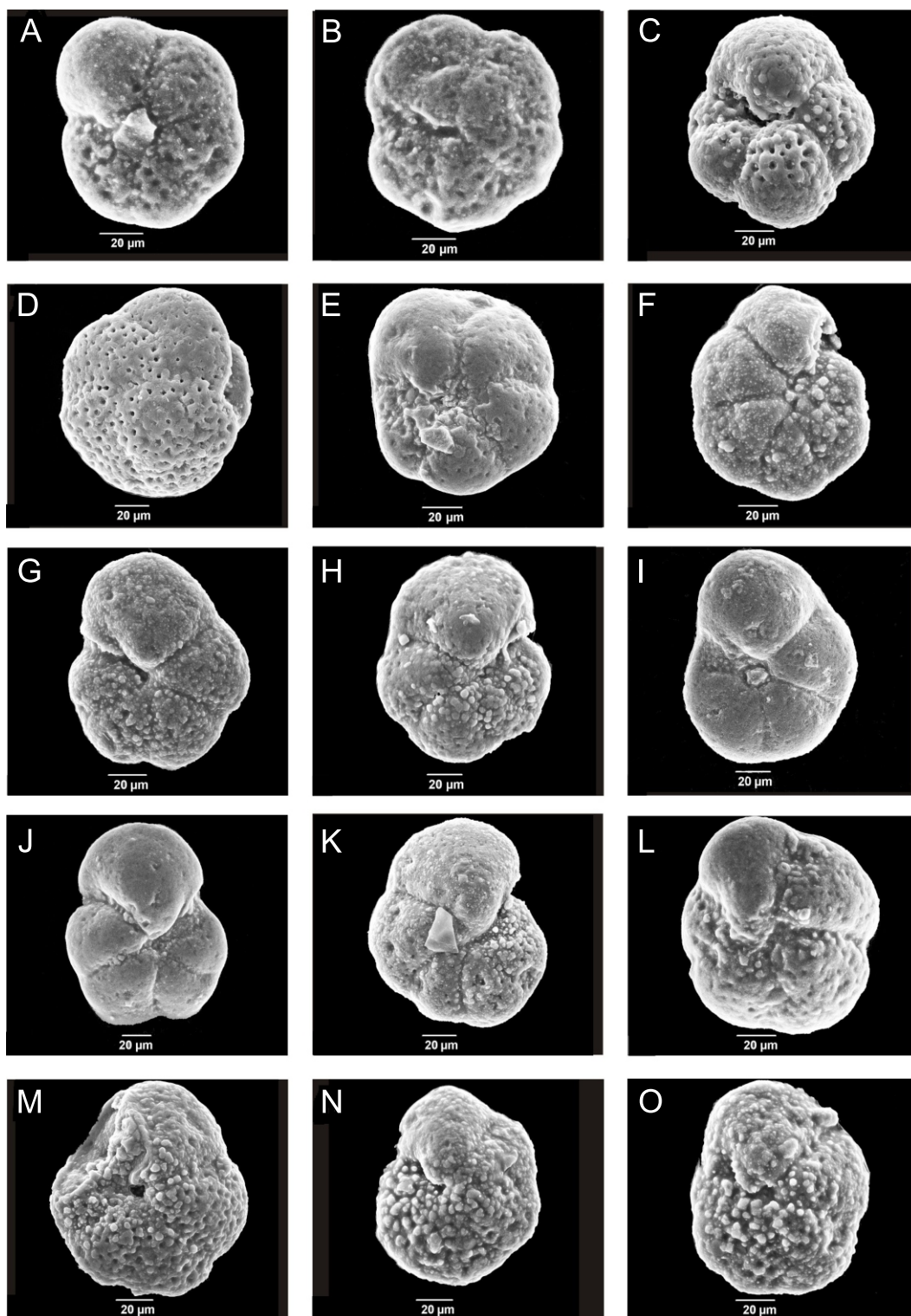
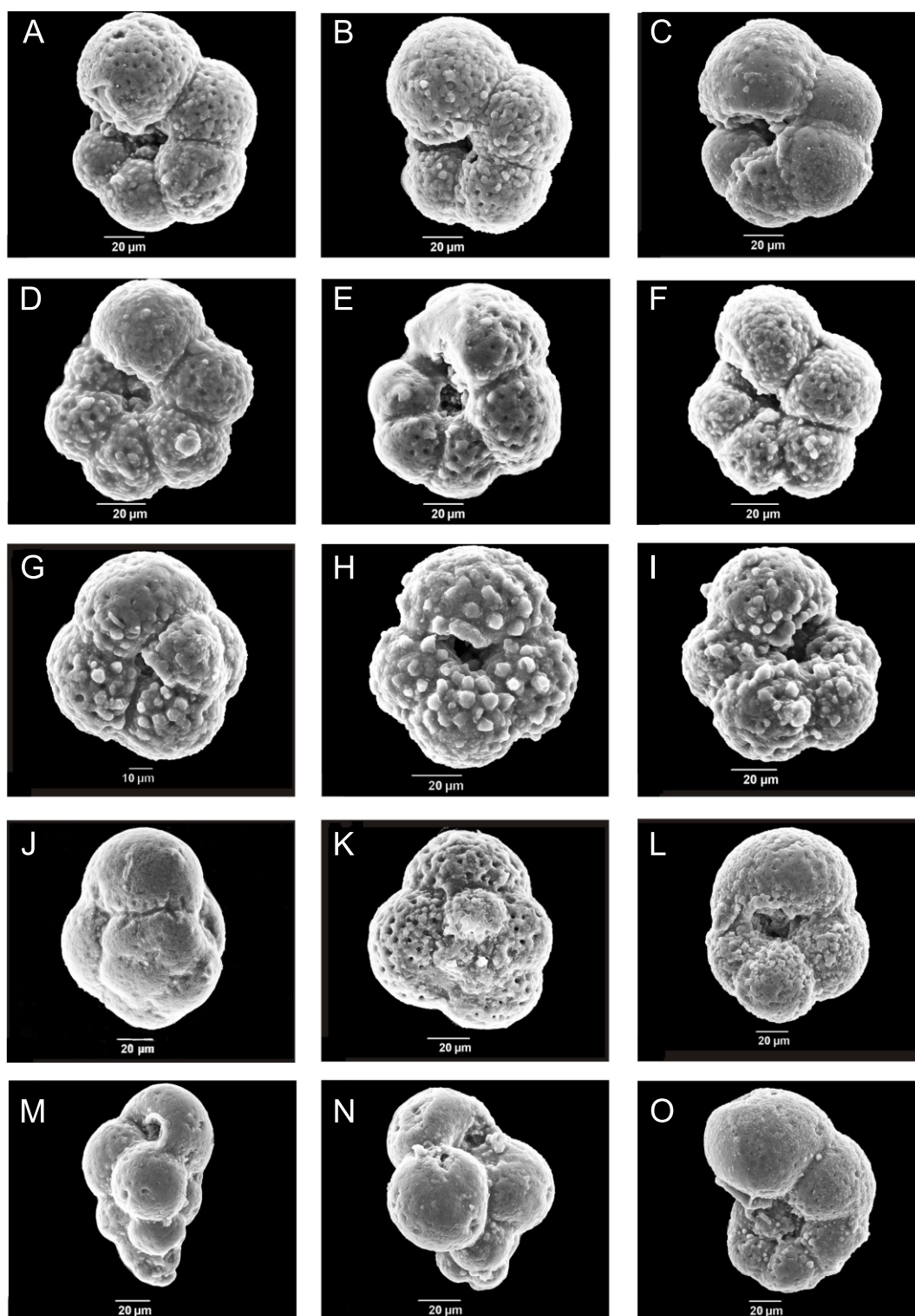


Fig. 16. Paragloborotaliid and globorotaliid species of foraminifers from the Kremna Fm.

**A, B** – *Paragloborotalia kugleri* (Bolli, 1957), umbilical sides, Stary Stream, WP 242; **C** – *Paragloborotalia incognita* (Walters, 1965), umbilical side, Waksmund 11; **D–F** – *Globorotalia peripheroronda* Blow and Banner, 1966: **D** – spiral side, **E** – umbilical side, Stary Stream, WP 242, **F** – umbilical side, Waksmund 11; **G–I** – *Globorotalia scitula praescitula* Blow, 1959, umbilical sides: **G, H** – Waksmund 11, **I** – Stary Stream, WP 242; **J, K** – *Globorotalia* cf. *Glob. archeomenardii* Bolli, 1957, umbilical sides: **J** – Stary Stream, WP 242, **K** – Waksmund 11; **L** – *Globorotalia birnageae* Blow, 1959, umbilical side, Stary Stream, WP 242; **M–O** – *Globoconella miozea* (Finlay, 1939), umbilical sides, Waksmund 11





**Fig. 17.** Globigerinid, chiloguembelinids and tenuitellinid species of foraminifers from the Kremna Fm.

**A–C** – *Globigerina ottnangiensis* Rögl, 1969, umbilical sides, Waksmund 11; **D, E** – *Globigerina ciperoensis* Bolli, 1954, umbilical sides, Waksmund 11; **F** – *Globigerina ciperoensis angustisuturalis* Bolli, 1957, umbilical side, Waksmund 11; **G** – *Globigerina bollii* Cita and Premoli Silva, umbilical side, Waksmund 11; **H, I** – *Globigerina falconensis* Blow, 1959, umbilical sides, Waksmund 11; **J, K** – *Globigerinoides* cf. *primordius* Blow and Banner, 1962, spiral sides: J – Stary Stream, WP 242, K – Waksmund 11; **L** – *Globigerina woodi* Jenkins, 1960, umbilical side, Waksmund 11; **M, N** – *Chiloguembelitra samwelli* (Jenkins, 1978), side views, Waksmund 11; **O** – *Tenuitella inaequiconica* (Subbotina, 1960), umbilical side, Waksmund 11

(*P.*) *incognita* defines the Early Miocene Zone M2/N5 by its appearance between the LO of *Paragloborotalia kugleri* and FO of *Glob. praescitula* (Berggren et al., 1995). *Glob. peripheroronda* evolved from older species of *Paragloborotalia kugleri* and developed to ancestral forms of the Early Miocene globorotaliids.

## INTERPRETATION

### BIOSTRATIGRAPHY

**Calcareous nannofossils.** The oldest assemblage among all the samples investigated came from the Skotnicki Stream section. This sample contains an assemblage not older than middle Eocene (NP 16). It is characterized by the presence of *Ch. grandis*, *Cyclicargolithus floridanus*, *Discoaster barbadensis*, *D. saipanensis* and *Ericsonia formosa*.

The uppermost part of the Poprad Sandstone Mb. of the Magura Fm. and the basal portion of the Kremna Fm., which are exposed in Biała Woda Stream section, were assigned to NN1. Such a zone assignment is based on a continuous range of *Sphenolithus conicus*, *S. dissimilis* and *S. delphix* following the disappearance of *D. bisectus* (see Oszczypko and Oszczypko-Clowes, 2010, 2014).

A younger age was determined in samples from the Chapel St. Kinga, Kozłeczki Stream, Huba, Frydman, Knurów and Waksmund sections. Qualitative studies enabled determination to the Lower Miocene (NN2 Zone). The *Discoaster druggii* Zone – NN2 is defined between the first appearance of *Discoaster druggii*, and the last occurrence of *Triquetrorhabdulus carinatus* (Martini and Worsley, 1970). It is noteworthy that *Helicosphaera scissura* and *H. ampliapertura* are not present in residual flysch basins; these species are typical of the Pannonian region and the stratotypes of the Eggenburgian (see Holcová, 2002, 2005). The above-mentioned species do not occur in the samples. The coexisting taxa, which were used to determine the biostratigraphic position are as follows: *Umbilicosphaera rotula* (with a stratigraphic range of NN2–NN16), and *Sphenolithus disbelemnus* Fornaciari and Rio (1996), ranging NN2–NN3. According to Young (1998), such a nannofossil association is characteristic of the NN2 Zone. The same age was determined from the Stary Stream section (see samples WP242 1–3 in Oszczypko and Oszczypko-Clowes, 2014).

**Foraminiferal microfauna from the Kremna Fm. (Stary Stream and Waksmund sections).** The presence of *Glob. scitula praescitula* is considered to be a most important datum, which appeared not before 18.5 Ma (Berggren et al., 1995). This species stratigraphically overlapped the Middle–Upper Burdigalian Zone (N6). The association of globorotaliids is completed by the species *Globorotalia bimageae* and *Glob. cf. kingmai*, which are known to have FOs in Zone NN4b (Chaisson and Leckie, 1993).

Planktonic foraminifers provide data for a Lower Miocene age of the Kremna Fm. Some of them are Late Oligocene–Early Miocene species of globigerinids (e.g., *Globigerina ciperoensis*, *Globigerinoides primordius*, *Globigerina woodi*), but there are also marker species of the M1 Zone (*Paragloborotalia kugleri*, *Globigerina ciperoensis ottnangiensis*). Nevertheless, the presence of descendant species such as *Globorotalia peripheroronda* and *Globorotalia (Paragloborotalia) incognita*, points to a younger age (M2/N5 Zone). This is also most evident from the appearance of *Globorotalia scitula praescitula* at the base of the M3/N 6 Zone (FO – 18.5 Ma), which is associated with other Burdigalian species (*Globorotalia bimageae*, *Glob. cf. kingmai*). The important specimens of the assemblage are planktonic foraminifers such as *Globoconella miozea* and

*Globorotalia cf. archeomenardii*. The *Globorotalia* species differ partly in FO datums. The base of *Globorotalia (Globoconella) miozea* is dated at 16.70 Ma (Berggren et al., 1995), followed by the FO of *Globorotalia archeomenardi* at 16.50–16.26 Ma (Scott et al., 1990; Wade et al., 2011). However, in the Parathetys, the FO of *Globorotalia (Globoconella) miozea* is known from the Lower Burdigalian M2 Zone (B. Olszewska, personal communication, 2018). Additionally *Globorotalia cf. Glob. archeomenardii*, being the conformis species, cannot be the basis for determining a Late Burdigalian age.

Nevertheless, some transitional forms such as *Globorotalia pseudomiozea* appeared as early as 17.6 Ma in Chron C5Dn (e.g., Berggren, 1977; Keller, 1981). Magnetostratigraphic data reveal the FO of *Globorotalia miozea* at the beginning of C5Cn.3n (Berggren et al., 1995), while Turner et al. (2007) correlated this bioevent with the slightly older magnetozone C5Cr. The upper limit of the C5Cr Zone corresponds to 17.6 Ma, which is close to the LOs of *Sphenolithus disbelemnus* and *S. conicus* in the top of the Burdigalian Stage (17.95 Ma – Maiorano and Monechi, 1997; Bown and Dunkley Jones, 2012). These sphenoliths occur also in Ottnangian deposits of nannoplankton zone NN2 and NN3 in the Alpine-Carpathian Foredeep (e.g., Roetzel et al., 2007).

### AGE DETERMINATION OF REWORKED NANNOFOSSIL ASSEMBLAGES

The precise age determination of Paleogene assemblages is not easy, especially as an overlap pattern of several index species is present. The only typical Early Eocene taxa is *Discoaster lodoensis* (NP12–14). The most abundant taxa are long-ranging species including *D. barbadensis* (NP10–20), *Ericsonia formosa* (NP 12–21), *Helicosphaera bramlettei* (NP14–23), *Lanternithus minutus* (NP16–22), *Reticulofenestra hillaie* (NP16–22) and *R. umbilica* (NP16–22).

Their stratigraphic ranges span from the Middle Eocene to the Early Oligocene. These taxa may constitute either Middle Eocene, Late Eocene or even Early Oligocene assemblages. The presence of the Middle Eocene may be dated by *Chiasmolithus grandis* (NP11–17).

The presence of *Isthmolithus recurvus* suggests that part of the assemblage may be not older than the NP19/20 Zone (Upper Eocene) and not younger than NP22 (Lower Oligocene), as *R. umbilica* is the index species for the upper limit of Zone NP22.

### PALAEOECOLOGY OF KREMNA FORMATION FROM HUBA SECTION

Quantitative analysis of the coccolith assemblages from the samples collected from the Pod Huba Stream has allowed a palaeoenvironmental analysis of the deposits studied. For this purpose, account was taken of matching palaeoecological preferences of species in terms of temperature and nutrient content. As noted earlier, long-lived species such as *Coccolithus pelagicus* and *Sphenolithus moriformis* are both autochthonous and reworked; the calculation followed by the interpretation should be considered as an approximation of palaeoecological conditions.

Temperature is one of the most important factors influencing the biogeography of calcareous nannoplankton in sedimentary basins (i.e., Wei and Wise, 1990 and references therein; Wei et al., 1992; Agnini et al., 2006; Gibbs et al., 2006; Villa et al., 2008 and references therein). Based on the analysis of autochthonous species, the assemblages are dominated by cold water taxa. Among these, *Coccolithus pelagicus* and



*Cyclocargolithus floridanus* are the most characteristic. *C. pelagicus* is today a subpolar species. Its preferred water temperature ranges from  $-1.5$  to  $+15^{\circ}\text{C}$ , and its largest concentration is at temperatures of  $2$ – $12^{\circ}\text{C}$  (Okada and McIntyre, 1979; Winter et al., 1994; Ćorić and Rögl, 2004). Therefore, *Coccolithus pelagicus* is widely used as a palaeotemperature proxy for cold waters in palaeoceanographic studies, as a qualitative/semiquantitative parameter (McIntyre and Bé, 1967, 1970). In contrast to such an interpretation are the results of Cachao and Moita (2000) showing that *Coccolithus pelagicus* occurs in the Iberian upwelling system. Hence, the presence of *C. pelagicus* off Iberia and other areas such as northwestern and southwestern Africa, suggests that this species has an affinity to upwelling areas. *C. pelagicus* optimum conditions and maximum temperatures can be extended to  $16$  and  $18^{\circ}\text{C}$ . At high latitudes *Cyclocargolithus floridanus* is practically not present. It is, however, found in temperate latitudes, less frequent high or lower ones (Wei and Wise, 1990). Species preferring moderate water include also *Coronocyclus nitescens* and *Umbilicosphaera rotula*.

The only warm-water species is *Sphenolithus moriformis*. It is more common in low latitudes than in high ones. It was also more common around the continents or seamounts than in the open ocean (Perch-Nielsen, 1985).

## DISCUSSION

Between the Biała Woda Valley in the east and the Biały Dunajec River in the west (Fig. 2), there is a morphological and tectonic depression between the southern slope of the Gorce and Beskid Sądecki ranges and the PKB. This depression is occupied by the deposits of the Kremna Fm. (Aquitania–Burdigalian), formerly known as the Szczawnica Fm. (Upper Paleocene/Lower Eocene, see Burtan et al., 1981; Birkenmajer and Oszczypko, 1989 and references therein). This formation is composed mainly of thin- to medium-bedded turbidites with intercalations of dark marly mudstones. There are also subordinate thick-bedded sandstones and exotic conglomerates, as well as thick beds of Łącko-type marls. East of the Biała Woda fault, the Kremna Fm. overlies the PoSM of the Magura Fm. (Upper Oligocene). Similar relationships have been identified by some of us (Oszczypko et al., 2005a; Oszczypko and Oszczypko-Clowes, 2010, 2014) near Kremna (East Slovakia) and along the Polish–Slovak border (Dubne–Ruska Vola) near Leluchów. The Kremna Fm. type of deposits has been recognized also between Eastern Slovakia (Laborec Beds, Humenné area; Matašovský and Andreyeva-Grigorovich, 2002) and the Horna Orava region in Western Slovakia (Oszczypko-Clowes et al., 2013), at a distance of  $\sim 200$  km. Probably, deposits similar to the Kremna Fm. continue, along the PKB to the east, up to the Ukrainian Carpathians (e.g., Drahovo Fm. of the Marmarosh Flysch, see Oszczypko et al., 2005b; Hnylko and Hnylko, 2016). Oligocene/Miocene deposits, similar to the Kremna Fm., have been recognized as the Zawada Fm. south of Nowy Sącz in the Rača Sub-unit of the Magura Nappe (Oszczypko et al., 1999; Oszczypko and Oszczypko-Clowes, 2002). The presence of the Kremna Fm. in the Bystrica Sub-unit is also not excluded.

The results of our research suggests that around the Oligocene/Early Miocene boundary in the Polish part of the OWC, there were two residual flysch basins: a southern one located in front of the uplifted PKB, and the CWC. The narrow residual Magura basin was located at the front of the PKB, between Humenné in the east and the Horna Oravá region in the west. The northern residual basin was located on the European Platform, in front of the overriding accretionary wedge of the

Carpathian flysch nappes. In the Middle Miocene this basin was transformed into the Carpathian Foredeep (e.g., Kováč et al., 2016, 2017). On this basis it can be inferred that Oligocene/Miocene sediments were deposited in a narrow residual Magura Basin.

On the basis of palaeotransport measurements it can be concluded that the Kremna–Zawada Basin was supplied from the SE, probably from the South Magura source area, which was active during the Paleogene (Oszczypko et al., 2016; Kováč et al., 2016). To a small extent, the Kremna Basin may have been supplied from the partially emergent PKB. This is suggested by the presence of small olistoliths of Upper Jurassic limestones in the Kremna Fm. (the Durbaska Massif along the Polish/Slovak boundary, Oszczypko and Oszczypko-Clowes, 2014). These deposits formerly have been assigned to the Eocene/Oligocene as the Zlatny Beds (e.g., Golonka and Rączkowski, 1984). Recently, Golonka et al. (2015) distinguished two stages of olistostrome formation; during the Late Cretaceous/Paleocene (e.g., Jarmuta Basin) and during the Paleogene (e.g., Zlatna Basin).

The palaeogeographical position of the Kremna–Zawada Basin is shown on Figure 18. The Kremna Fm. could be regarded as synorogenic deposits of the residual Magura Basin, developed in the course of the orogenic shortening and uplifting of the Western Outer Carpathians. The Kremna–Zawada Basin may be regarded as a kind of “piggyback basin” which developed simultaneously with the onset of formation of the Carpathian Foredeep at the front of the WOC orogen. This is documented by the Aquitanian transgressive deposits over the platform basement and beneath the Carpathian overthrust, recognized west of Kraków in the Andrychów 6 borehole (Oszczypko and Oszczypko-Clowes, 2003).

The tectonic contact of the Kremna/Zawada residual basin with the PKB was active after the Burdigalian and until the Sarmatian. During that interval, this contact zone was periodically dominated both by stretching/subsiding/deposition periods as well as by periods of compression (thrusting and strike-slip faulting). In a broader regional perspective, the Oligocene and Early Miocene evolution of the Western Outer Carpathian basins, including the Kremna/Zawada Basin, are discussed extensively in recent publications by Kováč et al. (2016, 2017).

The Early Miocene foraminiferal microfauna of the Kremna Fm. provides an important insight into the palaeogeography of the Magura Basin. Similar associations of Early Miocene foraminifers have been described from the Zawada Fm. (Oszczypko et al., 1999), Zebrzydowice and Vorotyshche fms. of the Carpathian Foredeep and Stebnyk/Stebnyk Unit (Subbotina, 1960; Odrzywolska-Bieńkowska and Olszewska, 1996; Garecka and Olszewska, 1997, 1998), the Lower Miocene formations of the Waschberg Unit and Nord Alpine Foreland Basin (Rögl and Nagymarosy, 2004; Roetzel et al., 2006; Grunert et al., 2010a, b, c), and the Hida Formation of the Transylvanian Basin (Filipescu and Beldean, 2008; Beldean and Filipescu, 2012). The most important components of this microfauna are globorotaliids, which are known mainly from the Indo-Pacific area. The presence of abundant globorotaliids in the Lower Miocene formations of the Magura Basin implies its communication with the Indo-Pacific Ocean and the inflow of open marine waters. The appearance of the *Globorotalia praescitula* coincided with the onset of the major cool temperate event MiB (Scott et al., 1995), which is also constrained in the Central Paratethys to about  $17.8$  Ma (Grunert et al., 2010a, b, c). Descendant species like *Globoconella miozea* developed a crust in response, to inhabit cool-water masses of mesopelagic and bathypelagic environments (Scott, 1972). Therefore, globorotaliids of the *praescitula*–*miozea* lineage provide the

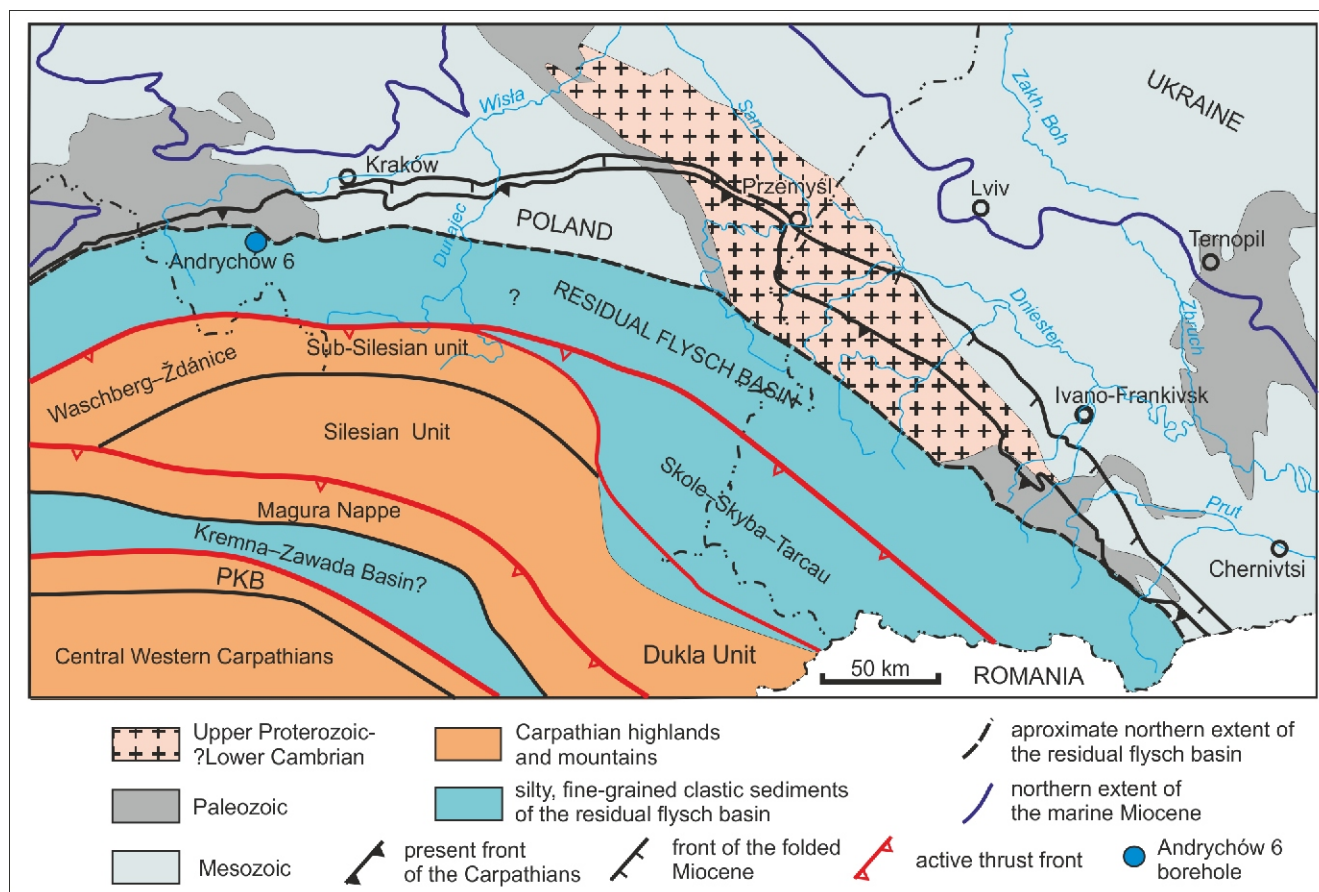


Fig. 18. Early Burdigalian palinspastic palaeogeographic map of the northern sector of the Western Carpathian basin system (based on Oszczypko et al., 2016, supplemented)

principal bioevents for the late Early Miocene zonation of sub-arctic and transitional areas (Berggren et al., 1995). Early Miocene climatic cooling facilitated a migration of *Globorotalia praescitula* and another keeled and encrusted globorotaliids from high to middle and low latitudes. They also occupied deep-water environments of the Early Miocene Magura Basin.

The Early Miocene flysch basin of the Magura Nappe differs considerably from surrounding basins of the Carpatho-Pannonian realm by deep- and cool-water conditions, an absence of the mixed layer and warm to temperate-water planktonic species (e.g., *Globigerinoides* species, helicosphaerids). Such morphotypes of globorotaliid and globoconellid species belong to thermocline habitats, which reproduced in waters colder and deeper than those of the surface mixed layer species (Keller, 1985; Norris et al., 1994). This points to depth stratification and circulation of water masses in a deep-water basin. Moreover, globorotaliid species such as *Glob. praescitula* were opportunistic forms (Scott et al., 1995), indicating a high level of trophic resources, which may have been elevated by upwelling activity in the Magura residual basin. In mid-Burdigalian time, upwelling conditions were also recorded along the Paratethyan coasts (e.g., Roetzel et al., 2006; Grunert et al., 2010a, b, c).

## CONCLUSIONS

1. In the tectonic depression between the PKB and the Gorce-Beskid Sądecki ranges, the Kremna Formation flysch deposits, up to 1000 m thick, have been recognized.
2. The age of these deposits, formerly known as Late Paleocene/Early Eocene Szczawnica Fm., is determined to be Aquitanian/Burdigalian, based on new research on calcareous nannoplankton and foraminifera.
3. Palaeotransport measurements indicate sediment supply from the SE.
4. A significant amount of reworked foraminifera and calcareous nannoplankton suggests the feeding of flysch material from Eocene erosional massifs.
5. The length of the residual Kremna/Zawada Basin, open to the east, was at least 200 km and the width was ~50 km.
6. The late Miocene/Pliocene Nowy Targ-Orava Basin is a successor structure to the Kremna Basin.

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