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The Paleogene and early Neogene stratigraphy of the Beskid Sądecki Range and Lubovnianska Vrchovina (Magura Nappe, Western Outer Carpathians)

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ABSTRACT:

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The lithostratigraphy and biostratigraphy of the Bystrica/Tylicz and Krynica facies zones of the Magura Nappe have been studied in the Beskid Sadecki Range and Lubovnianska Vrchovina (Polish and Slovak parts of the Western Outer Carpathians respectively). The new, Tylicz Zone is established, and the Szczawnica, Zarzecze, Magura and Kremna formations are redefined and described. These formations, spanning over 35 myrs, represent a synorogenic deep-water turbidites depositional system that dominated the southern part of the Magura Basin after the collision of the Alcapa Mega Unit with the Czorsztyn/Oravic ridge. The calcareous nannoplankton zones NP14–NP25 (Middle Eocene to Late Oligocene) and NN1–NN2 (Early Miocene) were recognized.

Key words: Lithostratigraphy; Biostratigraphy; Calcareous nannoplankton; Paleogene, Early Miocene; Bystrica (Tylicz); Krynica zones; Magura Nappe; Western Flysch Carpathians.

INTRODUCTION

This paper reports on new litho- and biostratigraphical (based on calcareous nannoplankton) studies of the Paleogene to lower Neogene (Lower Miocene) deposits of the Magura Nappe (Bystrica/Tylicz and Krynica zones) in the Beskid Sądecki (Poland) and Lubovnianska Vrchovina (Slovakia) ranges (Text-fig. 1). The studies were carried out mainly in the Krynica–Muszyna–Tylicz area, with additional fieldwork in the Szczawnica area and north of the Stara Lubovnia area (Slovakia). As a result, the existing stratigraphic standard scheme of the Paleogene deposits in these areas (Birkenmajer and Oszczypko 1989; Oszczypko *et al*. 1990; Oszczypko 1991) was considerably revised.

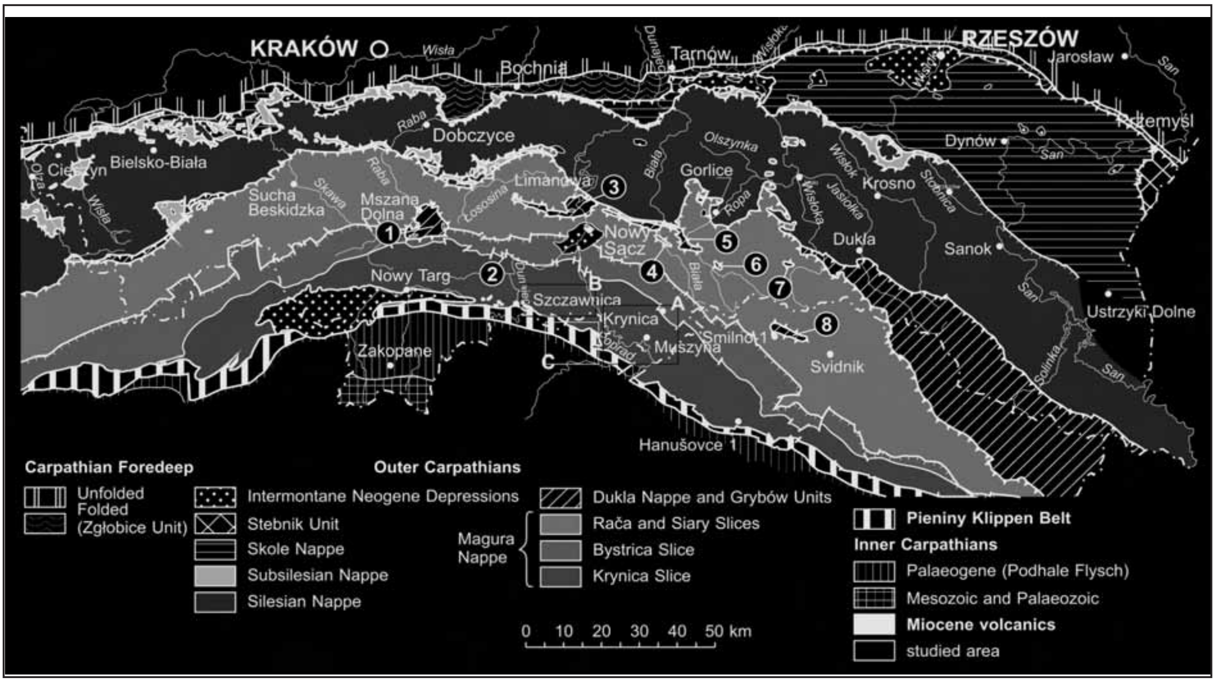
PREVIOUS WORK

The first results of preliminary investigations in the region were published by Walter and Dunikowski (1883), Paul (1884) and Uhlig (1888). Subsequently, the region was studied in the context of the project *Geological Atlas of Galicia*: the Muszyna sheet, published by Szajnocha (1896), and Stara Lubovna and Szczawnica sheets, published by Uhlig (1890). Since 1903, geological research in Krynica was carried out by Zuber (1916, 1918), who also initiated drilling of a deep borehole (Zuber I) for the prospection of mineral waters. A few years later Nowak (1924) published the first detailed geological map of Krynica. The map portrayed two tectonic units of different lithostratigraphic successions. The northern unit was named "Parautochtonous", whereas the southern one was referred to as the "Krynica Thrust Sheet". The boundary between these units was located along the southern slope of the Parkowa Mt. Nowak (1924) initiated the drilling of Zuber II, another deep borehole in the area.

In 1933–1953, the Krynica area was mapped at the scale of 1:25,000 by H. Świdziński, with the results published by him in 1939, 1961a, b, and summarized in his 1972 paper "*Geology and mineral waters of Krynica*". Świdziński (1972) followed Nowak's (1924) ideas, distinguishing and describing, in the Magura Nappe of the Krynica area, two facies-tectonic zones, referred to by him as the Sącz and Krynica zones. Subsequently, Koszarski *et al.* (1974) distinguished in the Magura Nappe (from north to south) the Siary, Rača, Bystrica (=Sącz) and Krynica facies zones.

Ostrowicka (1966) distinguished variegated shales within the Magura Beds of the Piwniczna area, which enabled three lithostratigraphic units (members) to be established. A similar subdivision of the Magura Beds in the Wysowa area (Rača facies zone) was then given by Węcławik (1969a). Węcławik's (1969a, b) reports on the Magura Nappe in the Tylicz and Mochnaczka areas gave remarkable insight into the geology of the region. He distinguished a transitional Tylicz Zone, between the Bystrica (Sącz) and Krynica zones, which he characterised as having Bystrica (Sącz) Zone type development in the lower part and Krynica Zone-type development in the upper part. This concept was questioned by Oszczypko (1979), who suggested that the Tylicz Zone represents the tectonic superposition of the Bystrica and Krynica zones of the Magura Nappe. According to him, the boundary between these zones (subunits) runs along the contact of the red shales with *Reticulophragmium amplectens* (Middle–? Late Eocene) and the Hieroglyphic Beds (sensu Węcławik 1969a, b). These beds were regarded by Oszczypko (1979) as an equivalent of the Zarzecze beds of the Krynica Zone. This was supported by the identification of scarce Early Eocene calcareous nannoplakton in Hieroglyphic Beds.

Birkenmajer and Dudziak (1981) studied the litho- and biostratigraphy of the Paleogene deposits of the Krynica Zone in the peri-Pieniny Klippen Belt area. They assigned the Szczawnica Formation to the Middle Paleocene, the sub-Magura beds to the Late Paleocene–Early Eocene, the Łącko marls (at the top of the Szczawnica Formation) to the Early Eocene, the Magura sandstone to the Early–Middle Eocene, and the Frydman Formation to the Paleocene–Early Eocene. In their subsequent papers, they documented the Late Paleocene to Early Eocene age of the Magura-type Paleogene flysch



Text-fig. 1. Geological sketch-map of the Polish Carpathians (based on Żytko *et al.* 1989, modified), with location of areas studied: A – Krynica-Muszyna-Tylicz area, B – Krościenko-Szczawnica area, C – Stara Lubovnia area (east Slovakia). Tectonic windows: 1 – Mszana Dolna, 2 – Szczawa, 3 – Klęczany, 4 – Grybów, 5 – Ropa, 6 – Uście Gorlickie, 7 – Świątkowa, 8 – Smilno deposits [Szczawnica Formation (Złatne Member), Zarzecze Formation, Łącko marls and Piwniczna Sandstone Member of the Magura Formation] in the Pieniny Klippen Belt (Birkenmajer and Dudziak 1988a) and dated the terminal flysch deposits in the Magura Basin as Oligocene (Birkenmajer and Dudziak 1988b).

Alexandrowicz *et al.* (1984) correlated the lithostratigraphic units of the Krynica Zone between the Nowy Targ and Piwniczna.

The new litho-and biostratigraphic standard schemes have been applied within the Krynica and Bystrica facies zones (Birkenmajer and Oszczypko 1988, 1989; Oszczypko 1991; and Oszczypko *et al*. 1990, 1999a).

Recently, new geological mapping and litho- and biostratigraphical studies in the Beskid Sądecki Range were carried out by the Authors, with the first results published by Oszczypko-Clowes (2001), Oszczypko and Zuchiewicz (2007) and Oszczypko *et al.* (2005, 2006).

LITHOSTRATIGRAPHY

Bystrica Zone

East of the Dunajec River, the northern slopes of the Beskid Sądecki Range are composed of the Paleogene deposits of the Bystrica Zone, which are in tectonic contact with the Krynica Zone (Oszczypko 1979; Birkenmajer and Oszczypko 1989; Oszczypko *et al*. 1999a; Oszczypko and Zuchiewicz 2007). To the east of the Mochnaczka and Muszynka rivers, there is a sedimentary transition between the Bystrica and Krynica zones, described by Węcławik as the Tylicz Transitional Zone (Text-fig. 2).

The Bystrica Zone is composed of the Eocene deposits of the Łabowa, Beloveza, Żeleźnikowa and Magura formations (Węcławik 1969 a, b; Sikora 1970; Oszczypko 1973, 1979; Oszczypko *et al.* 1999a). A formal lithostratigraphical scheme for the Bystrica facies Zone was proposed by Oszczypko (1991). The lower and upper parts of the Paleogene succession of the Bystrica Zone were studied in the Żeleźnikowa and Krynica sections respectively.

Łabowa Formation

The lower part of the formation consists of red shales, and its upper part is composed of thin-bedded flysch with intercalations of red shales. The formation is up to 100 m thick and is known from the Żeleźnikowa Wielka, Nawojowa, Łabowa, Uhryń and Mochnaczka sections (Text-fig. 2). Based on the agglutinated foraminifers, *Nodelium velascoense* (Cushman), *Trochamminoides irregularis* (White), *Saccammina complanatata* (France), and *Saccammina placenta* (Grzybowski), the formation was dated as Early Eocene (Węcławik 1969b). The variegated shales were deposited in hemipelagic conditions below the CCD; with an upward increase in the influx of low-density turbidite currents (see Oszczypko 1991).

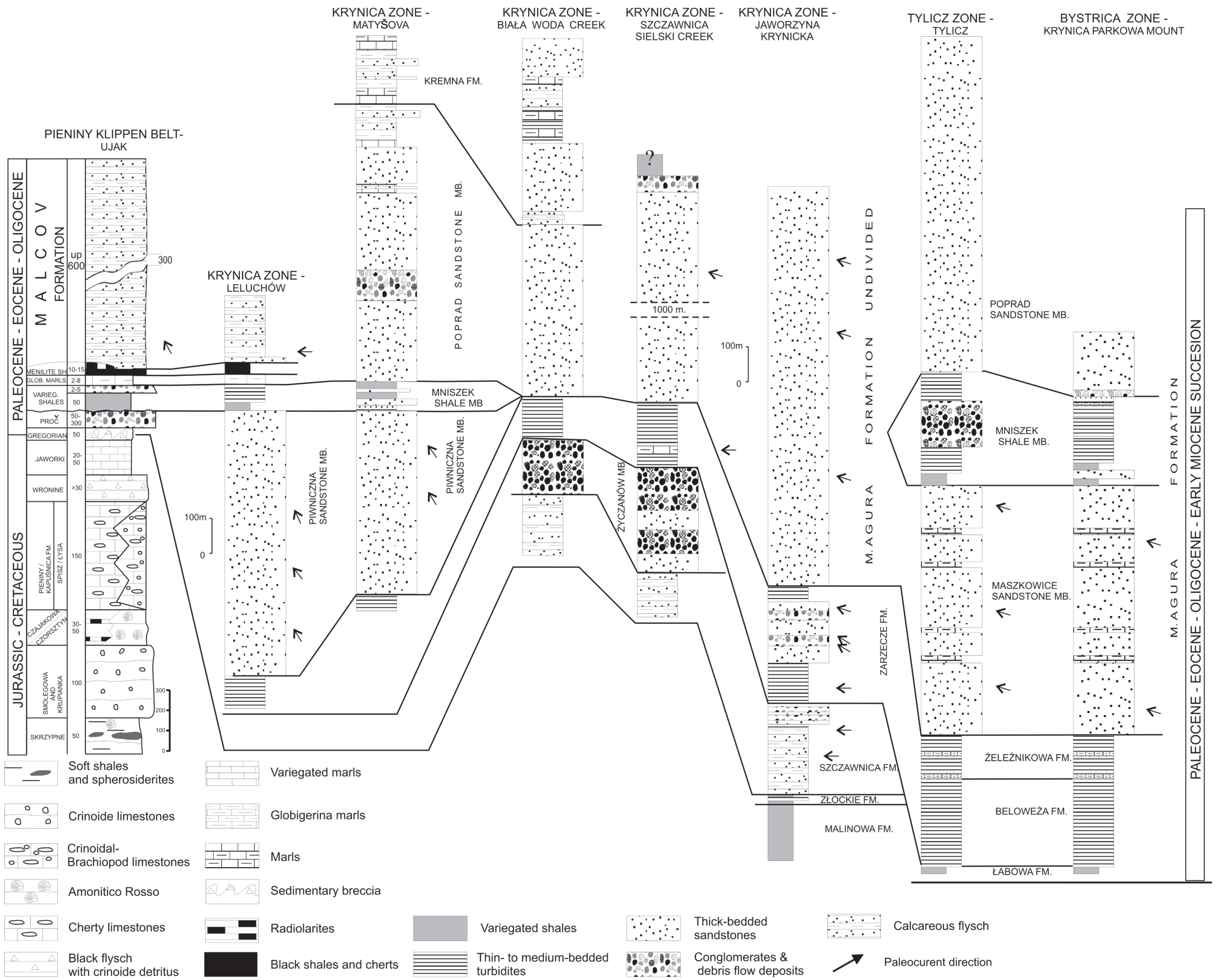
Beloveža Formation

The formation, up to 300 m thick, is composed of very thin and thin-bedded turbidities with a predominance of argillaceous deposits (Text-figs 2, 3). The lower part of the formation consists of blue-grey, fine-grained calcareous sandstones, 1–5 cm thick, with Tcd Bouma intervals (facies D2.3, Pickering *et al*. 1986). Higher up in the succession, the thickness of the sandstones increases up to 20–40 cm (Oszczypko 1986). The material composing the Beloveža Formation was derived from the south-east (Sikora 1970). The lower boundary of the formation is sharp, placed at the top of variegated shale (Łabowa Shale Formation), beneath thin-bedded turbidites. Its upper boundary represents the transition to the overlying medium-bedded turbidites with intercalations of the Łącko marls (Żeleźnikowa Formation, Text-figs 2, 3, 2) The formation is dated as latest Early Eocene–Middle Eocene (Dudziak 1991). The Beloveža Formation was deposited by low-density turbidity currents and represents basinal and partly lobe-fringe turbidites (Oszczypko 1991).

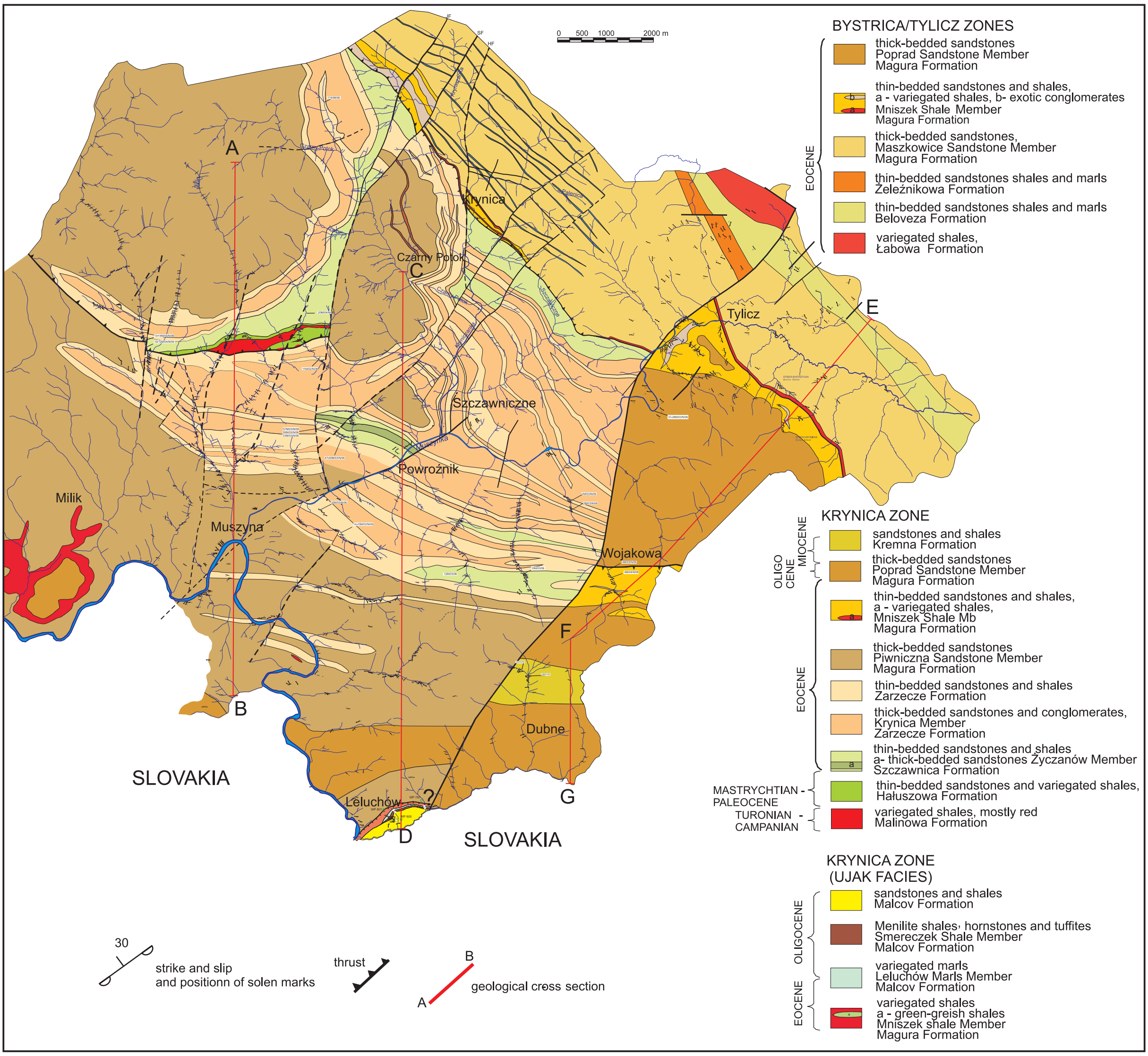
Żeleźnikowa Formation

Uhlig (1888) described the Łącko marls from the Magura Nappe. Several years later Świdziński (1947) showed that the Łącko marls do not represent a single stratigraphic horizon, but form intercalations within various Paleogene deposits of the Magura Nappe. Węcławik (1969a) subdivided the then Łącko marls into the lower and upper Łącko beds, referred to subsequently as the Żeleźnikowa Formation and the Maszkowice Sandstone Member of the Magura Formation respectively (Oszczypko 1991).

The Żeleżnikowa Formation, 250–350 m thick, is composed of alternating grey-blueish calcareous sandstones, marls and marly shales. The sandstone/shale ratio varies from 1.2:1, in the lower part of the formation, to 2.1:1 in the upper part (Oszczypko 1986). The sandstones are thin- to medium-bedded, sporadically thick-bedded, with predominant Tcd Bouma divisions. In the Żeleźnikowa section, these beds are intercalated by dark grey Łącko marls, 50–350 cm thick. The graded bedding, cross-lamination and parallel lamination characterising the Łącko marls support their turbidite origin (Oszczypko



Text-fig. 3. Lithostratigraphic logs of the Beskid Sądecki Range and adjacent part of the Lubovnianska Vrchovina Range



Text-fig. 2. Geological map of the Muszyna, Krynica,Tylicza and Leluchów area (partly after Oszczypko and Zuchiewicz 2007)

1991). The marls are composed of siliciclastic biogenic and argillaceous-carbonate material. The biogenic material consists primarily of sponge spicules, foraminifers, peloids and coccoliths (Oszczypko 1991). The Żeleźnikowa Formation shows coarsening- and thickening-upwards sequences (Text-fig. 3) and palaeocurrent directions from the southeast and east. Both the lower and upper boundaries of the formation are isochronous (Oszczypko 1991). In the type section, the formation was dated as Middle Eocene (NP16 calcareous nannoplankton Zone of Martini 1971) (Dudziak 1991).

Equivalents: Bystrica Formation (beds). The Żeleźnikowa Formation could be regarded as fringe-lobe sequences, prograding towards the north, deposited by both siliciclastic and carbonate turbidity currents (Oszczypko 1991).

Magura Formation

In the Bystrica and Tylicz zones, the Magura Formation has been subdivided into the Maszkowice Sandstone Member, the Mniszek Shale Member and the Poprad Sandstone Member (Oszczypko 1991) (Text-figs 2, 3).

Maszkowice Sandstone Member: This member is represented by thick-bedded (60–120 cm), fine- to very coarse-grained, poorly sorted, muscovite sandstones with calcareous-muddy cement (Text-fig. 4A). These sandstones display Tabc Bouma intervals. The sandstones are poorly cemented and contain numerous clasts of mudstones, up to 15 cm in diameter; they pass upwards into strongly bioturbated mudstones, rich in mica flakes and flakes of coalfield plants (Oszczypko 1991).

The sandstones are intercalated by soft, dark grey marlstones (5 to 20 cm thick) or sandy-muddy couplets, up to 1 m thick. There are also thick- to very thick-bedded (50–200 cm), clast-rich granule conglomerates, and amalgamated sandstones. In the Krynica area, the Maszkowice Member contains rare packets, up to few metres thick, of Łącko-type marls (Text-fig. 4B, see also Świdziński 1972; Oszczypko *et al.* 1999a; Oszczypko and Zuchiewicz 2007). These strata display coarsening- and thickening-upwards sequences, typical of a channel-lobe turbidite system. The bottom surfaces of the sandstones display grooves and flute casts indicating palaeocurrent direction from the northeast to east. In the Krynica–Tylicz area, the thickness of the Maszkowice Member reaches 700–800 m. This member belongs to the Middle Eocene calcareous nannoplankton zones NP16–17 (Oszczypko-Clowes, in Oszczypko *et al*. 1999a).

Mniszek Shale Member: In the Krynica area (Text-figs 2, 3, 4C) the Mniszek Shale Member is represented by thin-bedded flysch with two packets of red shales at the base (Oszczypko 1979; Oszczypko *et al*. 1990, 1999a; Oszczypko and Zuchiewicz 2007). The red shales are visible on the southern slope of the Parkowa Góra Hill and were penetrated by Zuber's (I–IV) and B-2 boreholes (Oszczypko and Zuchiewicz 2007). These shales contain Middle Eocene assemblages with *Reticulophragmium amplectens* (Świdziński 1972). In the Zuber III and IV boreholes, conglomerates and thick-bedded sandstones overlying the upper intercalation of red shales were penetrated. The total thickness of the Mniszek Shale Member in these boreholes is up to 250 m (Oszczypko and Zuchiewicz 2007). Based on the presence of the NP18 calcareous nannoplankton Zone at the base (Oszczypko 1991; Dudziak 1991), the age of this member can be considered as not older than Late Eocene.

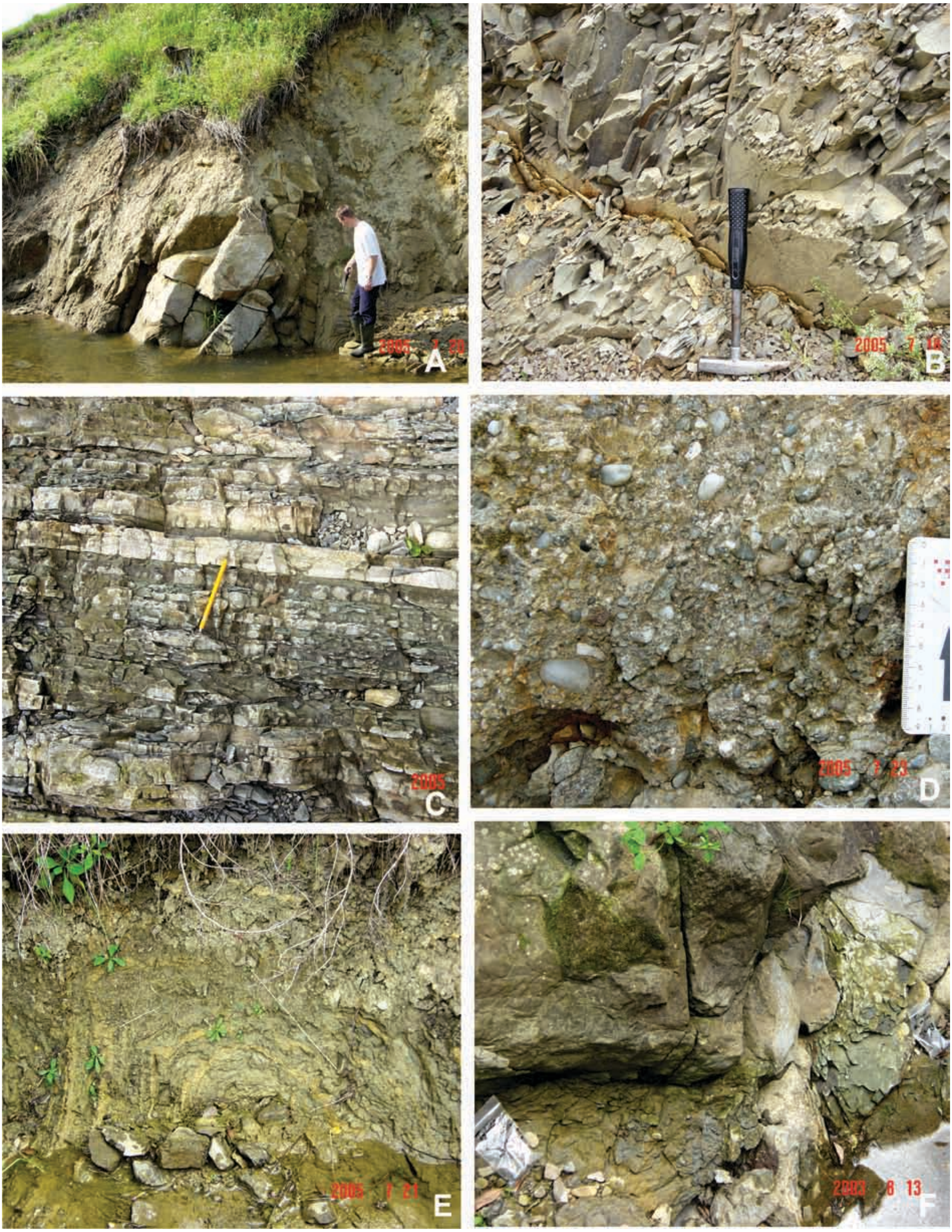
Poprad Sandstone Member: In the Krynica area, the Mniszek Shale Member passes progressively, in an overturned position, into thick-bedded sandstones at least 200–250 m thick, which have been named the "Zuber sandstones" (Świdziński 1972). According to Oszczypko *et al*. (1999a) and Oszczypko and Zuchiewicz (2007) these sandstone are an equivalent of the Poprad Sandstone Member of the Magura Formation.

Tylicz Zone

To the east of the Mochnaczka and Muszynka rivers (Text-fig. 2), the Eocene succession of the Bystrica Zone passes upwards into the younger Late Eocene to Oligocene deposits of the Tylicz transition facies Zone (Węcławik 1969b). In this area, the east-trending red shales of the Mniszek Shale Member are traced from the Mochnaczka stream up to the Polish–Slovak state boundary (Text-fig. 2). These red shales, up to 30–50 m thick, are overlain by thin-bedded turbidites 250–300 m thick (Text-figs 2, 3). These beds were described by Węcławik (1969a) as the Hieroglyphic Beds of Late Eocene age; while Oszczypko (1979) regarded these beds as the Zarzecze Formation of Early to Middle Eocene age. According to our new litho and biostratigraphical data, these beds represent the upper part of the Mniszek Shale Member of the Magura Formation. The lower portion of these beds is dominated by blue-grey flysch (Text-fig. 4C), whereas in the upper portion green-grey colours predominate. The lower portion of the flysch contains lenticular conglomerate and sandstone bodies (Text-figs 2, 3) located on the left bank of the Muszyna river and partly in the bedrock of the river (see also Mochnacka and Węcławik 1967; Węcłąwik 1969b). The basal 75 m thick paraconglomerate packets are composed of pebbly mudstones deposited by cohesive debris flow (Text-fig. 4D). Higher up in the section, there are two packets of thick-bedded sandstones, each up to 50 m thick. In general, these coarse clastic deposits display fining- and thinning-upwards sequences. These exotic conglomerates contain numerous carbonate pebbles of Triassic to Oligocene age (Olszewska and Oszczypko 2010). The Tylicz conglomerates pass upwards into the upper part of the Mniszek Shale Member, represented by thin-bedded shaley flysch (Text-fig. 4E) containing rich foraminiferal assemblages with *Chilostomella chilostomelloides* (Vašicek), characteristic of the Late Eocene (Węcławik 1969a, b). These conglomerates can be correlated with conglomerates drilled in the Zuber III–IV boreholes.

Poprad Sandstone Member

The highest part of the succession in the Tylicz Zone is the Poprad Sandstone Member, which is at least 600–800 m thick and composed of thick-bedded turbidites with sporadic intercalations of 0.5–1.5 m packets of thin-bedded flysch (Text-figs 2, 3, 4F). These beds were described by Węcławik (1969b) as the Magura Beds. The thick-bedded sandstones are dark grey, rusty-weathering, mainly fine-grained with calcareous cement. The basal portion of the beds contains big muddy clasts up to 20 cm in diameter (Text-fig. 4F) in which we found Oligocene calcareous nannoplankton. According to Węcławik (1969a, b), his Magura Beds contain numerous submarine slumps.



Text-fig. 4. Typical deposits of the transition between the Bystrica and Tylicz facies zones. A – Thick-bedded poorly cemented sandstones of the Maszkowice Sandstone Member (Middle Eocene) of the Magura Formation. Muszynka River east of Tylicz; B – Łącko Marls of the Maszkowice Sandstone Mb. Muszynka River east of Tylicz; C – Grey marly mudstones and very thin-bedded sandstones, at the top of the red shales with *Reticulophragmium amplectes*. The lower portion of Mniszek Shale Mb. (Late Eocene–Oligocene). Muszynka River at Tylicz; D – Pebbly mudstone

Krynica Zone

In this area, the Paleogene deposits are composed of the Szczawnica, Zarzecze and Magura formations, while the Kremna Formation belongs to the Early Miocene (Text-figs 2, 3, 5, 6).

Szczawnica Formation

This formation was established by Birkenmajer and Oszczypko (1988, 1989). In the Krynica–Muszyna area, the base of the formation is exposed in the Jastrzębik and Szczawniczek stream sections, situated a few kilometres northeast of Muszyna (Oszczypko *et al*. 1990). In these stream sections, the variegated shales of the Malinowa Shale Formation (Turonian–Campanian) (Text-figs 2, 3, 7A) pass upwards into the Złockie Formation. This formation is represented by an at least 50–60 m thick complex of thin-bedded, non-calcareous, dark grey flysch strata (Text-fig. 7B) with sporadic intercalations of red shales. These strata contain agglutinated foraminifera from the Maastrichtian – Paleocene boundary interval. The lower boundary of the overlying Szczawnica Formation is located against the last appearance of red shales.

The lower part of the Szczawnica Formation is represented by blue-grey, thin- (5–7 cm) to medium- (25–30 cm) bedded, fine- to medium-grained, calcareous sandstones, which display Tbc and Tbcd Bouma intervals (Text-figs 2, 3, 7C, D). There are sporadic intercalations of thick-bedded coarse-grained sandstones and conglomerates with Tbc intervals. Higher up in the section, there occurs thin- to medium-bedded calcareous flysch, at least 300 m thick (Text-fig. 3). The complete succession of the Szczawnica Formation is known from the Jastrzębik section, whereas in the Czarny Potok and Szczawiczne sections only the upper part of the formation is visible. In both the Jastrzębik and Szczawniczek stream sections, the highest part of the formation is characterized by the occurrence of very thin-bedded (2–5 cm) flysch facies (Tcd turbidites) and a gradual transition to the overlying Zarzecze Formation.

In the Krynica area, the Szczawnica Formation is exposed in the middle reach of the Czarny Potok stream, close to the lower ski station "Jaworzyna", in the southwest part of the village of Słotwina, as well as in the middle reach of the Szczawiczne and Źródlany streams (see Oszczypko *et al*. 1999a; Oszczypko and Zuchiewicz 2007). In older publications, these strata were assigned to either the lower Hieroglyphic Beds (Nowak 1924), Beloveža Beds (Świdziński 1972), or to the Zarzecze Formation (Chrząstowski *et al*. 1993). The best exposures of the Szczawnica Formation are situated in the middle reach of the Szczawiczne stream (Text-fig. 2). This section displays thin- (5–7 cm) to medium-bedded (25–30 cm), fine- to medium-grained, calcareous, grey-blueish sandstones with parallel and ripple cross-lamination (Tbc and, sometimes, Tbcd Bouma intervals). Thick-bedded, coarse-grained (Tabc) sandstones are observed in places. In the Czarny Potok and Szczawiczne stream sections, the highest part of the Szczawnica Formation is represented by very thin-bedded (2–5 cm), fine-grained sandstones (Tcd), intercalated with blueish, poorly calcareous shales. In the Czarny Potok stream, 50 m northwest of the lower ski station, a packet of dark, 1 m-thick soft marls was identified (Oszczypko *et al*. 1999a). In the Krynica–Muszyna area, the boundary between the Szczawnica and Zarzecze formations is not well defined but can be located roughly at the base of the first packet of the Krynica conglomerates (e.g., Szczawiczne section) or at the boundary between the Szczawnica and Zarzecze lithofacies (Czarny Potok, Szczawiczne and Złockie streams).

The boundary between the Szczawnica and Zarzecze formations is well defined in the northern part of the Krynica Zone, near the town of Rytro on the Poprad River. In this area, the highest part of the Szczawnica Formation is represented by the Życzanów Sandstone Member (Birkenmajer and Oszczypko 1989). The Życzanów Sandstone Member, up to 70 m thick, splits into two conglomeratic-sandstone lenses separated by thin- to medium-bedded turbidites (Oszczypko 1985; Oszczypko and Porębski 1986a). The lower part of this section is represented by very thick beds (up 5 m) of amalgamated, very coarse-grained sandstones and granule conglomerates with normal and inverse grading (Text-fig. 7E). The sole surfaces are sharp and covered with flutes and large grooves. The palaeotransport is directed towards the west and west-southwest (Oszczypko 1985).

In the Szczawnica–Krościenko area, the Szczawnica Formation (Text-fig. 5) is dominated by thick-bedded, calcareous sandstones, rich in small carbonate clasts with *Lithothamnium*, with sporadic intercalations of thin- to medium-bedded sandstones (Text-fig. 7F). In the Sielski stream section, the upper part of the Szczawnica Formation, at least 300 m thick, is exposed in the core of an anticline. The formation is represented by dark grey, thin-to medium-bedded turbidites (1:1 sandstone/shales ratio). The fine-grained, calcareous sandstones display Tbc Bouma intervals, while the mudstone/shaley intercalations are usually not calcareous. In this section, the hinge

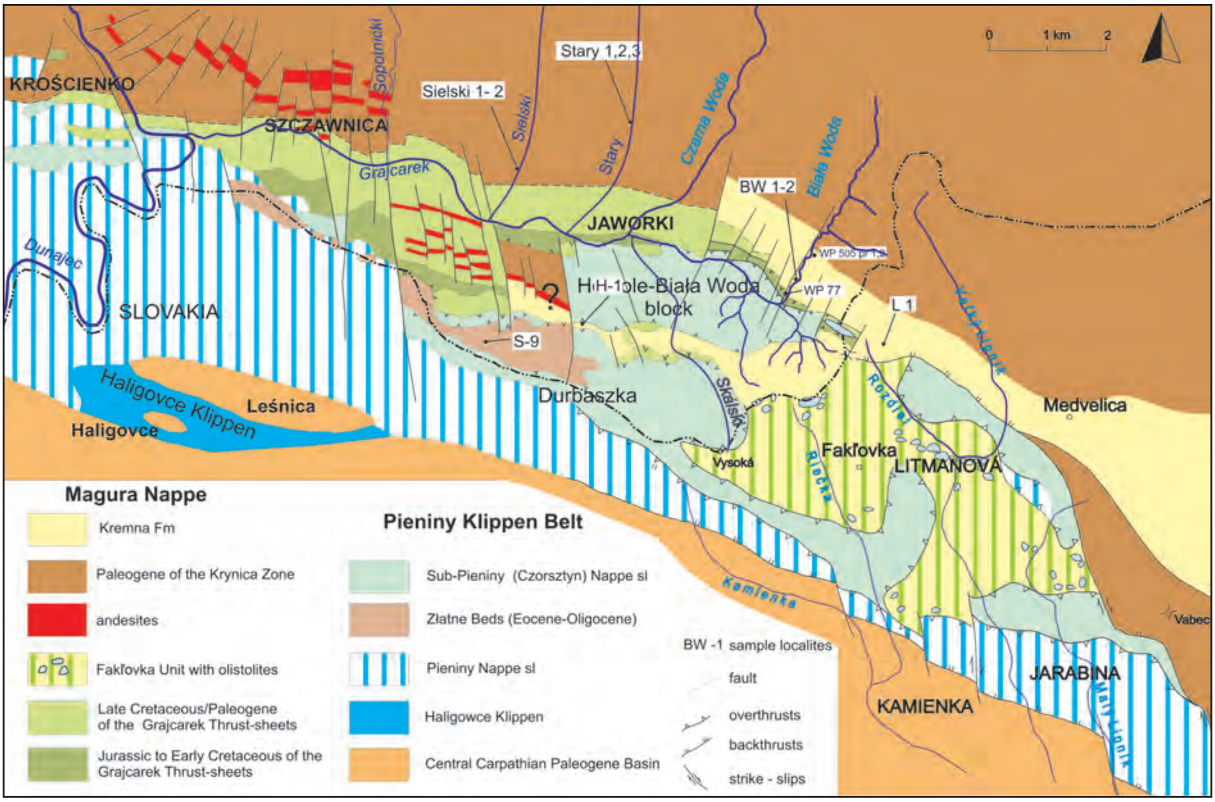
conglomerate of the Mniszek Shale Member Muszynka River south of Tylicz; E – Grey-greenish, marly shales and siltstones of the upper part of Mniszek Shale Mb. Southern slope of the Muszynka River near Tylicz; F – Big clasts of the shaley marlstones (s. 37M/03/N and 38M/03/N) at the base of the Poprad Sandstone Member (Oligocene). Bedrock of the Muszynka River south of Tylicz of the anticline displays the conglomerates and sandstones of the Życzanów Sandstone Member. This member can probably be correlated with exotic conglomerate beds recognized in the Kroscienko and Jaworki area (Alexandrowicz *et al*. 1984). The Szczawnica Formation, up to 500 m thick, is relatively strongly tectonized, and bears frequent calcite veins. In both the Krynica–Muszyna and Krościenko–Szczawnica areas, the formation contains significant amounts of chrome spinels supplied from the southeast (Oszczypko and Salata 2005).

Zarzecze Formation

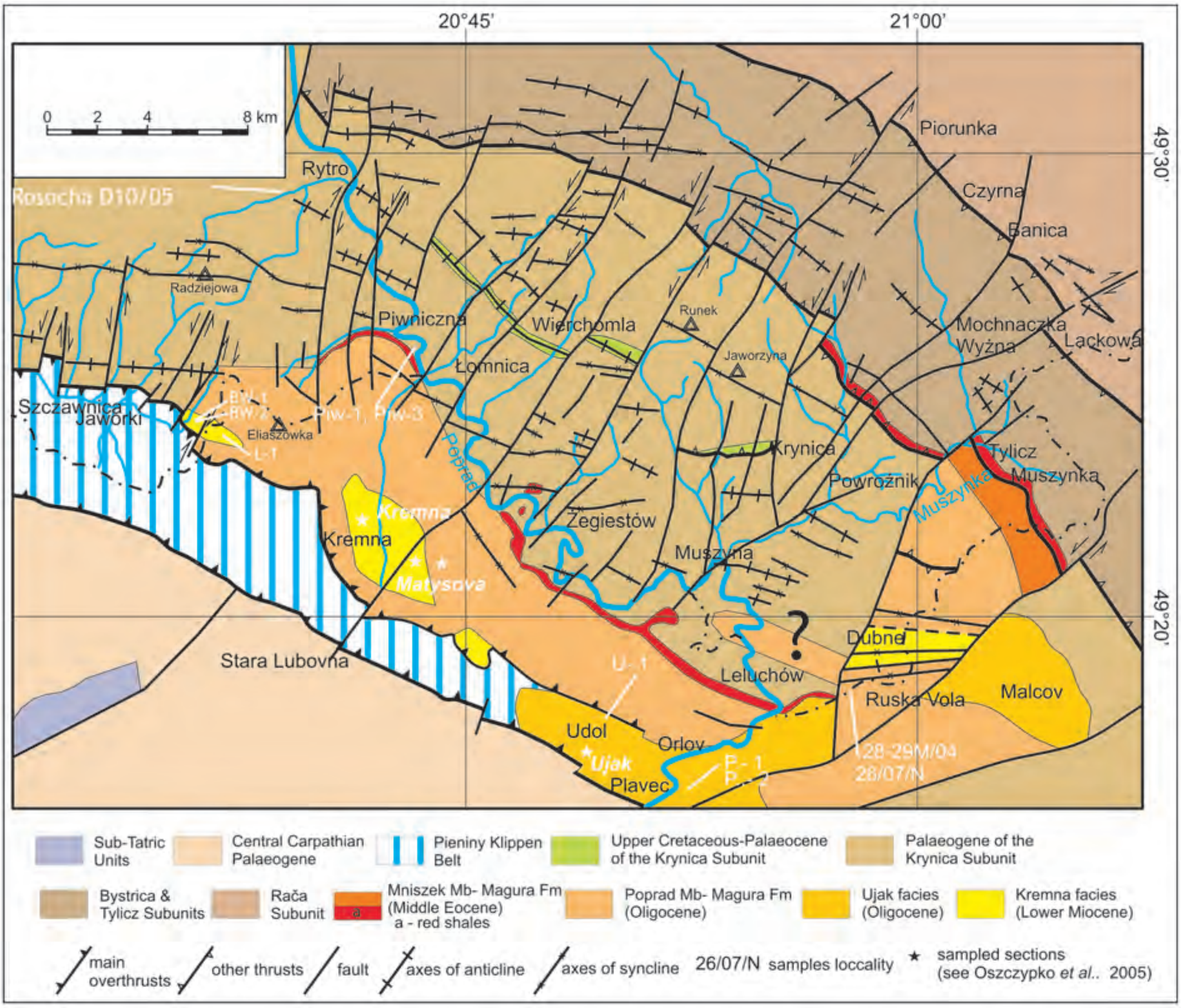
The Szczawnica Formation is succeeded by the Zarzecze Formation, composed of thin- to medium-bedded turbidites (Oszczypko 1979; Birkenmajer and Oszczypko 1989), formerly known as the Upper Hieroglyphic (Nowak 1924) or Beloveža Beds (Świdziński 1972). The total thickness of the formation reaches 600–650 m in the Krynica area (Oszczypko 1979; Oszczypko *et al*. 1999a), 650–700 m in the Złockie–Powroźnik area, 400 m at Wojkowa and 200 m in the Sielski stream near Szczawnica (Text-fig. 3). A typical sequence begins with thin- to medium-bedded sandstones alternating with dark grey marly mudstones and claystones (Tex-fig. 8A). The fine- to medium-grained calcareous sandstones display mainly Tbc and rarely Tbc+conv Bouma intervals (Text-fig. 8B). The formation consists of thin-bedded, blueish-grey calcareous sandstones, alternating with dark grey mudstones and marly claystones. The claystones are green when weathered, whereas the sandstones tend to weather to a rusty colour (Text-fig. 8C, D, E). The sandstone soles show current marks which indicate palaeotransport towards the northwest. Trace fossil assemblages with *Paleodictyon* have been observed in this formation (Nowak 1924; Oszczypko *et. al*. 1999a). In the left bank of the Dunajec river at Krościenko (Text-fig. 8F, St. Barbara Chapel), in the Sealskin stream at the village of Szlachtowa, as well as in the Stary stream, the basal portion of the Zarzecze (Text-fig. 6) flysch contain 2 m-thick packets of dark grey Łącko-type marls.

The Zarzecze flysch strata contain one to a few metres thick packets of thick-bedded sandstones, pebbly sandstones, and gravelstones belonging to the Krynica Sandstone Member, whose thickness ranges from 10 to 550 m (Text-figs 2, 3). There are also sporadic thick beds of pebbly mudstones (Złockie and Wilcze streams) containing exotic material dominated by milky quartz, accompanied by metamorphic, igneous and volcanic rocks, and rare pebbles of Mesozoic carbonates (Oszczypko 1975; Oszczypko *et al*. 2006).

Krynica Member sandstones and conglomerates, 250 m thick, were identified on the slope of the Jaworzyna Krynicka Mt. (Text-fig. 2). In the Szcza-



Text-fig. 5. Geological sketch-map of the Małe Pieniny Mts (based on Oszczypko et al. 2010, supplemented)



Text-fig. 6. Geological sketch-map of the Beskid Sądecki Range and adjacent part of the Lubovnianska Vrchovina Range (based on Oszczypko and Zuchiewicz, supplemented)

wiczne stream, the member showed palaeotransport towards the northwest. This lithofacies displays features of channel deposits.

In the Szczawnica area (Text-figs 3, 5), the boundary between the Życzanów Sandstone Member of the Szczawnica Formation and the Zarzecze Formation can be observed in the Sielski stream. The lower part of the Zarzecze Formation here is up to 100 m thick and consists of thin-bedded, blueish-grey calcareous sandstones, alternating with dark grey mudstones and marly claystones. This part of the formation contains packets of dark grey and blueish marls of the Łącko-type, up to 2–3 m thick.

Magura Formation

In the Magura Nappe, all of the highest mountains (Beskid Wysoki, Beskid Wyspowy, Gorce and Beskid Sądecki ranges) are built up of the Magura sandstones, muscovitic, thick-bedded sandstones (Text-figs 2, 3), described originally by Paul (1868) in the Orava Region (north Slovakia). For more than 100 years, these sandstones were known as the Magura muscovite beds (see Książkiewicz 1958, 1966; Sikora and Żytko 1960; Sikora 1970; Węcławik 1969a; Oszczypko 1973) and then later defined as the Magura Formation (Birkenmajer and Oszczypko 1988, 1989; Oszczypko 1991). In the Krynica Zone, this formation overlies the thin-bedded flysch of the Zarzecze or Szczawnica formations (Birkenmajer and Oszczypko 1989; Oszczypko *et al*. 1990, 1999a).

The Magura Formation is dominated by thick- and very thick-bedded sandstones and conglomerates. The sandstone/conglomerate couplets, which are up to a few dozen metres thick, are intercalated by shale packets a few metres thick. The sandstones are fine to coarse/very coarse-grained, with illite-carbonate cement, and display mainly the Ta Bouma interval, rarely Tb and Tc. The finding in the Krynica Zone of Middle to Late Eocene variegated shales with *Reticulophragmium amplectens* Grzybowski (1966) enabled the subdivision of the Magura Formation into the Piwniczna Sandstone, Mniszek Shale and Poprad Sandstone members (Text-fig. 3) (Birkenmajer and Oszczypko 1989;

Text-fig. 7. Typical Paleogene lithofacies of the Krynica Zone. A – Variegated shales of the uppermost portion of the Malinowa Shale Formation (Campanian–Maastrichtian). Złockie Creek; B – Thin-bedded fine-grained calcareous sandstones with intercalations of dark grey non-calcareous mudstone. Basal portion of the Szczawnica Formation (Lower Eocene) Jastrzębik Creek; C – Thin-bedded turbidites of the middle portion of the Szczawnica Formation (Lower Eocene), Jastrzębik Creek; D – Grey marly shales with intercalations of thin-bedded sandstones Szczawnica Formation, Jastrzębik Creek; E – Thick bedded amalgamated granule to coarse-grained sandstones of the Życzanów Sandstone Member (Lower Eocene). Uppermost part of the Szczawnica Formation in the Życzanów section; F – Thin-bedded to medium-bedded turbidites of the Szczawnica Formation, left bank of the Dunajec River at Łąkcica near Krościenko

Oszczypko 1991). In the central part of the Krynica Zone, where the Mniszek Shale Member does not occur, distinguishing between the Piwniczna and Poprad Sandstone members is difficult, and often resulted in overestimation of the thickness of the former. In our opinion, both sandstone members differ in the character of the mudstone intercalations, which are calcareous in the Poprad Sandstone Member, and non-calcareous in the Piwniczna Sandstone Member.

Piwniczna Sandstone Member: The member is characterized by the presence of conglomerates, thick-bedded sandstones and pebbly mudstones with subordinate intercalations of thin-bedded sandstones, mudstones and claystones (Birkenmajer and Oszczypko 1989). The mudstones and claystones are usually non-calcareous. The basal part of the member was described in detail in the Baszta section, Tylmanowa (Oszczypko 1985; Oszczypko and Porębski 1986b), and in the Wierchomla Wielka quarry (Bromowicz and Uchman 1992).

In the Baszta section, the thick-bedded, 20–25 m-thick sandstone sets are composed of massive sandstone beds, 0.7–1.5 m thick, usually fine- to medium-grained and sporadically conglomeratic. The sets are separated by 5–8 m-thick sets of thin-bedded turbidites (Text-figs 9A–D). The thick-bedded, poorly sorted sandstones are composed of quartz, feldspars, muscovite and lithoclasts of metamorphic, igneous, volcanic, and sedimentary rocks. The sandstone cement varies from calcareous to argillaceous. The sandstones display graded bedding, parallel lamination and ripple cross-lamination at the top. Locally, amalgamation of sandstone beds is observed, as well as loadcasts and incised channels (Text-fig. 9C). The clastic material was derived from the south and southeast (Text-fig. 3). These sandstones contain a heavy mineral assemblage dominated by garnet.

In the Wierchomla Wielka quarry, a 200 m-thick succession of the member is exposed, represented by grey, thick-bedded (40–720 cm), muscovite, lithic vac sandstones with subordinate intercalations of sandy mudstones (Bromowicz and Uchman 1992). The fine- to medium-grained sandstones, with siliceous cement, contain dispersed granule grains and horizons with clasts up to 15 cm in diameter; these sandstones belong to to the A1.4 class (Pickering *et al.* 1986) and are accompanied by thick-bedded turbidites with Tabc Bouma intervals.

In both sections, the *Cruziana* and *Nereites* ichnofacies have been found (Bronowicz and Uchman 1992). In the road-cutting in the Poprad Valley, south of Muszyna, very thick (up to 5 m), massive, non amalgamated sandstone beds were observed (Text-figs 2, 9E). In this exposure, we also found a submarine slump composed of folded pebbly mudstones (Text-figs 9F, 9G). The upper part of the Piwniczna Sandstone Member (exposed e.g. in Mniszek near Piwniczna and Rosocha near Rytro), which contains locally packets of exotic-bearing fine-grained conglomerates and pebble mudstones (Oszczypko 1975; Oszczypko *et al.* 2006), forms submarine slumps (Text-figs 10A, B, C). These conglomerates are also known from the Krościenko–Szczawnica area.

Mniszek Shale Member: The member is composed of red shales with *Reticulophragmium amplectens*, overlain by thin-bedded flysch. It has been recognized on the western slope of the Poprad valley in the Piwniczna (Mniszek–Hanuszów–Kosarzyska) area (Ostrowicka 1966; Oszczypko 1979; Golonka and Rączkowski 1981, 1984; Birkenmajer and Oszczypko 1989; Oszczypko *at al*. 1990; Oszczypko-Clowes 2001) and in the Żegiestów–Milik–Andrzejówka area (Chrząstowski *et al*. 1993). It is also known from the western slope of the Poprad Valley (Nemčok 1990a, b). The thickness of the member varies from a few dozen metres up to 150 m (on the Zapała Hill, northeast of Andrzejówka, Text-figs 2, 3).

In eastern Slovakia (Krynica (Čergov) Zone), the Middle–Late Eocene variegated beds (equivalent of the Mniszek Shale Member) occur between the Čergov and Strihov sandstones (Nemčok 1990a, b).

Poprad Sandstone Member: The member is exposed in the Poprad valley, between Piwniczna and Leluchów. It is known from the Hanuszów stream near Piwniczna (Ostrowicka 1966; Golonka and Rączkowski 1981, 1984; Birkenmajer and Oszczypko 1989; Oszczypko-Clowes 2001) and from the Zapała Hill between Andrejówka and Milik (Text-fig. 2). Usually, only the basal, 100–150 m-thick part of the member is exposed. Continuation of the Magura Formation from the Krynica–Muszyna–Leluchów area is visible in the northern part of the Lubovnianska Vrchovina Range, southwest of the Poprad River. This part of the Krynica facies Zone (see Nemčok 1990a, b) belongs to the Čergov beds (Middle Eocene), variegated shales (Middle–Late Eocene) and Strihov beds (Middle–Late Eocene). The Čergov and Strihov beds are represented by thick-bedded sandstones with sporadic mudstone/claystone intercalations, whereas the variegated beds are dominated by red shales with Mn concretions, and thin-bedded flysch. These deposits can be correlated with the Piwniczna, Mniszek and Poprad members respectively (Oszczypko *et al*. 2005). In the Lubovnianska Vrchovina Range the Poprad Sandstone Member (Strihov beds) forms the 4–6 km-wide Hraničné–Kremna–Matyšova synclinal zone (see Nemčok1990a; Oszczypko *et al*. 2005). The Poprad Sandstone Member, up to 1000 m thick, is underlain by the Mniszek Shale Member and

Text-fig. 8. A – Dark grey thin-bedded, calcareous sandstones with intercalations of mudstones. Lower portion of the Zarzecze Formation in the lower stretch of the Życzanów Stream; B – Sub-vertical thin- to medium-bedded fine- to coarse-grained sandstones with intercalation of dark grey mudstones, rusty-coloured when weathered. Zarzecze Formation in the Szczawniczek Stream section; C – Medium-bedded sandstones intercalated by 60 cm-thick packet of very thin-bedded sandstone/ mudstone couplets, Zarzecze Formation in the Szczawniczek Stream section; D – Thick-bedded Krynica type sandstone passing upwards into rusty weathering, thin- to very thin-bedded, very fine-grained sandstones and grey marly mudstones, Zarzecze Formation, Szczawniczek Stream section; E – Thin-bedded sandstones and dark grey, non-calcareous shales of the upper portion of the Zarzecze Formation, Szczawniczek; F – The Łacko-type grey marls at the top of the thick-bedded sandstone. St. Kinga Chapel, left bank of the Dunajec River at Krościenko overlain by the Kremna Formation (Oszczypko *et al*. 2005). In the Hraničné, Lipnik and Matyšova sections, this formation is represented by coarse- to very coarse-grained, thick-bedded (0.40 to 2 m thick) sandstones, with sporadic intercalations of dark grey, marly mudstones. A characteristic feature of these deposits is the occurrence of Magura-type sandstones and 1.5–2.0 m-thick intercalations of dark grey to greenish calcareous Łącko type marly mudstones. In the Jarabina section, these deposits pass upwards into thick- and very thick-bedded Magura-type sandstones, which reveal a palaeocurrent direction towards the west. Exposures of the Poprad Sandstone Member have been also observed in the Leluchów–Malcov road-cutting, at the village of Ruska Vola.

Kremna Formation

The Kremna Formation (Early Miocene) has been recently established in the Kremna–Matyšova area (eastern Slovakia) by Oszczypko *et al*. (2005). In the Stara Lubowna area, these deposits were formerly known as: "Nördliche Grenzzone" (Uhlig 1890), "flisz przedskałkowy" i "międzyskałkowy" (Horwitz 1935), "Kremna facies" (Matejka 1959; Stranik and Hanzlikova 1968) and "Kremna flysch development" (Nemčok 1990 a, b) of Palaeocene–Late Eocene age. The lower boundary of the formation is gradational from the thick-bedded turbidites of the Poprad Sandstone Member of the Magura Formation, whereas the upper boundary is erosional. The formation varies in thickness, from 200–300 m in the Matyšova and Dubne section (Text-fig. 3), up to 500–600 m in the Kremna section.

The formation is composed of thin- to medium-bedded turbidites (Tbc) (Text-fig. 10D) with intercalations of thick-bedded (1.0–2.0 m) massive sandstones, sometimes with mudstone clasts. The sandstones are intercalated by 1.5–8.0 m-thick packets of dark grey marly shales and laminated marls (Text-figs 11A, B). These medium- to coarse-grained sandstones are usually calcareous and reveal a palaeotransport towards the north-west and north.

The Kremna Formation occurs in the axial zone of the Hraničné–Kremna–Matyšova syncline (Oszczypko *et al*. 2005). Towards the west, along the PKB, it extends to the Slovak–Polish boundary. New exposures of the formation have been recently documented by the authors at the front of the Pieniny Klippen Belt in Litmanova (eastern Slovakia) and in the Biała Woda Valley near Szczawnica. On the Slovak side, this formation has been sampled in the upper reach of the Rozdiel stream in Litmanova (samples Lit. 1–4, GPS: N49°22'45.21"; E20°36'58.1"), while on the Polish side we sampled exposures in the Biała Woda and Jasielnik streams near Jaworki (Text-fig. 5, samples BW 1, 2 – GPS N49° 23'.986; E20° 35'.500; WP 505 pr 1, 2 – GPS N49°24'191"; E20°35'.711"). In the Biała Woda and Jasielnik sections, the Kremna Formation is represented by strongly tectonized massive sandstones and fine conglomerates, with packets of grey marly mudstones of the Łącko type. There are also intercalations of detritic coarse-grained limestones (WP 77 – GPS N49° 23'.826; E20° 35'.309). According to Prof. B. Olszewska (pers. comm.) this grainstone contains strongly recrystallized foraminifera indicating the 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*.

On the geological maps by Birkenmajer (1979) and Golonka and Rączkowski (1981) these beds have been included in the Szczawnica Formation and the Magura Formation (beds).

Ujak lithofacies of the Krynica Zone

Książkiewicz and Leško (1959) described Late Eocene to Oligocene deposits in the east Slovakian sector of the Magura Nappe that differed from those known from the Magura succession. These deposits display a similarity to the Menilite–Krosno development of the Middle Group of the Outer Carpathian nappes (see Książkiewicz 1977 and references therein). Książkiewicz and Leško (1959) showed that these deposits [*Globigerina* Marl, Menilite Shales and Krosno (Malcov) beds], also known as the Ujak lithofacies (Stranik and Hanzlikova 1968), are younger strata of the Magura succession. These deposits were later discovered in the east Slovakian sector of the Pieniny Klippen Belt (Leško and Samuel 1968), and in the form of small erosional outliers in the Magura Nappe in Poland (Oszczypko 1973). One of the most interesting occurrences of the Ujak lithofacies is known from Ujak (Udol)–Lubotin in Slovakia and Leluchów in Poland (Text-fig. 6), where it overlaps both the Pieniny Klippen Belt and the southern edge of the Magura Nappe. The contact zone between the Krynica Zone and Ujak successions in Leluchów is not exposed, but could be reconstructed (Text-figs 2, 6).

Finally, exposures of the Krynica Zone succession are visible along the Leluchów–Muszyna road and in the road-cutting on the country road north of the Greek-Catholic Church in Leluchów. The exposures consist of thick-bedded (0.4–2.5 m) muscovite sandstone and conglomerate of the Magura Formation. Recently a few metres of red, non calcareous shales, underlain by thick-bedded sandstones, were penetrated in a shallow bore-

Text-fig. 9. A – Thick-bedded, amalgamated sandstones with infrequent intercalations of thin-bedded flysch. Piwniczna Sandstone Member of the Magura Formation in the Baszta section, left bank of the Dunajec River at Tylmanowa; B – Thin- to medium-bedded flysch packet in the middle part of the Baszta section; C – Incision of submarine channel in thick-bedded sandstone body, Baszta section; D – Thick-bedded amalgamated sandstones, with large loadcasts at base of sandstone bed (the upper part of the picture); E – Very thick-bedded massive Magura-type sandstone. Piwniczna Sandstone Member, right bank of the Poprad River, Muszyna–Folwark; E – Debris flow and submarine slump with minor fold, Piwniczna Sandstone Member, right bank of the Poprad River, Muszyna–Folwark; F – Thick-bedded pebbly mudstones, rich in milky quartz pebbles and granules. Krynica Member or lowermost part of the Piwniczna Member, Wilcze stream near Muszyna hole located close to where the Smereczek stream flows into the Poprad River (former checkpoint on the state boundary). This sequence represents the transition from the Mniszek Shale Member to the Piwniczna Sandstone Member and is probably overlain by a minimum 50 m-thick complex of thin-bedded flysch with intercalations of red shales with *Reticulophragmium amplectens* described by Blaicher and Sikora (1967).

Malcov Formation

The Malcov Formation was established by Birkenmajer and Oszczypko. The results of detailed litho- and biostratigraphical studies of the Leluchów section, on the right bank of the Poprad River, close to the Polish–Slovak border (Text-figs 2, 6), were published by Oszczypko (Clowes) (1996) and Oszczypko-Clowes (1998, 1999, 2001). The main section is located along the creek and path, close to the Greek-Catholic Church.

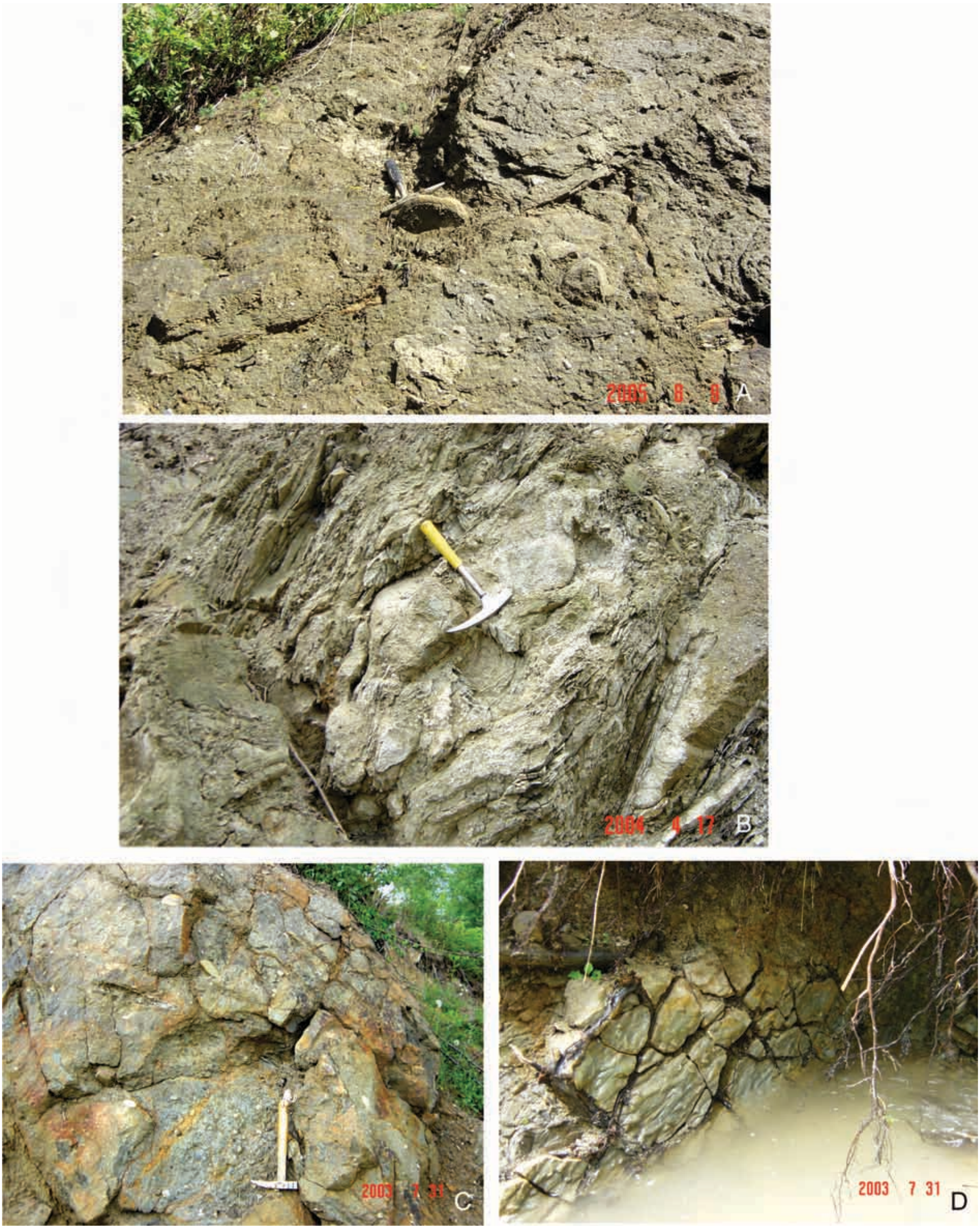
After an exposure gap a few metres thick between the Magura Sandstone Formation of the Krynica Zone and the Ujak facies, the Leluchów Marl Member succession (known also as Sub-Menilite *Globigerina* Marls, see Birkenmajer and Oszczypko 1989 begins with basal 0.5 m to 2.5 m-thick green and grey marly shales with numerous calcite veins, covered by a 4 m-thick unit of red, greyish-green, greenish and olive marls (Text-figs 11C, D, see also Oszczypko (Clowes) 1996; Oszczypko-Clowes 1998, 1999, 2001). The Leluchów Marl Member is covered by a 19 m-thick Smereczek Shale Member, represented by dark Menilite-like shales (see Blaicher and Sikora 1967). The lowermost portion of this member reveals a marly development with a few tuffite intercalations, and a thin (2–5 cm) intercalation of hornstones at the top. In this part of the section, two thin intercalations of detritic Bryozoa-*Lithothamnium* limestones were found. The upper portion of the Menilite Shales consists of black, non-calcareous, bituminous shales with a few layers of coarse-grained, thick-bedded sandstone. At the top of the Smereczek Shale Member, occurs a 25 m packet of coarse-grained, thick-bedded muscovite sandstones (1.0–1.5 m) with intercalations of green marly claystones and medium-bedded sandstones with Tabc Bouma intervals (Text-figs 11E). These sandstones are regarded as the equivalent of the Poprad Sandstone Member. In the highest part of the Leluchów section occur thin-bedded turbidites of the Malcov Formation. These flat-lying, south-dipping strata consist of Krosno Formation-like, dark-grey marly shales with intercalations of thin bedded (10–12 cm), cross-laminated calcareous sandstones (Text-figs 11F, G). A similar developmente of the Malcov Formation is known from exposures in the Ujak (Udol) villages near Stara Lubovna (Text-figs 6, 11H). The upper part of the Malcov Formation, represented by dark grey marly shales with intercalations of thin- to medium-bedded muscovite sandstones, was sampled at the Plaveč, on the right side of the Poprad River (N49°16’03.1”; E20°51’40.9”).

“Autochthonous Magura Paleogene”

Birkenmajer (1986) proposed a multi-stage tectonic model for the evolution of the PKB. This model showed that the Laramide accretionary wedge (Grajcarek Unit) at the front of the Pieniny fold-arc was formed from the Jurassic–Maastrichtian succession on the southern part of the Magura Basin. During the Paleocene, the Grajcarek Unit was back-thrust over the PKB tectonic units and then subsided and filled with Magura autochthonous Paleocene–Eocene flysch. These deposits are well preserved inside the PKB in the Małe Pieniny Mts. and located east of the Dunajec River. Inside the PKB, between the Czorsztyn-Niedzica and Branisko-Pieniny nappes, appears a wide zone (up to 1 km) known as the “autochthonous Magura Paleogene”. Its development reveals lithological features which are common to the Jarmuta–Proč and Magura formations. These deposits have been regarded as the youngest members of the PKB mantle (Birkenmajer and Pazdro 1968) and correlated with the Sub-Magura Beds (Lower Eocene) and the Magura Sandstone (Lower–Middle Eocene). Later, these deposits have been included in the Szczawnica, Zarzecze and Magura formations (Birkenmajer and Oszczypko 1989). These formations were regarded as latest Paleocene–Early Eocene in age (see Birkenmajer and Oszczypko 1989). In the Sztolnia stream and upper reach of the Homole stream we sampled the intercalation of the Łącko type marls (Zarzecze Formation, see Birkenmajer and Oszczypko 1989) for nannoplankton studies. Recently, we have also studied the structural relationship of the “autochthonous Magura Paleogene” to the Czorsztyn–Niedzica and Branisko–Pieniny nappes. According to our observations, the “Autochthonous Magura Paleogene” in the Małe Pieniny Mts. appears in a tectonic window, beneath the PKB nappes (see also Oszczypko and Jurewicz 2008; Oszczypko et al. 2010).

Lithstratigraphic correlation

The progress in litho- and biostratigraphical studies of the Magura Nappe requires a new insight into the late Paleogene lithostratigraphic correlation of the Bystrica and Krynica facies zones. The present day lithostratigraphy of the Magura Formation in the Krynica and Bystrica facies zones was established by Birkenmajer



Text-fig. 10. Debris-flow deposits with exotic-bearing paraconglomerates of the Magura Formation. A – Pebbly mudstones deformed by submarine slump of the upper part of the Piwniczna Sandstone Mb. Rosocha stream, left tributary of the Poprad River at Rytro; B – Submarine slump (pebbly mudstone in the medium-grained conglomerate of the upper part of the Piwniczna Sandstone Member) Piwniczna–Hanuszów, left bank of the Poprad River; C – Pebbly mudstones with exotic material. Poprad Sandstone Member. Left bank of the Smereczek Stream at Leluchów; D – Thin-bedded sandstones and marly shales of the Kremna Formation (Oligocene/Lower Miocene), Dubne section and Oszczypko (1989), and Oszczypko (1991). These authors subdivided the Magura Formation into the following: Piwniczna, Mniszek and Poprad members in the Krynica Zone and the Maszkowice, Mniszek and Poprad members in the Bystrica Zone. Unfortunately this subdivision is valid only in areas where the key correlation horizon (red shales of the Mniszek Shale Member) occurs. It is found along the boundary of the Bystrica and Krynica facies zones and along the upper reach of the Poprad River (Text-figs 2, 3, 5). This horizon has not been recognized in the middle and southwestern parts of the Krynica facies zone. A similar situation can also be observed in some parts of the Bystrica Zone (eg. the Nawojowa–Żeleźnikowa area).

In the Beskid Sądecki Range, the Poprad Sandstone Member was mapped only in the Piwniczna (Hanuszów) and Żegiestów–Andrzejówka areas and in the adjacent area of the Lubovnianska Vrchovina Range (Nemčok 1990a, b). In the authors' opinion this occurrence of the Poprad Sandstone Mb. in the Gorce and Beskid Sądecki ranges is probably much more extensive, especially in the larger synclinal zones, where the thickness of the Magura Formation ranges up to 2000 m. This includes the Jaworzyna Krynicka, Radziejowa–Prehyba, and Dzwonkówka synclinal zones (Text-figs 3, 5, 6). In the uppermost part of the Magura sandstone sequences of the Radziejowa and Dzwonkówka sections there are very small exposures of red shales accompanied by exotic-bearing conglomerates (Jaksa-Bykowski 1925; Golonka and Rączkowski 1981; Kulka *et al*. 1985). The lithostratigraphical position and age of these shales are not clear, but an olistolith provenance of these beds cannot be excluded. To the west of the Dunajec River, the Poprad Sandstone Member may occur on the southern slope of the Gorce Range, between the Pieniążkowice and Kluszkowce areas.

In the Oravska Jasenica (western Slovakia, Orava region), the Magura Sandstone has been dated as Oligocene by Sotak (2006), based on planktonic foraminiferal assemblages. These sandstones are in the same position as the Poprad Member.

In the southern part of the Krynica facies zone of the Magura Nappe in Poland and Slovakia, the Kremna Formation occurs on top of the Poprad Sandstone Member (Text-figs 3, 5, 6). The geographical extent of this formation is much greater than the authors have so far considered. The Early Miocene Kremna Formation can be correlated with other Early Miocene deposits known from the contact zone between the Magura Nappe and the PKB (Rogoźnik and Stare Bystre sections see Cieszkowski 1992) and from the Nowy Targ PIG 1 borehole (Paul and Poprawa 1992). In the opinion of the authors, the Malcov beds described at the same time from the Samorody section in the Nowy Targ area (Cieszkowski and Olszewska 1986; Cieszkowski 1992) can be regarded as the Kremna Formation. Moreover, deposits similar to those of the Kremna Formation have been described in the Czorsztyn–Frydman area (Birkenmajer and Dudziak 1981; Birkenmajer and Oszczypko 1989) as the Frydman Formation.

Similar deposits are also known from the peri-PKB zone in the Humenne area of east Slovakia (Matašovsky and Andreyeva-Grigorovich 2002). Early Miocene Kremna-like deposits were also found in the tectonic windows in the Pieniny Klippen Belt in the Małe Pieniny Mts. (see also Oszczypko *et al*. 2010). These deposits were regarded (Birkenmajer 1979 and later papers) as "Autochthonous Magura Paleogene". At the boundary between the Rača and Bystrica facies zones, the Lower Miocene Zawada Formation is equivalent to the Kremna Formation (Oszczypko *et al*. 1999b; Oszczypko and Oszczypko-Clowes 2002). The Kremna Formation can be regarded as terminal flysch deposits in the southern part of the Magura Basin (Oszczypko-Clowes 2010).

STRUCTURE

The study area belongs to the southern part of the Magura Nappe and is bounded to the south by the Pieniny Klippen Belt (Text-figs 2, 5, 6, 12). This part of the Magura Nappe belongs to the Bystrica and Krynica subunits. It is a deeply immersed part of the Magura Nappe in Poland, with the most completely preserved youngest deposits (Oligocene–Early Miocene). In general, the Beskid Sądecki Range has a block-folded structure, in which oblique slip faults play an important role. Their orientation changes from E–W to NW–SE in the Sczawnica area to NE–SW in the Krynica–Muszyna area (Text-figs 2, 5, 6).

Bystrica Subunit (Text-figs 3 and 12) is located in the northwestern part of the Krynica–Muszyna area. This subunit is built up of subvertical thrust sheets (Oszczypko *et al.* 1999a; Oszczypko and Zuchiewicz 2007). The northern limbs of the anticlines and the southern limbs of the synclines are tectonically reduced (see Świdziński 1972). The synclines are broad and sometimes secondarily folded. The Bystrica and Krynica subunits are divided by the subvertical, north-dipping reverse Krynica fault (Text-fig. 6, see also Świdziński 1972; Oszczypko *et al.* 1999a and Oszczypko and Zuchiewicz 2007). East of the Mochnaczka and Muszynka rivers, the Eocene succession of the Bystrica

Zone passes upwards into the late Late Eocene–Oligocene deposits of the Tylicz transitional facies Zone (Węcławik 1969b). The northern part of the Tylicz Zone is represented by 2 km-wide thrust sheet built up of a narrow, diapir-like anticline, composed of the Beloveža Formation. The secondary folded syncline is composed of thick-bedded sandstones and Łącko-type marls of the Maszkowice Sandstone Member of the Magura Formation.

The lower part of the Tylicz Zone succession is strongly deformed, with overturned folds, whereas its upper part consists of strata dipping gently southwards. Węcławik (1969b) interpreted this tectonic disconformity as having been caused by the Late Eocene Illyrian phase, which affected the east Slovakian sector of the Magura Nappe (Leško and Samuel 1968).

The **Krynica Subunit** is arranged into NW–SE-trending narrow anticlines and broad synclines, built up of the Piwnicza Sandstone Member (Oszczypko *et al.* 1999a; Oszczypko and Zuchiewicz 2007). East of the Poprad River, the northern and southern groups of synclines, separated by the Wiechomla Mała–Szczawniczek–Złockie–Jastrzębik–Powroźnik–Wojkowa anticlinal zone, are visible (Text-fig. 12). The northern group comprises the Runek–Jaworzyna Krynicka, Góra Krzyżowa, and Krynica Wieś synclines. The thickness of the Magura Formation attains 500 m in the Góra Krzyżowa syncline and up to 2000 m in the Jaworzyna Krynicka syncline (Text-fig. 12). The southern group comprises the Wierchomla Wielka–Milik–Muszyna–Wilcze-synclines, with the thickness of the Magura Formation in this area oscillating between 900 and 1500 m. The strata of the Bystrica and Krynica subunits are cut by two to three sets of kathetal transverse joints, and one to two kathetal longitudinal joints, in respect to the strike of map-scale folds (see Oszczypko and Zuchiewicz 2007).

CALCAREOUS NANNOFOSSILS

Methods

All samples were prepared using the standard smear slide technique for light microscope (LM). The investigation was carried out under LM–Nikon–Eclipse E 600 POL, at a magnification of 1000× using parallel and crossed nicols. Several of the specimens photographed under LM are illustrated in Text-figs 13–14, and the stratigraphical ranges of the taxa recognised are given in Tables 1–3.

Results

The vast majority of the samples yielded very poor and badly preserved nannofossil assemblages. Some specimens could not be identified because of strong etching and mechanical damage of the placoliths, especially their central areas. The relative abundance in the samples is usually low. The scarcity of index species makes the age determination very difficult. Only in rare cases were the assemblages rich enough to enable zonal assignment.

During the field work, 132 samples were collected from sections located along the following streams: Szczawnik, Szczawniczek, Jastrzębik, Wojakowski, Słupie, Młynne, Wilcze, Zimne, Rusina, Dubne and from exposures in the following villages: Leluchów Wierchomla, Złockie, Szczawniczek, Mniszek.

Samples: 1-4M/02/N, 9-10M/02/N, 12M/02/N, 27-28M/02/N, 3M/03/N, 6M/03/N, 8M/03/N, 13M/03/N, 18-19M/03/N, 22-23M/03/N, 27-30M/03/N, 36M/03/N, 39-40M/02/N, 42M/02/N, 44-45M/02/N, 51M/02/N, 54M/02/N, 52M/03/N, 1M/04/N, 5M/04/N, 6M/04/N, 8-9M/04/N, 15-16M/04/N, 30-34M/04/N, 16-19M/04/N and 21-26M/04/N do not contain any nannofossils. The samples 5M/02/N, 7M/02/N, 23-26M/02/N, 29M/02/N, 5M/03/N, 7M/03/N, 9M/03/N, 11M/03/N, 16-17M/03/N, 20-21M/03/N, 25M/03/N, 31-32M/03/N, 34-35M/03/N, 37-38/M/03/N, 41M/02/N, 43M/02/N, 46M/02/N, 56M/02/N, 2-3M/04/N, 7M/04/N, 20M/04/N, 47-48/98, D16a-17a/05, 4M/03/N, and 4M/04/N yield very poor and badly-preserved nannofossil assemblages. All these samples are not older than Eocene.

Bystrica / Tylicz zones

Magura Formation

Maszkowice Sandstone Member: Most samples were barren and only two samples (48/98 and 47/98) contained determinable nannoplankton species. The assemblage from sample 48/98 (Text-fig. 2) is moderately diverse. The most characteristic species are *Chiasmolithus grandis*, *Chiphragmoalithus acanthodes*, *Chiasmolithus solitus*, *Coccolithus pelagicus*, *Cyclicargolithus floridanus*, *Discoaster binodosus*, *Dis-*

Text-fig. 11. The youngest deposits of the Magura Succession (Krynica Zone). A – Thick-bedded sandstones with packets of marly mudstones and shales of the Kremna Formation; exposure along the Piwniczna–Stara Lubovna road; B – Sub-vertical, dark brown and grey marly shales with sandstone intercalations. Kremna Formation at Matyšova section; C – Red marls of the Leluchów Marl Member of the Malcov Formation. Leluchów. Photo. B. Żydek; D – Red and olive marls of the Leluchów Marl Member of the Malcov Formation. Leluchów; E – Thick-bed-

ded Magura type sandstone at the top of the Smereczeki Shale Member, Leluchów. photo B. Żydek; F – Marly shales of the Malcov lithofacies, Leluchów. Photo. B. Żydek; G – Medium-bedded, fine-grained sandstone with convolution. Malcov Formation, Leluchów. Photo. B. Żydek; H – Thick bedded sandstones, with intercalations of marly shales. Malcov Formation. Ujak *coaster deflandrei*, *Ericsonia formosa*, *Neococcolithes dubius*, *Sphenolithus radians* and *Zygrhablithus bijugatus*. The stratigraphically youngest species is *Cy. floridanus*, first appearing in the upper part of the NP16 Zone (Aubry 1985). The presence of this species and of *Ch. solitus*, the last occurrence of which marks the upper boundary of the NP16 Zone, indicates the upper part of the NP16 Zone for the whole assemblage.

Sample 47/98 contains: *Ch. grandis*, *Co. pelagicus*, *Cy. floridanus*, *Dictyococcites bisectus*, *Discoaster strictus, Discoaster saipanensis*, *Discoaster tani*, *Discoaster tani nodifer* and *Reticulofenestra umbilica*. The lack of *Ch. solitus* and the presence of *Discoaster tani*, a characteristic event of the midddle part of the NP17 Zone (see Bukry 1973) indicates the Middle Eocene NP17 Zone (see also Dudziak 1991; Oszczypko 1991)

Mniszek shale Member: The red shales of the member are non-calcareous and thus without calcareous nannoplankton. Some samples with nannoplankton were collected from thin-bedded flysch: samples D16a–D17a/05/N, collected along the Muszynka river at Tylicz (Text-fig. 2), and samples 4M/04/N and 4M/03/N in the upper reach of the Wojakowski stream (Text-fig. 2).

The assemblage is moderately diverse. The relative abundance usually varies from 10 to 15 species per observation field. The most abundant species are *Coccolithus pelagicus, Ericsonia formosa* and *Sphenolithus radians*; *Discoaster binodosus*, *Discoaster distinctus*, *Transversopontis pulcher*, *Zygrhablithus bijugatus* and *Discoaster barbadiensis* are less numerous. The stratigraphically youngest taxon present in the assemblage is *Nannotetrina* sp., indicative of the NP15 Zone. This suggests that these beds are of Middle Eocene age. However, the presence of Oligocene foraminifera in limestone pebbles (Olszewska and Oszczypko 2010), as well as their lithostratigraphical position, indicates a younger age of the succession. Consequently, the nannofosil assemblage is interpreted herein as redeposited.

Magura Formation

Poprad Sandstone Member: Samples 37M/03/N and 38M/03/N collected by the Tylicz–Powroźnik road, near the bridge, contain a fairly abundant (6–8 specimens per field of observation) nannofossil association. This association is moderately rich taxonomically and characterized by an abundance of placoliths. The autochthonous assemblage is represented by the following species: *Coccolithus eopelagicus*, *Coccolithus pelagicus*, *Cyclicargolithus abisectus*, *Cyclicargolithus floridanus*, *Dictyococcites bisectus*, *Pontosphaera multipora*, *Pontosphaera plana*, *Reticulofenestra lockerii*, *Reticulofenestra dictyoda, Sphenolithus dissimilis* and *Sphenolithus moriformis*. The FO of *Cyclicargolithus abisectus* is usually found close to the FO of *Sphenolithus ciperoensis* (zonal marker of the base of the NP24 Zone) and thus can be used to approximate the boundary between the NP23 and NP24 zones (Martini and Műller 1986). However, Melinte (2005) identified the FO of *C. abisectus* in the lower part of the NP23 Zone, well below the FO of *S. ciperoensis*). Taking into account the absence of *Lanternithus minutus*, *Orthozygus aureus*, *Transversopontis fibula* and *Chiasmolithus oamaruensis*, which has its LO in the upper part of the NP23 Zone (see Melinte 2005), it is possible to assign the samples to the NP24 Zone. Additionally, *Sphenolithus dissimilis* first appears in the NP24 Zone (see Perch-Nielsen 1985).

Krynica Zone

Szczawnica Formation

Most of the samples collected from this formation were barren. Low-diversity assemblages were found only in samples from the lowermost part of the formation (Text-fig. 2): 10M/03/N (Słupie stream), 12M/03/N (Młynne), 10M/04/N, 11M/04/N, 12M/04/N (Szczawnik), 47M/03/N, 48M/03/N, 49M/03/N, 50M/03/N, and 20M/04/N (Jastrzębik stream). The assemblage is composed of *Chiasmolithus eograndis*, *Chiasmolithus solitus*, *Discoaster barbadiensis*, *Discoaster distinctus*, *Discoaster kuepperi*, *Ericsonia formosa*, *Sphenolithus editus* and *Sphenolithus moriformis*. Such a composition suggests that the age of these samples is not older than the Early Eocene (i.e., upper part of the NP12 Zone). It is important to stress that these assemblages are present in the lowermost part of this formation, on top of the Złockie Formation.

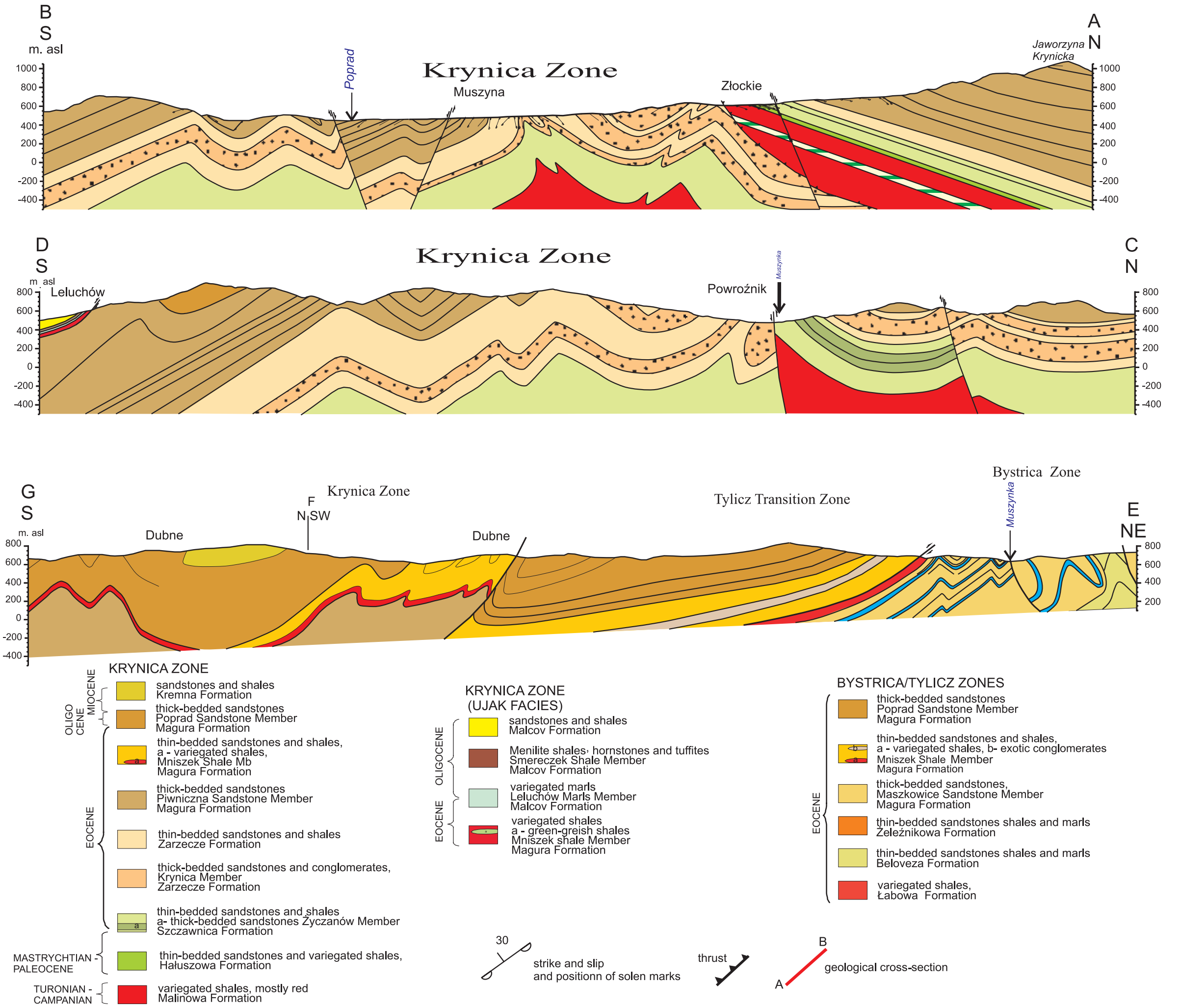
Zarzecze Formation

The formation was sampled in both the Muszyna and Szczawnica areas (Text-fig. 2).

The oldest assemblage found in the Zarzecze Formation was described from samples (Text-fig. 2) 1M/03/N, 2M/03/N (Wojakowski stream), 11M/02/N (Jastrzębik stream) and 119/98 (Urdy stream). The nannofosssil abundance (per observation field) in the samples varies from more than 15 species in sample 11M/02/N to 6–9 species in samples 1M/03/N and 2M/03/N. The most abundant species are *Coccolithus pelagicus*, *Ericsonia formosa* and *Sphenolithus radians*. Less abundant are *Discoaster barbadiensis*, *Discoaster binodosus*, *Discoaster distinctus*, *Discoaster elegans*, *Transversopontis pulcher* and *Zygrhablithus bijugatus*. Stratigraphically youngest is the index species *Discoaster bifax*. There is some controversy concerning the range of this species. According to Okada and Bukry (1980) it marks the lower boundary of the CP14a Zone (NP16 sensu Martini 1970), whereas Aubry (1983) proved its first occurrence to be as low as the lower part of NP14.

The lower part of the Zarzecze Formation was also sampled in the Sielski stream (Text-fig. 5). The nannoplankton assemblages from samples Sielski 1, Sielski 2 and Sielski 3 (Text-fig. 5) are moderately well preserved. The autochthonous species are represented by *Chiasmolithus gigas*, *Coccolithus pelagicus*, *Discoaster binodosus*, *Dictyococcites bisectus*, *Discoaster deflandrei*, *Ericsonia formosa*, *Sphenolithus moriformis, Sphenolithus radians* and *Zygrhablithus bijugatus.* The stratigraphically youngest species is *Chiasmolithus gigas* which, according to Okada and Bukry (1980), is the index species for their CP13b Subzone, i.e., an equivalent of the middle part of the NP15 nannofossil Zone (*sensu* Martini 1970). The same assemblage was found in samples from the Stary stream (Text-fig. 5).

The youngest assemblages identified so far come from the following samples: 6M/02/N, 8M/02/N (Szczawnik stream), 53M/03/N, 55M/03/N, 57M/03/N (Jastrzębik stream, Text-fig. 2), 13M/04/N, 14M/04/N (Szczawnik stream), 33M/03/N (Muszyna near the water-spring "Grunwald", Text-fig. 2) and 14M/03/N, 15M/03/N (Wilcze stream). The assemblages are moderately well preserved, moderately diverse taxonomically, and the specimens are abundant (with 10–15 specimens per observation field). The autochthonous assemblage is characterized by the presence of *Chiasmolithus grandis*, *Coccolithus eopelagicus*, *Coccolithus pelagicus*, *Discoaster binodosus*, *Dictyococcites bisectus*, *Discoaster deflandrei*, *Ericsonia formosa*, *Nannotetrina* sp., *Sphenolithus radians* and *Zygrhablithus bijugatus*. The stratigraphically youngest species is *Nannotetrina* sp., the index species of the



Text-fig. 12. Geological cross-sections

NP15 Zone (Middle Eocene). At the same time, the species characteristic of the NP16 Zone such as *Cyclicargolithus floridanus, Helicosphaera compacta* and *Reticulofenestra umbilica* (Levin), have not been found (see Aubry 1986).

Magura Formation

Piwniczna Sandstone Member (Text-fig. 2): Samples Piw-1 and Piw-3 (submarine slump) (Text-figs 6, 10B) contain fairly abundant assemblages (with 10 specimens in each observation field). The assemblages contain *Braarudosphaera bigelowii*, *Chiasmolithus expansus*, *Chiasmolithus solitus*, *Coccolithus pelagicus*, *Coccolithus eopelagicus*, *Discoaster barbadiensis*, *Discoaster binodosus*, *Discoaster deflandrei*, *Discoaster distinctus*, *Ericsonia fenestrata*, *Ericsonia formosa*, *Helicosphaera dinesenii*, *Helicosphaera heezeni*, *Pontosphaera multipora, Sphenolithus moriformis*, *Sphenolithus radians, Transversopontis pulcher, Transversopontis pulcheroides* and *Zygrhablithus bijugatus*. The most abundant are: *Co. eopelagicus*, *Co. pelagicus*, *E. formosa* and *Sph. moriformis.* The presence of the forms listed, and the lack of such species as *Chiasmolithus gigas*, *Cyclicargolithus floridanus* and *Helicosphaera compacta*, suggests that the assemblages may represent the lowest part of the NP16 Zone.

The Rosocha sample D10/05/N (submarine slump, Text-figs 6, 10B) contains a fairly abundant and diverse nannofossil assemblage composed of *Chiasmolithus grandis*, *Coccolithus pelagicus*, *Cyclicargolithus floridanus*, *Dictyococcites bisectus*, *Discoaster strictus*, *Discoaster tanii*, *Discoaster tanii nodifer*, *Discoaster saipanensis*, *Ericsonia formosa*, *Helicosphaera compacta*, *Pontosphaera multipora*, *Pontosphaera plana*, *Sphenolithus pseudoradians*, *Sphenolithus radians* and *Zygrhablithus bijugatus*. The presence of *Discoaster tanii* is characteristic of the middle part of the NP17 Zone (see Bukry 1973). Additionally, these samples contain flat specimens of *Neococcolithes minutus,* indicative of the NP17 Zone (Aubry 1986). Neither *Chiasmolithus solitus* nor *Chiasmolithus oamaruensis*, species characterizing the Late Eocene NP 18 Zone, were found in these samples. The latter was found in an assemblage described by Dudziak (in Oszczypko et *al*. 1990) from the Milik quarry near Muszyna.

Poprad Sandstone Member: Samples 28M/04/N and 29M/04/N, 26/07/N, collected by the Ruska Vola–Čirč road (Text-fig. 2), contain a well preserved and moderately abundant nannofossil assemblage (7–9 specimens per observation field). The association is dominated by: *Coccolithus pelagicus*, *Cyclicargolithus floridanus* and *Reticulofenestra minuta*. Less frequent are *Reticulofenestra dictyoda*, *Sphenolithus conicus, Sphenolithus dissimilis* and *Zygrhablithus bijugatus*.

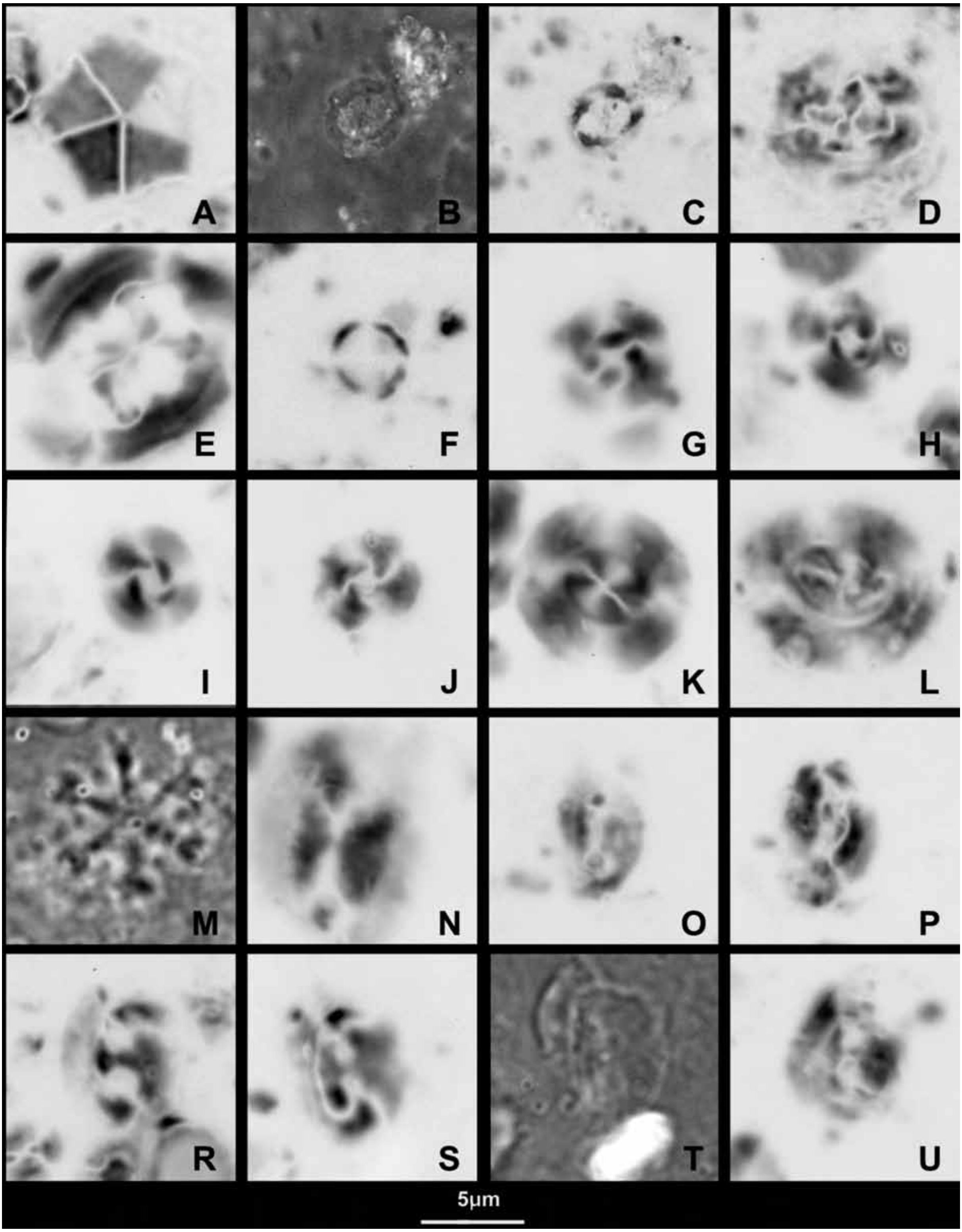
The zonal assignment (higher part of the NN1 Zone) is based on a co-occurrence of *Sphenolithus conicus* and *S. dissimilis,* and the disappearance of *Dictyococcites bisectus*, the last occurrence of which defines the base of the NN1 Zone (Perch-Nielsen 1985, 1986; Berggren *et al*. 1995; Fornaciari and Rio 1996; Young 1998). The rare occurrence of *Sphenolithus conicus* as well as the lack of *Sphenolithus delphix* may suggest that the nannofossil assemblage belongs to the highest part of the NN1 Zone. The biostratigraphic range of *Sphenolithus delphix* is still problematic. This taxon was reported by Aubry (1985) from the NP25 and NN1 zones. Melinte (2005) and Svabenicka *et al.* (2007) also placed the FO of this species in the higher part of the NP25 Zone, though, according to Young (1998) and Shackleton *et al.* (2000), this short-lived nannofossil (22.98 Ma to 23.24 Ma. see Shackleton *et al.* 2000) is only characteristic of the upper part of the NN1 Zone. The FOs and LOs of *Sphenolithus delphix* seem to be reliable datum levels for the Paratethys region (Rögl and Nagymarosy 2004; Oszczypko-Clowes in Oszczypko *et al*. 2005).

The slightly older NP25 Zone was determined from the Poprad Member in the Matyšova section (Text-fig. 6) (Oszczypko *et al.* 2005). The recognition of this zone is based on the first occurrence of *Sphenolithus conicus* and its co-occurrence with *Cyclicargolithus abisectus, Dictyococcites bisectus* and *Zygrhablithus bijugatus.* The FO of *Sph. conicus* has been traditionally used as the base of the NN1 Zone. However, Bizon and Műller (1979), Biolzi *et al.* (1981) and Melinte (1995, 2005) have observed the FO of this species as low as in the upper part of the NP25 Zone. The same age was determined in a sample collected in Homole (Text-fig. 5, sample H-1).

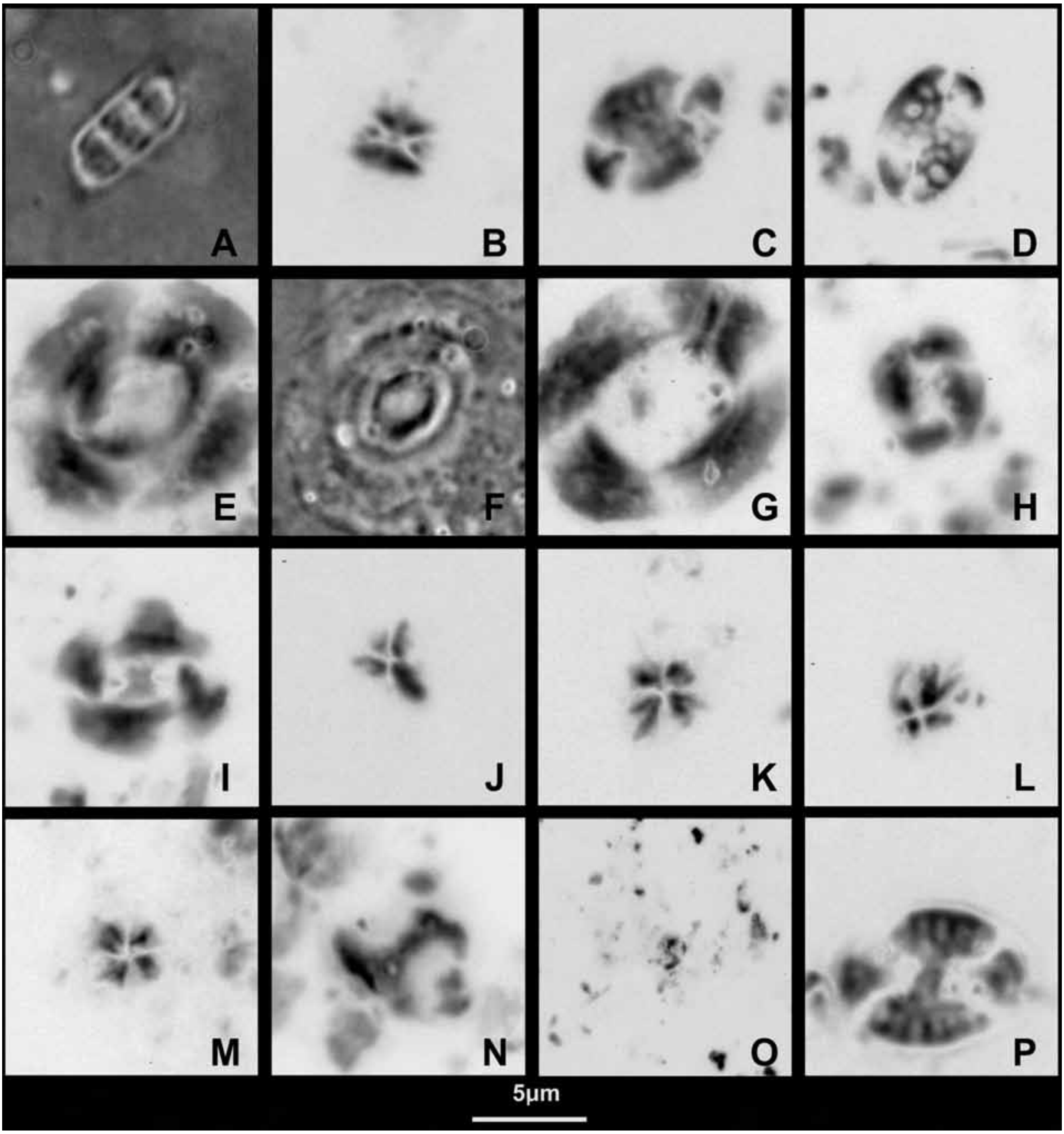
Malcov Formation

The age of particular members of the Malcov Formation (Text-fig. 2) is as follows: the Leluchów Marl Member belongs to the NP19–20, 21 and 22 zones

Text-fig. 13. LM microphotograph of calcareous nannoplankton. A – *Braarudosphaera bigelowii* (Gran and Braarud) Deflandre sample 4M/03/N; B – *Chiasmolithus solitus* (Bramlette and Sullivan) Locker, sample 12M/03/N; C – *Chiasmolithus solitus* (Bramlette and Sullivan) Locker, sample 12M/03/N; D – *Chiasmolithus gigas* (Bramlette and Sullivan) Radomski, sample Sielski 1; E – *Chiasmolihus grandis* (Bramlette and Riedel) Radomski, sample 24M/03/N; F – *Coronocyclus nitescens* (Kamptner) Bramlette and Wilcoxon, sample P-2; G – *Cyclicargolithus abisectus* (Műller) Wise, sample 37M/03/N; H – *Cyclicargolithus abisectus* (Műller) Wise, sample P-1; I – *Cyclicargolithus floridanus* (Roth and Hay *in* Hay *et al.*) Bukry,



sample 48/98; J – *Cyclicargolithus floridanus* (Roth and Hay in Hay *et al.*) Bukry, sample 13/02/N; K – *Dictyococcites bisectus* (Hay, Mohler and Wade) Bukry and Percival, sample U–3; L – *Dictyococcites bisectus* (Hay, Mohler and Wade) Bukry and Percival, sample P-1; M – *Discoaster deflandrei* Bramlette and Riedel, sample D10/05/N; N – *Helicosphaera compacta* Bramlette and Wilcoxon, sample D10/05/N; O – *Helicosphaera compacta* Bramlette and Wilcoxon, sample 29/04/N; P – *Helicosphaera intermedia* Martini, sample P-1; R – *Helicosphaera recta* Haq, sample P-2; S – *Helicosphaera recta* Haq, sample U-3; T – *Helicosphaera recta* Haq, sample U-3; U – *Helicosphaera recta* Haq, sample 28M/04/N



Text-fig. 14. LM microphotograph of calcareous nannoplankton. A – *Isthmolithus recurvus* Deflandre, sample 38M/03/N; B – *Lanternithus minutus* Stradner, sample Piw 1; C – *Pontosphaera multipora* (Kamptner) Roth, sample D10/05/N; D – *Pontosphaera rothi* Haq, sample P – 2; E – *Reticulofenestra hillae* Bukry and Percival, sample U-3; F – *Reticulofenestra umbilica* (Levin) Martini and Ritzkowski, sample 47/98; G – *Reticulofenestra umbilica* (Levin) Martini and Ritzkowski, sample 47/98; H – *Reticulofenestra ornata* Műller, sample 37M/03/N; I – *Reticulofenestra lockeri* Műller, sample 38M/03/N; J – *Sphenolithus delphix* Bukry, sample BW 1, K – *Sphenolithus dissimilis* Bukry and Percival, sample 38M/03/N; L – *Sphenolithus dissimilis* Bukry and Percival, sample BW-2; M – *Sphenolithus moriformis* (Bronnimann and Stradner) Bramlette and Wilcoxon, sample 10M/03/N; N – *Transversopontis fibula* Gheta in Gheta *et al.,* sample 28/04/N; O – *Transversopontis obliquipons* (Deflandre in Deflandre and Fert) Hay, Mohler and Wade, sample 28/04/N; P – *Transversopontis pulcheroides* (Sullivan) Baldi-Beke, sample Piw-3.

(Oszczypko-Clowes 1998, 1999), the Smereczek Shale Member to the NP23 Zone, and the Malcov lithofacies in the Leluchów section and in the Nowy Sącz I borehole to the NP24 Zone.

New samples from Udol (U-3) and Plaveč (P 1-2) area (Text-fig. 6) yielded a reasonable well preserved and abundant nannofossil assemblage. Each of the observation fields contains at least 20 species. The assemblage is dominated by *Coccolithus pelagicus* and *Cyclicargolithus floridanus*. Slightly less abundant are

Cyclicargolithus abisectus, Reticulofenestra dictyoda, Reticulofenestra lockerii and *Sphenolithus dissimilis. Dictyococcites bisectus* is still present but is very rare. The other biostratigraphically important species are *Sphenolithus conicus* and *Pontosphaera rothi.* The presence of these two species indicate the latest Oligocene NP25 Zone (Melinte 1995; see also Aubry 1986).

Kremna Formation

A detailed biostratigraphic interpretation of the Kremna Formation from the Matyšova and Kremna sections was given by Oszczypko-Clowes (in Oszczypko *et al.* 2005).

The zonal assignment was based on the co-occurrence of the following species: *Sphenolithus conicus*, *S. disbelemnos*, *Reticulofenestra pseudoumbilica* and *Triquetrorhabdulus carinatus.* According to Young (1998), the FO of *Sphenolithus disbelemnos* and/or *Umbilicosphaera rotula* is a reliable biostratigraphic event characteristic of the lower limit of the NN2 Zone. Shackleton *et al.* (2000) showed that *S. disbelemnos* appeared at 22.67 Ma (see also Raffi *et al.* 2006). This has proved to be an important datum level for the Paratethys region (Rögl and Nagymarosy 2004; Oszczypko-Clowes in Oszczypko *et al*. 2005).

Additionally, new samples were collected in Litmanova and Biała Woda near Szczawnica (Text-figs

	Bystrica/ Tylicz Zone							
	Maszkowice St. Mb.		Mniszek Shale Mb.				Poprad St. Mb.	
	SŁOTWINY		TYLICZ		WOJAKOWSKI		TYLICZ	
	48/98	47/98	D16a/ 05/N	D17a/ 05/N	4M/ 03/N	4M/ 04/N	37M/ 03/N	38M/ 03/N
Braarudosphaera bigelowii	X	X	X	X	X	X		
Chiasmolithus eograndis			X	X	X	X		
Chiasmolithus expansus	X	X						
Chiasmolithus gigas			X	X	X	X		
Chiasmolithus grandis	X	X	X	X	X	X	R	R
Chiasmolithus solitus	X							
Coccolithus pelagicus	X	X	X	X	X	X	X	X
Cyclicargolithus abisectus							X	X
Cyclicargolithus floridanus	X	X					X	X
Dictyococcites bisectus		X					X	X
Discoaster barbadiensis			X	X	X	X	R	R
Discoaster binodosus	X	X	X	X	X	X		
Discoaster deflandrei	X	X					X	X
Discoaster distinctus	R	R	R	R	R	R		
Discoaster kuepperi								R
Discoaster lodoensis							R	R
Discoaster mohleri	R	R	R	R	R	R		
Discoaster multiradiatus	R	R	R	R	R	R		X
Discoaster salisburgensis	X	X						X
Discoaster strictus		X	X	X	X	X		
Discoaster tanii		X						R
Discoaster tanii nodifr		X						
Discoaster wemmelensis							R	R
Ericsonia formosa	X		X	X	X	X	R	R
Helicosphaera compacta							X	X
Isthmolithus recurvus							X	X
Lanternithus minutus								
Nannotetrina fulgens			X	X	X			
Nannotetrina sp			X	X	X			
Neococcolithes dubius	X	X					X	X
Pontosphaera multipora	X	X	X	X	X		X	X
Reticulofenestra dictoda								
Reticulofenestra lockerii							X	X
Reticulofenestra ornata							X	X
Reticulofenestra umbilica		X						
Sphenolithus conicus								
Sphenolithus dissimilis							X	X
Sphenolithus moriformis	X	X	X	X	X	X	X	X
Sphenolithus radians	X	X	X	X	X	X	R	R
Transversopontis pulcher	X	X	X	X	X	X	X	X
Tribranchiatus orthostylus	R	R						
Zygrhablithus bijugatus	X	X	X	X	X	X	X	X

Table 1. Stratigraphical ranges of calcareous nannoplankton from Bystrica/Tylicz Zone. X – autochthonous species, R – reworked species

6 and 5, samples: L-1, BW 1-2, WP 505 pr 1-2) and also in the middle reach of the Dubne stream (Text-fig. 2, samples 24M/03/N and 26M/03/N) near Leluchów. The abundance varies from more than 25 species per observation field in sample 24M/03/N down to 10 species (per observation field) in samples 26M/03/N. The autochthonous assemblage of samples 24M/03/N, 26M/03/N and L-1 consists of *Coccolithus pelagicus*, *Coronocyclus nitescens*, *Cyclicargolithus floridanus*, *Cyclicargolithus luminis*, *Discoaster deflandrei*, *Helicosphaera euphratis*, *Pontosphaera plana*, *Pontosphaera multipora*, *Reticulofenestra dictyoda*, *Sphenolithus conicus*, *Sphenolithus disbelemnos* and *Sphenolithus moriformis.* A semi-quantitative study of the autochthonous nannoplankton assemblage indicates the dominance of placoliths over other morphological types (eg asteroliths, sphenoliths, helicospheres). The assemblage is dominated by *Coccolithus pelagicus* and *Cyclicargolithus floridanus* (at least 1 specimen per observation field); *Reticulofenestra dictyoda, Sphenolithus conicus* and *Sphenolithus moriformis* are also present but in much smaller numbers. The youngest species which determines the age (Burdigalian) is *Sphenolithus disbelemnos*; the absence of *Cyclicargolithus abisectus, Dictyococcites bisectus* and *Zygrhablithus bijugatus* indicates the NN2 Zone.

A slightly older age was determined in samples BW 1-2, WP 505 pr 1-2. The zonal assignment is based on the co-occurrence of *Sphenolithus conicus*, *S. delphix* and *S. dissimilis* and the absence of *Dictyococcites bisectus*. According to Perch-Nielsen (1985), Berggren *et al*. (1995), Fornaciari and Rio (1996) and Young (1998) the LO of *Dictyococcites bisectus* defines the base of the NN1 Zone. The occurrence of *Sphenolithus delphix* marks the Oligocene / Miocene boundary (Young 1998).

"**Autochtonous Magura Paleogene**"

The samples were collected in the Sztolnia (7-10/07/N) and Homole (H 1-2) streams (Text-fig. 5). The majority of samples were barren. Samples 9/07/N and H-1 contain very low diversity nannofossil assemblages. The assemblages comprise: *Braarudosphaera bigelowii*, *Coccolithus pelagicus*, *Helicosphaera compacta*, *Helicosphaera perch-nielseniae*, *Sphenolithus dissimilis* and *Sphenolithus* aff. *disbelemnos*. The presence of the latter taxon suggests the NN2 Zone, although this is not confirmed by any of the other typical species of this zone such as *Discoaster druggii*, *Reticulofenestra pseudoumbilica* or *Sphenolithus conicus*.

DISSCUSSION

Although the stratigraphical studies of the Magura Nappe started more than 100 years ago, our understanding of its chronostratigraphy is still very incomplete. This is a result of the facies development, characterized by thick-bedded, siliciclastic turbiditic sandstones with an almost total absence of fauna. This applies mainly to the Paleogene sediments of the Bystrica and Krynica zones. An important qualitative change was brought about by the application of calcareous nannoplankton research. From the incomplete range of nannoplankton zones present (NP10, 12, 16–18) the age of these deposits has been determined approximately as Early to Middle Eocene (Birkenmajer and Dudziak 1981, 1988a; Oszczypko *et al.* 1990). The youngest assemblages were sometimes documented in the external zones, mainly in the Siary Zone. This has had a significant impact on the palaeogeographic and palaeotectonic reconstructions, not only for the Magura Basin but also for the whole of the Outer Carpathians sedimentary area.

Although the mechanism of flysch deposition was already well recognized, the role and scale of the redeposition of microfaunas, especially nannofossils, was clearly underestimated. Over time, we feel sure that the nannofossils studied contain at least two associations: an older, much less abundant association named the "allochthonous" association and a younger referred to as the "autochthonous" association. This is in accordance with the very small number of earlier reports concerning the young age of the deposits in the Bystrica and Krynica zones (Cieszkowski 1992; Oszczypko *et al.* 1999b; Oszczypko and Oszczypko-Clowes 2002; Oszczypko *et al.* 2005; Matašovsky and Andreyeva-Grigorovich 2002*).* The studies conducted recently by the authors have proved this hypothesis.

This enabled the discovery of the Oligocene and Early Miocene sediments in the Beskid Sądecki and the Lubovnanska Vrchovina ranges respectively, which hitherto were considered as Eocene in age.

The nannoplankton assemblages of the Kremna Formation can best be compared and correlated with those of the Zawada Formation (Oszczypko *et al.* 1999b; Oszczypko-Clowes 2001; Oszczypko and Oszczypko-Clowes 2002). The calcareous nannofossil association from the lowermost part of the Zawada Formation includes *Cyclicargolithus abisectus*, *C. floridanus*, *Sphenolithus conicus*, *Sp. dissimilis*, *Sp. delphix* and *Triquetrorhabdulus carinatus*. Such an assemblage, in the absence of *Dictyococcites bisectus*, is believed to be indicative of the NN1 Zone, which defines the Oligocene/Miocene boundary. The upper part of the

	Krynica Zone																									
	Szczawnica Formation										Zarzecze Formation															
	SŁUPIE	MŁYNNE	JASTRZĘBIK				SZCZAWNIK				WOJAKOWSKI		JASTRZ.	SZCZAWNIK		WILCZE		MUSZYNA	JASTRZĘBIK			SZCZAWNIK		SIELSKI		
	10M/03/N	12M/03/N	47M/03/N	48M/03/N	49M/03/N	50M/03/N	20M/04/N	10M/04/N	11M/04/N	12M/04/N	1M/03/N	2M/03/N	11M/02/N	6M/02/N	8M/02/N	14M/03/N	15M/03/N	33M/03/N	53M 03/N	55M/03/N	57M/03/N	13M/04/N	14M/04/N	1	2	3
Braarudosphaera bigelowii	X	X		X	X	X	X	X	X	X	X			X	X	X		X	X	X	X					
Chiasmolithus bidens												X														
Chiasmolithus eograndis				X	X	X											X									
Chiasmolithus expansus																X										
Chiasmolithus gigas															X		X							X	X	X
Chiasmolithus grandis		X											X			X	X	X	X	X	X	X				
Chiasmolithus oamaruensis																										
Chiasmolithus solitus		X						X	X	X							X									
Chiasmolithus sp.																X										
Coccolithus pelagicus	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Coronocyclus nitescens																										
Dictyococcites bisectus																		X	X	X	X	X		X	X	X
Dictyococcites sp.																										
Discoaster barbadiensis				X	X	X		X	X	X	X	X	X				X									
Discoaster bifax												X	X													
Discoaster binodosus								X	X	X		X	X		X	X	X							X	X	X
Discoaster deflandrei								X	X	X		X												X	X	X
Discoaster distinctus				X	X	X																				
Discoaster kuepperi				X	X	X																				
Discoaster lodoensis												R		R												
Discoaster mohleri																		R	R	R	R	R				
Discoaster multiradiatus	X			X	X	X	X	X	X	X								R	R	R	R	R				
Discoaster salisburgensis													R			R	R									
Ericsonia fenestrata								X	X	X																
Ericsonia formosa	X	X		X	X	X	X	X	X	X		X			X		X							X	X	X
Fasciculithus tympaniformis							R	R	R	R								R	R	R	R	R				
Lanternithus minutus																		X	X	X	X	X				
Nannotetrina fulgens																	X	X	X	X	X	X				
Nannotetrina sp														X				X	X	X	X	X				
Neococcolithes dubius																X										
Pontosphaera multipora																										
Sphenolithus moriformis	X			X	X	X	X				X	X	X	X		X		X	X	X	X	X		X	X	X
Sphenolithus pseudoradians																	X									
Sphenolithus radians		X										X		X		X	X							X	X	X
Sphenolithus spiniger											X	X		X												
Toweius magnicrassus												R	R			R										
Transversopontis pulcher															X		X									
Transversopontis pulcheroides												X														
Tribranchiatus orthostylus								R	R	R	R	R	R		R	R	R									
Zygrhablithus bijugatus											X	X			X			X	X	X	X	X		X	X	X

Table 2. Stratigraphical ranges of calcareous nannoplankton from Krynica Zone

	Krynica Zone																
	Piwniczna St. Mb			Poprad St. Mb.				Malcov Fm.			Kremna Formation						
	PIWNICZNA		ROSOCHA	OBRUCNE			HOMOLE	UDOL	PLAVEČ	PLAVEČ	D U B N E		BIAŁA WODA				LITMANOVA
	Piw -1	Piw -3	D10/ 05/N	28M/ 04/N	29M/ 04/N	26M/ 07/N	H -1	U -3	P - 1	P - 2	24M/ 03/N	26M/ 03/N	BW -1	BW -2	BW 505 -1	BW 505 -2	L -1
Braarudosphaera bigelowii	X	X	X	X	X	X					X	X					X
Chiasmolithus eograndis	X	X	X														
Chiasmolithus expansus	X	X		X	X	X											X
Chiasmolithus gigas	X						R				R	R	R	R	R	R	R
Chiasmolithus grandis			X								R	R					
Chiasmolithus sp.																	X
Chiasmolithus solitus	X	X															
Coccolithus pelagicus	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Coronocyclus nitescens				X	X	X			X	X			X	X	X	X	X
Cyclicargolithus abisectus				X	X	X		X	X	X			X	X	X	X	
Cyclicargolithus floridanus			X	X	X	X		X	X	X			X	X	X	X	X
Dictyococcites bisectus								X	X	X							
Dictyococcites sp.	X	X							X	X							
Discoaster barbadiensis	X	X	X				R				R	R					
Discoaster binodosus	R	R	R				R										
Discoaster deflandrei			X														X
Discoaster distinctus	R	R	R														
Discoaster kuepperi	R	R	R														
Discoaster lodoensis											R	R					
Discoaster mohleri																	R
Discoaster multiradiatus	R	R	R				R				R	R					R
Discoaster saipanensis			X								R	R					
Discoaster slisburgensis											R	R					
Discoaster tanii			X					R									
Discoaster tanii nodifer			X														
Ericsonia fenestrata	X	X		X	X	X											X
Ericsonia formosa	X	X	X	X	X	X									R	R	X
Helicosphaera ampliaperta																	X
Helicosphaera bramlettei				X	X	X											
Helicosphaera compacta			X	X	X	X	X	X			X	X	X	X	X	X	X
Helicosphaera euphratis				X	X	X		X									
Helicosphaera intermedia								X	X	X							
Helicosphaera perch-nielseaniae															X	X	
Helicosphaera recta				X	X	X		X	X	X							
Helicosphaera scissura															X	X	
Lanternithus minutus	X	X						R			R	R					
Nannotetrina fulgens																	X
Neococcolithes dubius				X	X	X											
Pontosphaera multipora			X				X		X	X							
Pontosphaera rothi									X	X							
Reticulofenestra callida				X	X	X	X										
Reticulofenestra dictyoda				X	X	X		X	X	X							
Reticulofenestra hillae								R	R	R							
Reticulofenestra lockerii								X	X	X							
Reticulofenestra ornata								X	X	X							
Reticulofenestra umbilica								R	R	R							
Sphenolithus calyculus							X								X	X	
Sphenolithus conicus				X	X	X	X	X	X	X			X	X	X	X	X
Sphenolithus delphix													X	X	X	X	
Sphenolithus disbelemnos											X	X					X
Sphenolithus dissimilis				X	X	X		X	X	X			X	X	X	X	X
Sphenolithus moriformis	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X
Sphenolithus predistentus								X									
Sphenolithus pseudoradians			X						X	X							
Sphenolithus radians													R	R	R	R	
Transversopontis fibula				R									R	R	R	R	
Transversopontis obiquipons				X	X	X											
Transversopontis pulcher									X	X			X	X	X	X	
Transversopontis pulcheroides		X		X	X	X		X	X	X			X	X	X	X	
Triquelorhabdulus carinatus													X	X	X	X	
Umbilicosphaera rotula											X	X					X
Zygrhablithus bijugatus	X	X		X	X	X		X	X	X			X	X	X	X	X

Table 3. Stratigraphical ranges of calcareous nannoplankton from Krynica Zone

Zawada Formation was assigned to the NN2 Zone, based on the presence of *Discoaster druggii*, *Sphenolithus disbelemnos* and *Reticulofenestra pseudoumbilica* (Oszczypko *et al.* 1999b; Oszczypko-Clowes 2001; Oszczypko and Oszczypko-Clowes 2002).

In the Lubovnianska Vrchovina area, the uppermost part of the Poprad Sandstone Member is composed of packages of calcareous greyish mudstones resembling the Łącko Marls. The Kremna Formation (Lower Miocene) should be correlated with other Lower Miocene deposits known from the contact zone between the Magura Nappe and the PKB (Cieszkowski 1992), and from the Nowy Targ PIG 1 borehole (Paul and Poprawa 1992). Similar deposits are also known from the peri-PKB zone in the Humenne area (Matašovsky and Andreyeva-Grigorovich 2002).

The research reported has shown that in the Krynica Zone and probably also in the Bystrica Zone flysch sedimentation persisted to the Oligocene and early Miocene.

In the middle part of the Krynica Zone, where the shales with *Reticulophragmium ampletens* do not occur, it is not possible to separate the Piwniczna Sandstone Member from the Poprad Sandstone Member. It is very likely that in this area the highest portion of the Piwniczna Sandstone Member may already belong to the Oligocene. Also unclear is the situation in the northern part of the Bystrica Zone, where the Poprad Sandstone Member does not occur.

Taking into account the researches of Dudziak (1991) and Oszczypko *et al.* (1990), we suspect that the youngest part of the Maszkowice Sandstone Member may also be of Oligocene age. In this case, the submarine siliciclastic fans of the Poprad Sandstone Member of the Krynica and Rača zones were separated by a siliciclastic-carbonate fan of the Maszkowice Sandstone Member of the Bystrica Zone. All of these fans were supplied from a source area to the southeast (Oszczypko 2006). The unification of lithofacies possibly took place in the Late Oligocene and Early Miocene, during the deposition of the Kremna and Zawada formations, in the Bystrica and Krynica zones respectively. Taking into account the new biostratigraphic data, the Zawada Formation should be included in the Bystrica succession rather than in the Rača succession, as previously thought (Oszczypko *et al*. 1999b). The so-called "autochthonous Magura Paleogene" inside the Pieniny Klippen Belt (Birkenmajer 1979, 1986 and subsequent works) is coeval (Late Oligocene to Early Miocene) with the Kremna Formation of the Krynica Zone. According to the preliminary data, the "Autochthonous Magura Paleogene" probably occurs in the tectonic windows (Oszczypko and Jurewicz 2008; Oszczypko *et al*. 2010).

The geological mapping and calcareous nannoplankton studies in the Tylicz area have shown that the contact between the Bystrica and Krynica zones is not tectonic everywhere as hitherto interpreted. This conclusion allows us to resurrect the earlier view of Węcławik (1969b) on the existence of the Tylicz transitional zone, between the Bystrica and Krynica facies zones.

The Paleogene and Lower Miocene formations of the Pieniny Klippen Belt and of the Krynica, Tylicz and Bystrica facies zones of the Magura Nappe, spanning over 35 myrs, represent a synorogenic deep-water turbidite depositional system which dominated the southern part of the Magura Basin after the collision of the Alcapa Mega Unit with the Czorsztyn /Oravic Ridge. The Late Eocene–Early Oligocene reorganization of the basin located along the Pieniny Klippen Belt suture zone resulted in the development of two sedimentary areas on both sides of PKB: the Central Carpathian Paleogene Basin south of the PKB, and the Magura Basin to the north. The Kremna Formation, with reworked material and microfossils from the Pieniny Klippen Belt and the older formations of the Magura Nappe, can be regarded as a "molasse" of terminal flysch deposits in the southern part of the Magura Basin.

CONCLUSIONS

- The Paleogene–Early Miocene formations of the Bytrica and Krynica facies zones have been redefined and redescribed based on new geological mapping and lithostratigraphical and calcareous nannoplankton studies.
- The new Tylicz Transitional Zone, recognised between the Bystrica and Krynica zones, was established in the Tylicz area. The Oligocene Poprad Sandstone Member has been documented in this zone.
- The Late Eocene–Late Oligocene Poprad Member of the Magura Formation and the Early Miocene Kremna Formation have been documented in a few new localities of the contact zone between the Magura Nappe and the Pieniny Klippen Belt, close to the Polish–Slovakian border.
- The "Magura autochthonous Paleogene", located inside the Pieniny Klippen belt, is dated as Late Oligocene–Early Miocene.
- The Paleogene and Lower Miocene formations of the Pieniny Klippen Belt and of the Krynica, Tylicz and Bystrica facies zones of the Magura Nappe, spanning over 35 myrs, represent a synorogenic deep-water turbidite depositional system, which dominated the southern part of the Magura Basin after collision of the Alcapa Mega Unit with the Czorsztyn /Oravic Ridge.

- The Late Eocene–Early Oligocene reorganization of the basin located along the Pieniny Klippen Belt suture zone resulted in the development of two sedimentary areas on both sides of PKB: the Central Carpathian Paleogene Basin south of the PKB, and the Magura Basin north of the PKB.

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