Annales Societatis Geologorum Poloniae (2025), vol. 95: 1–16 https://doi.org/10.14241/asgp.2025.04

OUTLINE OF THE GEOLOGICAL STRUCTURE OF THE WESTERN PART OF THE PIENINY KLIPPEN BELT IN POLAND

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Golonka, J., Chowaniec, J. & Waśkowska, A., 2025**.** Outline of the geological structure of the western part of the Pieniny Klippen Belt in Poland. *Annales Societatis Geologorum Poloniae,* 95: 1–16.

Abstract: The Pieniny Klippen Belt forms a narrow suture zone between the Central and Outer (Flysch) Carpathians and is composed of deposits, laid down in the Alpine Tethys. The lithostratigraphy and tectonic structure of the central part of Pieniny Klippen Belt west of the Białka River, in the area between Krempachy and Stare Bystre, were analysed. The Pieniny Klippen Belt is made up of a mixture of components of different ages and lithologies, referred to as a mélange, which was formed as a result of complex tectonic and sedimentary processes. In the lithological inventory, it contains rocks from the Jurassic up to the Miocene age, which originated in the syn-rift and synorogenic stages of Alpine Tethys evolution. Sedimentation in the Alpine Tethys took place in conditions from shallow- to deep-water, related to the development of the uplifted structure of the Czorsztyn Ridge in its central part. The carbonates and carbonate-siliceous rocks of the syn-rift stage are fragmented and occur in the form of blocks of different sizes within the flysch deposits of the synorogenic stage of development. The flysch deposits of the synorogenic stage are bounded by the results of activity of the accretionary prism, which started in the Albian in the Złatne Basin on the southern side of the ridge and successively prograded to the north. They began with marly and shale-dominated variegated facies, passing into facies with a significant proportion of sandstones. West of Białka River, the Pieniny Klippen Belt has a nappe structure. The sequence of nappes corresponds to that in the sedimentary area of the Alpine Tethys. The uppermost Złatne Nappe contains deposits that originated in the southern part of the basin, while the other nappes contain rocks, laid down in the more northern areas.

Key words: Pieniny Klippen Belt, Alpine Tethys, Magura Nappe, lithostratigraphy, tectonics, mélange.

Manuscript received 25 January 2024, accepted 12 April 2025

INTRODUCTION

The Pieniny Klippen Belt (PKB) marks the suture zone between the Central and Outer Carpathians (Fig. 1). East of the Białka River, it is represented by three mountain ranges: the Spisz Pieniny, Pieniny Właściwe, and Małe Pieniny, while west of the Białka River, no such ranges are distinguished. In this area, the PKB is partially covered by the Neogene and Quaternary formations of the Orava-Nowy Targ Basin (Chowaniec and Cieszkowski, 2009; Watycha *et al*., 2019a, b; Watycha and Boratyn, 2022a, b). The PKB has a complex structure, referred to as a mélange. It is formed by a mixture of components of different ages and lithologies. It is the result of the advanced tectonic processes that accompanied the formation of the PKB, including folding, displacement and uplift, as well as subaqueous mass movements. The complexity of this structure contributes to the difficulty in distinguishing tectonic units and assigning the lithostratigraphic units to the appropriate sedimentary areas (Golonka *et al*., 2018a, b, 2019a, b).

The present study analyses the geological structure of the area between Krempachy and Stare Bystre (Fig. 2) against the background of the general lithostratigraphy of the PKB and the geodynamic history of the Alpine Tethys, in which the rocks comprising the PKB were deposited.

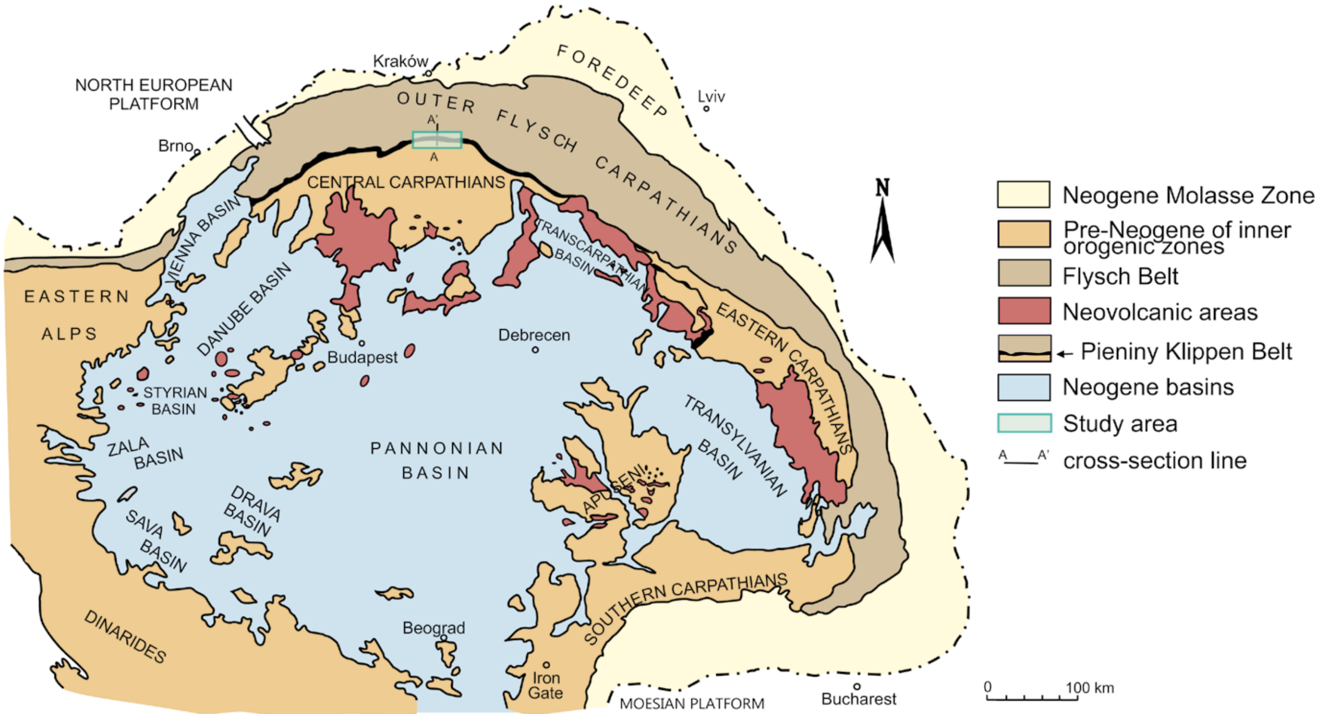

Fig. 1. General tectonic sketch of the Carpathians and adjacent areas, with locations of Figures 2 and 3 (after Golonka *et al.,* 2018b – modified and simplified).

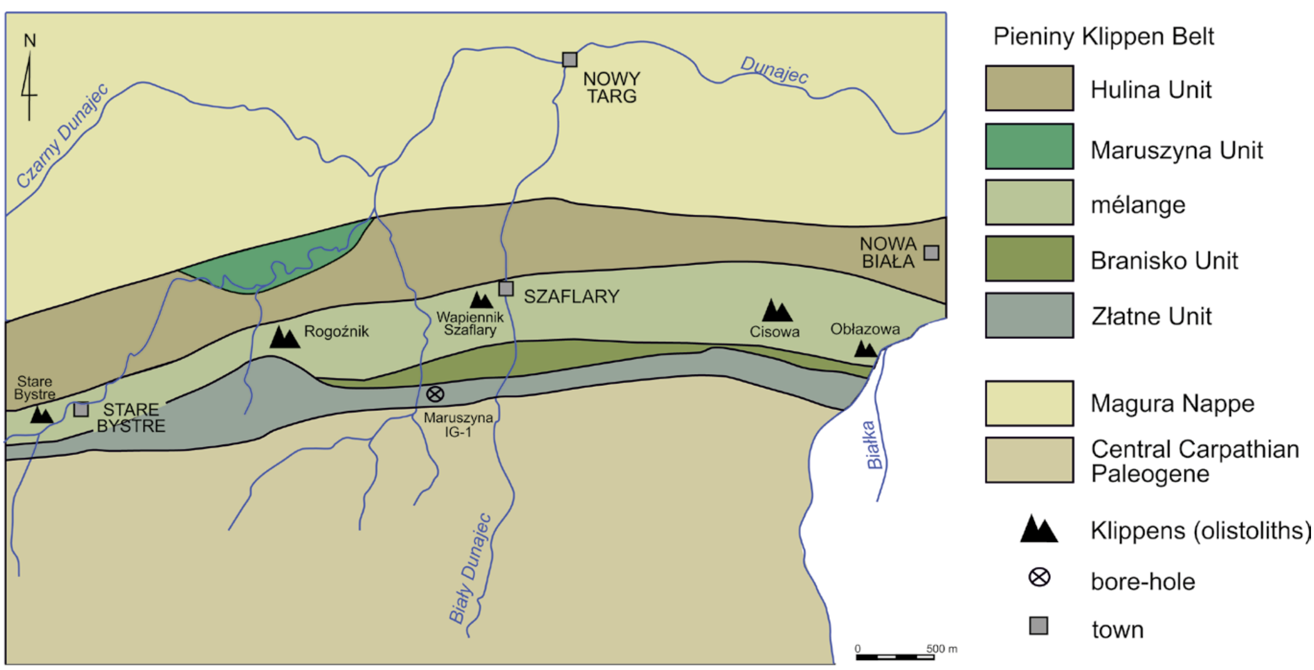

Fig. 2. Tectonic sketch of the Pieniny Klippen Belt in Poland, west of the Białka River.

STUDY AREA

The PKB (Fig. 1) is a narrow and very long structure, the width of which varies from a few hundred metres to 22 km, extending for a distance of about 600 km from near Vienna to Romania (Andrusov *et al.*, 1965; Birkenmajer, 1986; Golonka *et al.*, 2000, 2018b; Murovskaya *et al.*, 2025). It contains deposits that originated in the oceanic Alpine Tethys, developed on the north foreland of the Central Carpathians terrane from Jurassic to Neogene time (Golonka *et al.*, 2018a, b, 2019b, 2024). The PKB constitutes a flower structure that is bordered by two subvertical faults, formed in the Neogene (Fig. 3). The current PKB internal tectonic structure is a result of the Albian–Neogene geodynamic evolution, which was connected with movement of the accretionary prism, as well as the final transtensional and translational tectonic activity, related to motion along strike-slip faults. The Maruszyna, Hulina, Subpieniny, Pieniny, and Złatne internal tectonic units were distinguished in the Polish part of the PKB (Golonka and Sikora, 1981; Golonka

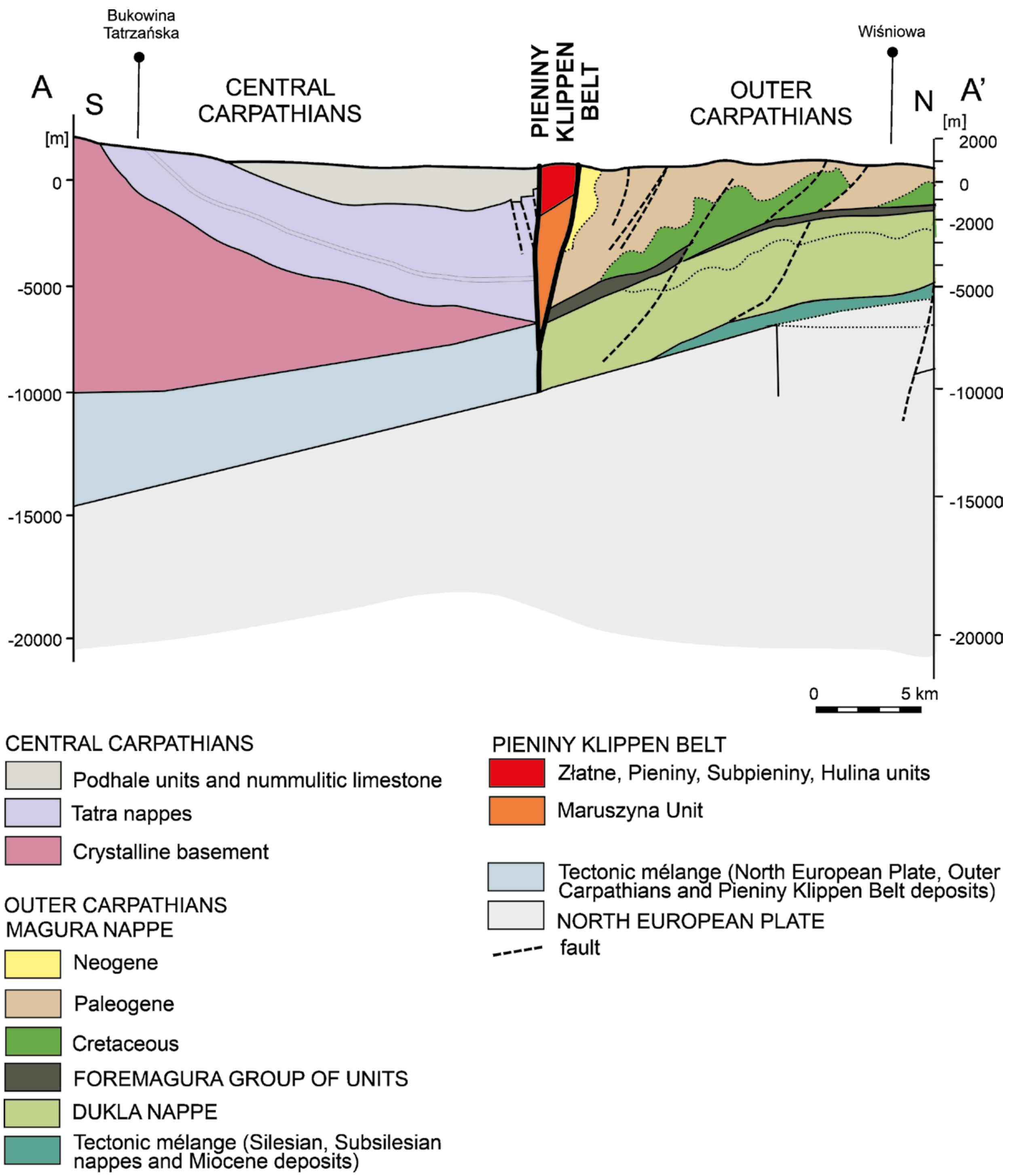

Fig. 3. Cross-section through the structure of the Carpathians in the Bukowina Tatrzańska–Wiśniowa (the position of the cross-section is marked on Figure 1; after Golonka *et al.*, 2019, modified).

et al., 2022, 2024). These units originally were thrust over each other. Birkenmajer (1977, 1979, 1986, 1988) distinguished the deposits of the Branisko facies succession in the Pieniny tectonic unit, and the Czorsztyn, Czertezik, and Niedzica successions in the Subpieniny Unit (Fig. 4).

The lithostratigraphy of these successions was formalized by Birkenmajer (1977). In the central part of the PKB, the landscape gradually descends westward from the Małe Pieniny to the Spisz Pieniny. Elevation and relief of the PKB are dependent on the geological structure and the proportion of hard rocks. In the eastern mountainous part, there is a significant proportion of Jurassic and Lower Cretaceous limestone and siliceous rocks that are more resistant to erosion, while in the west the dominant rocks are soft Upper Cretaceous and Paleogene clastics.

This analysis covers the western part of the PKB in Poland, west of Białka River from Nowa Biała to the Stare Bystre area, where the width of the PKB is about 1.5 to 2 km. A characteristic feature is the presence of various lithological sequences of different ages. The structure refers to

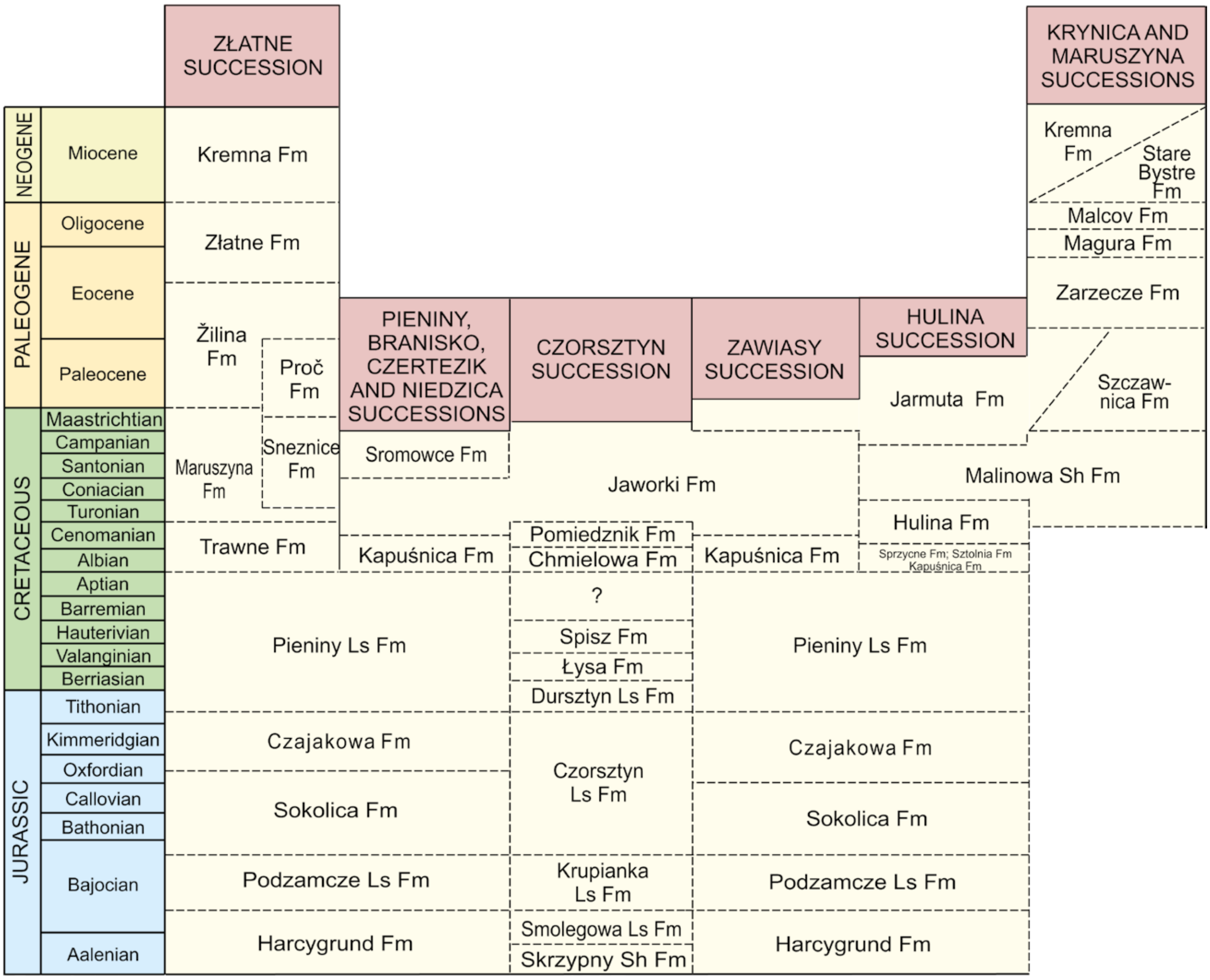

Fig. 4. Simplified lithostratigraphy of the Pieniny Klippen Belt sedimentary formations in Poland and the bordering part of Slovakia (after Golonka *et al*., 2019a, modified).

the mélange characteristics of the PKB, where limestone blocks occur as olistoliths in the surrounding flysch rocks that are different in nature (Fig. 2).

METHODS

The data come from several sources. The study included the analysis of publications and archival materials, a review of cartographic materials, geological and geophysical profiles, field work, including geological mapping and the documentation of outcrops, as well as stratigraphic and structural-tectonic studies and a reinterpretation of the Maruszyna IG-1 borehole profile. The information was integrated with data from gravity, seismic and geoelectric surveys (Golonka *et al*., 2018b, 2019a; Marzec *et al*., 2020, 2021; Porzucek *et al*., 2023; Bania and Mościcki, 2024; Bania *et al*., 2024; Cichostępski *et al*., 2024; Łój *et al*., 2025). The outline of the geological structure of the area presents a generalized stratigraphy of the PKB, with particular emphasis on the formations occurring in the study area, and a description of the tectonic structure, with reference to the sketch-map and geological cross-sections, contained in other papers in this special issue (Waśkowska and Golonka, 2024, 2025).

OUTLINE OF THE LITHOSTRATIGRAPHY OF THE PIENINY KLIPPEN BELT AGAINST THE BACKGROUND OF GEODYNAMIC HISTORY OF THE ALPINE TETHYS

The PKB deposits originated within the Alpine Tethys, in which the sedimentary areas of the Złatne and Magura basins were separated by the intra-basin uplift of the Czorsztyn Ridge during the Mesozoic times (e.g., Birkenmajer, 1977, 1986; Golonka and Sikora, 1981; Golonka and Rączkowski, 1984; Golonka and Krobicki, 2004; Krobicki and Wierzbowski, 2004; Krobicki *et al*., 2006; Oszczypko *et al*., 2010; Krobicki, 2018, 2023). The deposits of the Złatne Basin, as well as the Czorsztyn Ridge, mostly were included in the PKB structure, whereas the deposits of the Magura Basin only partially belong to the PKB, as they also form the Magura Nappe, which is a part of the Outer Carpathians (e.g., Golonka *et al*., 2006, 2008, 2018a, 2019a, b, 2022; Golonka and Waśkowska, 2014; Marzec *et al*., 2020, 2021; Szczęch and Cieszkowski, 2021; Kania and Szczęch, 2023; Szczęch and Waśkowska, 2023; Waśkowska and Szczęch, 2023). The stratigraphic inventory of the PKB is related to the sedimentary processes that took place in the Alpine Tethys. The Cretaceous and Paleogene flysch sequences (Figs 2, 4) were deposited mainly in the off-shelf zone of the southern margin of the Złatne Basin and within the Magura Basin. Carbonate sedimentation predominated on the Czorsztyn Ridge and its slopes in the Jurassic and Cretaceous, and the Pieniny, Branisko, Niedzica, Czertezik, and Czorsztyn successions, distinguished in Poland and adjacent countries, are included in this area (Birkenmajer, 1977, 1979, 2017; Wierzbowski *et al*., 1999, 2004, 2006, 2021; Golonka and Krobicki, 2004, 2023; Golonka *et al*., 2018a, b, 2022). The stratigraphic inventory of the PKB includes rocks, deposited from the Early Jurassic to the Neogene (Birkenmajer, 1977, 2017; Wierzbowski *et al*., 2006; Birkenmajer and Gedl, 2017; Golonka *et al*., 2018a; Watycha *et al*., 2019a; Watycha and Boratyn, 2022a; Fig. 4) and represent the different stages of the evolution of the Alpine Tethys.

They are known from outcrops, as well as from the deep borehole Maruszyna IG-1 (Chowaniec and Sokołowski, 1985; Chowaniec and Cieszkowski, 2009; Birkenmajer and Gedl, 2012; Golonka *et al*., 2019a; Marzec *et al*., 2020, 2021). Older than Jurassic and possibly Triassic dolomites have been described from the Maruszyna area by Watycha (2017), albeit without accompanying stratigraphic documentation. Their Triassic age was determined on the basis of correlation with formations in other areas of the PKB, i.e., the Haligovce area in Slovakia (Horwitz and Rabowski, 1930; Birkenmajer, 1953, 1959, 1977, 1986, 1988; Matějka, 1961; Potfaj, 2002).

A review of the stratigraphy of the area covers the entire spectrum of PKB deposits in the study area and includes formations distinguished in the structural units and also the rocks of olistoliths that occur within them, which are redeposited elements (cf. Waśkowska and Golonka, 2024, 2025).

The PKB facies reflect the geotectonic evolution of the Alpine Tethys. In the first stage, in the Early and Middle Jurassic, even before the formation of the Czorsztyn Ridge, the area was influenced by terrigenous and terrigenous-carbonate sedimentation taking place in oxygen-deficient environments (Tyszka, 1991, 1994; Górniak *et al*., 2008; Golonka *et al*., 2009). From the Pliensbachian, dark-coloured formations, i.e., dark grey limestones of the Szopka Formation, were formed, and in the latest Pliensbachian to the Aalenian, grey and spotted marls and marly limestones of the Krempachy Marl Formation were deposited. Subsequently, from the middle Pliensbachian to the late Pliensbachian, there was sedimentation of black, dark grey and greenish marly clays and shales of the Skrzypne Formation and dark shales of the Harcygrund Formation (Birkenmajer, 1977, 2017; Golonka *et al*., 2018a; Wierzbowski *et al*., 2006; Watycha *et al*., 2019a, b; Watycha and Boratyn, 2022a, b; Fig. 4). The Lower Jurassic deposits are assigned to the sedimentary sequences of the Pieniny, Branisko, Niedzica, Czertezik, and Czorsztyn successions (Birkenmajer, 1977, 2017; Golonka *et al*., 2018a; Watycha *et al*., 2019a; Watycha and Boratyn, 2022a), although due to the widespread uniformity of sedimentation, distinguishing separate successions before the formation of the Czorsztyn Ridge does not seem to be fully justified.

The sedimentation of dark-coloured formations in the Alpine Tethys ended at the beginning of the Middle Jurassic with the change in the configuration of the basin and the development of the Czorsztyn Ridge in its central part. During the uplift period, in the Bajocian, the isolated ridge structure witnessed the deposition of grey-blue, spotty marl limestones and marls of the Podzamcze Limestone Formation (Birkenmajer, 1977; Watycha and Boratyn, 2022a). The creation of the Czorsztyn Ridge resulted in the diversification of morphology, the formation of new sedimentary environments, and changes to intra-basin circulation. This affected the sedimentary regime in the basin in general, and in the Middle and Late Jurassic and Early Cretaceous, the Alpine Tethys was occupied by carbonate-siliceous sedimentation. Owing to the great diversity of facies at that time, sedimentary zones, characterized by peculiar depositional conditions, occurred on the ridge and in the areas immediately adjacent to it, with lithologies that correspond to particular successions. The formations in the highest areas of the Czorsztyn Ridge were included in the Czorsztyn Succession, while the formations of the slopes of the Czorsztyn Ridge and adjacent areas were included in the Pieniny, Branisko, Czertezik, and Niedzica successions (“successions” *sensu* Birkenmajer, 1977, 1986, with modifications by Wierzbowski *et al*., 2006, 2021). The relatively shallow-water sedimentation of the Czorsztyn Succession during the optimum development of the Czorsztyn Ridge, falling in the middle-upper Bajocian, was marked by the deposition of the white or whitish-grey organo-detrital limestones of the Smolegowa Formation. They are a type of crinoidal detrital limestone, locally enriched with f quartz grains, and crumbs of dolomite, limestone and shale. Above them, in the later Bajocian and earliest Bathonian, were deposited limestones of the Krupianka Formation, called red crinoidal limestone because of their characteristic reddish or reddish-grey coloration. In addition to numerous trochites, they contain admixtures of Jurassic and Triassic carbonate rocks and quartz (Birkenmajer, 1963, 1977, 2017). Subsequently, in the Bathonian of the central parts of the Czorsztyn Ridge, sedimentation of the Czorsztyn Limestone Formation – the common and typical Tethys Ammonitico rosso facies – began. Nodular red and pink limestones with cephalopod fossils were formed (Birkenmajer, 1963, 1977, 2017; Golonka *et al*., 2018a).

From the Bathonian, siliceous or carbonate-siliceous rocks were deposited in the central basinal areas and on the slopes of the ridge. Dark radiolarite cherts of the Sokolica Formation, thin-bedded crinoidal limestones with cherts intercalations and concretions of the Flaki Limestone Formation, as well as red and green radiolarites of the Czajakowa Formation were deposited. Radiolarites are found in the Złatne, Pieniny, Branisko, and Hulina successions in the eastern part of the PKB (Birkenmajer, 1977, 2017; Golonka and Sikora, 1981; Widz, 1991, 1992; Widz and De Wever, 1993; Watycha *et al*., 2019a; Watycha and Boratyn, 2022a) and outside the study area also in the Czertezik and Niedzica successions (Birkenmajer, 1977, 2017). Their thickness in the Pieniny and Branisko successions reaches tens of metres, and in the Złatne and Hulina successions, they are reduced to a few metres (Golonka and Sikora, 1981; Birkenmajer and Gedl, 2017; Watycha *et al*., 2019a; Watycha and Boratyn, 2022a).

In the Early Cretaceous, the sinking Czorsztyn Ridge was influenced by carbonate sedimentation (Aubrecht *et al*., 2006; Waśkowska and Golonka, 2024, 2025). Locally, it was already marked in the Tithonian by the deposition of the Dursztyn Formation, which consists of red and white limestones, white calpionellic limestones, Globochaete limestones, lumachellas, white crinoid limestones, detrital limestones and sedimentary breccias (Birkenmajer, 1977, 2017; Watycha and Boratyn, 2022a). During this time, the Rogoźnik Coquina was also formed, belonging to both the uppermost part of the Czorsztyn and the Dursztyn formations (Birkenmajer, 1977, 1979; Kutek and Wierzbowski, 1979; Krobicki, 1998; Krobicki and Golonka, 2012).

Pink, red, white and yellow organogenic limestones with brachiopods and crinoids, as well as the detrital limestones of the Łysa Formation, were formed in the Berriasian and Valanginian in the Czorsztyn Succession (Aubrecht *et al*., 2006; Birkenmajer, 1977, 1979, 2017). They are overlain by Valanginian–lower Hauterivian variegated, thin-bedded crinoidal limestones of the Spiš Formation (Krobicki and Wierzbowski, 1996; Watycha and Boratyn, 2022a).

From the Tithonian through the Early Cretaceous, carbonate-siliceous sedimentation of cherty limestones continued in the basinal and slope areas of the Alpine Tethys. White, creamy or grey limestones with intercalations of cherts (maiolica facies) of the Pieniny Limestone Formation were deposited. Their sedimentation continued into the Barremian (Birkenmajer, 1977) or into the early Albian (Golonka and Sikora, 1981; Watycha *et al*., 2019a, b; Watycha and Boratyn, 2022a). In the Branisko and Pieniny successions, they reach a thickness of several tens of metres, whereas in the Złatne and Hulina successions their thickness does not exceed 10 m (Birkenmajer, 1977, 2017; Golonka and Sikora, 1981; Birkenmajer and Gedl, 2017).

Towards the end of the Early Cretaceous, the sedimentation of cherty limestones transitioned to pelagic sedimentation, which resulted in the deposition of the carbonates of the Kapuśnica Formation on the slopes of the Czorsztyn Ridge in the Aptian and Albian, composed of dark grey siliceous shales, limestones and spotted marls (Birkenmajer, 1977, 2017). In the Albian, on the ridge, red and variegated nodular and marly limestones of the Chmielowa Formation were deposited. They were followed by the Albian and Cenomanian marly limestones with interbedded cherts of the Pomiedznik Formation (Birkenmajer, 1977, 2017; Watycha and Boratyn, 2022a).

Another change in the sedimentary regime is marked in the Cretaceous, when the Alpine Tethys entered the synorogenic stage. A phase of flysch sedimentation with a significant proportion of turbidites began. Geotectonic reorganization at the Early/Late Cretaceous and the stresses associated with it triggered gravitational flows that descended into the Złatne and Magura basins (Golonka *et al*., 2015, 2022). This resulted in the formation of flysch-type deposits, in the first phase dominated by marly and muddy variegated flysch (Trawne and Malinowa formations), while on the Czorsztyn Ridge, red, cherty and green marls and marly limestones of the Jaworki Formation were deposited during the Cenomanian–early Maastrichtian (Birkenmajer, 1977, 2017). The variegated turbidites were replaced at the end of the Cretaceous by a sandstone-shale flysch. In the Złatne Basin, turbidites of the Žilina Formation were deposited, passing upwards into the Paleogene mudstone-dominated flysch of the Złatne Formation. In the Magura Basin, the sandstone and sandstone-mudstone turbidites of the Jarmuta, Szczawnica, Zarzecze, Magura, and Malcov formations were formed. Sedimentation in the PKB area ended with the uniform deposits of the Kremna Formation

REMARKS ON THE CRETACEOUS-NEOGENE DEPOSITS OF THE ZŁATNE SUCCESSION

In the Albian–Cenomanian, flysch rocks of the Trawne Formation were deposited in the Złatne Basin (Sikora, 1962, 1971; Golonka, 1981; Golonka and Sikora, 1981; Golonka *et al*., 1981; Gasiński, 1983). These deposits were developed as fine-grained, thin- to medium-bedded sandstones, locally with conglomerate interbeds, overlain by calcareous grey and greenish mudstones. The Trawne Formation is best exposed in the Trawny Stream (Sikora, 1962, 1971, 1980; Gasiński, 1983) as well as in the Dursztyński Stream (= Kręty Stream). In the section of the Dursztyński Stream (Figs 5, 6), it consists of red, green and grey clayey or muddy marls, interbedded with thin-bedded sandstones, and generally has the character of marl-dominated variegated flysch.

Above the Cenomanian deposits of the Trawne Formation, the variegated shales, predominantly grey and greenish-grey with red intercalations occur. They contain packages of marly shales and rare very thin-bedded and thin-bedded sandstones; thicker sandstone beds and conglomerates also occur. These deposits have the character of shale-dominated flysch, the sedimentation of which began in the Turonian (the lower part contains assemblages of the Uvigerinammina jankoi Zone). They are the age equivalents of the Jaworki Marl Formation, deposited in the ridge area in the Cenomanian-Maastrichtian, and the Malinowa Shale Formation, which originated in the Turonian–Campanian in the Magura Basin on the opposite (northern) side of the ridge. Due to the differences in lithological development and distinct palaeogeographic position, it was tentatively proposed to establish an independent lithostratigraphic unit, provisionally named the Maruszyna Formation (Golonka *et al*., 2024). However, these deposits require more extensive studies in terms of lithological and biostratigraphic analyses to properly identify their lithostratigraphic range and their relationship to the Snežnica Formation, distinguished by Slovak geologists (Plašienka *et al*., 2021; Golonka *et al*., 2022), and to other possible equivalents. In terms of sedimentation, they are related to the underlying deposits of the Trawne Formation and are their natural continuation. Their outcrops are located in the Dursztyński (Kręty) and Trawny streams; analogous rocks are found in the Skrzypny Stream (= Mały Rogoźnik, Rogoźniczek) section (Fig. 7), which contains Maastrichtian marly shales with interbedded sandstones, mudstones, marls and conglomerates (Morgiel

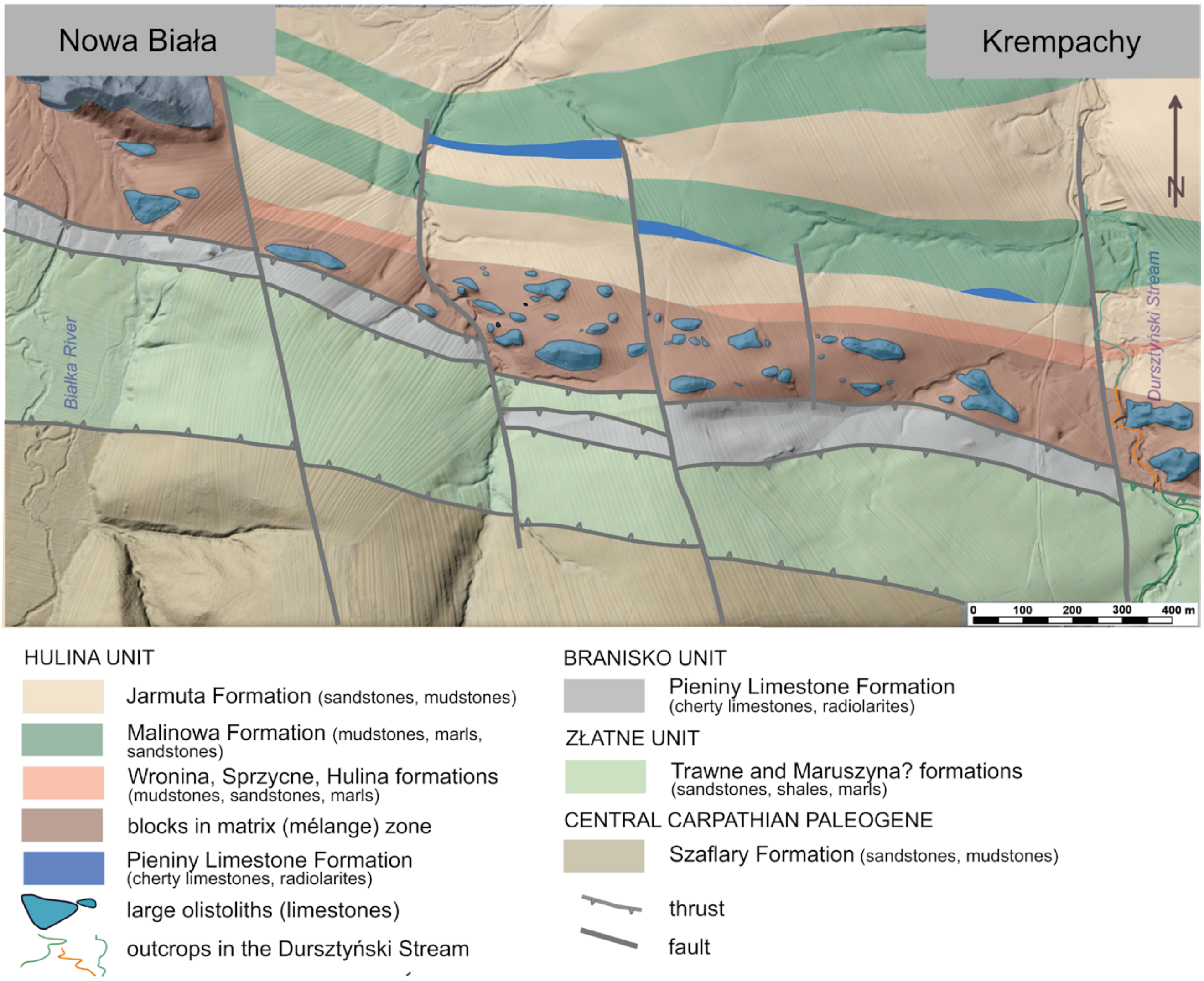

Fig. 5. Geological sketch of the Pieniny Klippen Belt in the western part of the Spisz Pieniny Mts. (after Cichostępski *et al.*, 2024, emended).

and Sikora, 1972, 1973; Birkenmajer and Jednorowska, 1983, 1987a, b; Kostka, 1993; Watycha *et al.*, 2019a, b).

The Upper Cretaceous deposits are overlain by Paleocene–Middle Eocene marls and marly shales (Morgiel and Sikora, 1972, 1973; Birkenmajer and Jednorowska, 1983; Watycha *et al.*, 2019a), which can be correlated with the Żylina and Złatne formations (Fig. 4; Golonka *et al.*, 2022). Because of their distinctive nature, the deposits in the Skrzypny Stream section have been distinguished as the Maruszyna Succession (Birkenmajer and Jednorowska, 1983; Kostka, 1993) but were previously included in the inventory of the Złatne Succession (Morgiel and Sikora, 1972, 1973). Inclusion in the Złatne Succession is also evidenced by the occurrence of the thinned cherty limestones of the Pieniny Limestone Formation (exposed below the bridge on the Szaflary – Maruszyna road in the Skrzypny Stream; Golonka and Sikora, 1981; Golonka, 2006). Alexandrowicz and Birkenmajer (1978) correlated deposits of the Skrzypny and Biały Dunajec sections with deposits of the Myjava Basin, while Sikora (1980) argued that the Myjava Basin and the Złatne Basin define the same sedimentary area.

REMARKS ON THE CRETACEOUS-NEOGENE DEPOSITS OF THE HULINA SUCCESSION

In the Hulina Succession of the Magura Basin, sedimentation of the Pieniny Limestone Formation and the Kapuśnica Formation was followed by the deposition of dark, anoxic Albian–Cenomanian turbidite shales of the Wronina Formation, developed as greenish and black shales with ferruginous concretions, and the Hulina Formation, which is composed of dark and greenish shales with lenses and interbeds of chert (Fig. 4; Birkenmajer, 1977, 1979). During this time, the dark flysch rocks of the Sztolnia Formation, which occur in the eastern part of the PKB outside of the study area, were also formed (Sikora, 1971; Oszczypko *et al.*, 2004, 2012). At the next stage, in the late Cenomanian and Campanian, there was deposition of red and variegated shales and marly shales, interbedded with fine-grained sandstones of the Malinowa Formation (Birkenmajer, 1977; Watycha and Boratyn, 2022a), followed by deposition of the Jarmuta Formation, which consists primarily

Fig. 6. Cretaceous Trawne Formation (Abian–Cenomanian) in the Dursztyński Stream. **A.** Grey sandstones and mudstones. **B.** Grey mudstones and sandstones. **C.** Deformed grey mudstones and sandstones. **D.** Red mudstone and marls.

of coarse-grained, medium- to fine-grained sandstones with intercalations of yellowish marly shales and with frequent conglomerate intercalations of Triassic, Jurassic and Cretaceous carbonate rocks of the PKB succession. It also contains packages of thin- to medium-bedded sandstones with shales and sedimentary mélanges, containing minor olistoliths and blocks (Watycha *et al*., 2019a; Watycha and Boratyn, 2022a). The age of these deposits is currently believed to be Middle Maastrichtian-Paleocene (Krobicki *et al*., 2006; Watycha and Boratyn, 2022a). The sedimentation of the Jarmuta Formation spread into the Krynica Zone, which laterally passes into the Szczawnica Formation. It was characterized by the deposition of thin- to medium-bedded sandstone and mudstone turbidites, which were formed in the more interior zones of the Magura Basin (Birkenmajer and Oszczypko, 1989; Ślączka *et al*., 2006). The Szczawnica Formation belongs to the so-called Ropianka facies, which developed regionally in the Magura Basin during the Late Cretaceous and Paleocene (Ślączka *et al*., 2006; Golonka and Waśkowska, 2014; Golonka *et al*., 2019b; Szczęch and Cieszkowski, 2021; Szczęch and Waśkowska, 2023). Flysch sedimentation continued into the Miocene, with the clastic deposits of the prism replaced by the deposits of the piggy-back basin. The youngest sediments of the Magura Basin in this area are Oligocene–Lower Miocene thin-bedded sandstone-mudstone turbidites of the Malcov Formation (Cieszkowski and Olszewska, 1986) and Miocene flysch of the Kremna and Stare Bystre formations (Cieszkowski, 1992; Oszczypko and Oszczypko-Clowes, 2010, 2014; Oszczypko *et al*., 2015; Kaczmarek *et al*., 2016).

In the study area, in the western part of the Spiš Pieniny Mountains (Fig. 5), mainly Cretaceous–Paleogene deposits of the Złatne and Hulina successions are exposed, and to a slightly lesser extent, deposits of the Branisko Succession occur. The Złatne Succession includes sedimentary series of the variegated flysch, while the Hulina Succession is represented by the Pieniny Limestone, Wronina, Hulina, Sprzycne, Malinowa, Jarmuta formations. The Malinowa and Jarmuta formations occupy the northern part of the study area and are also components of the matrix in the sedimentary mélange. The components of this mélange, found both in the matrix and in blocks (olistoliths), are

Fig. 7. Outcrops in the Skrzypny Stream. **A.** Pieniny Limestone Formation (condensed). **B–D.** Turonian variegated shale-dominated flysch.

also various Jurassic-Cretaceous rocks, associated with the depositional environment of the Czorsztyn Ridge. These include crinoidal limestones of the Smolegowa and Krupianka formations, the Czorsztyn Limestone Formation of the ammonitico rosso facies, the Łysa, Spisz, Chmielowa, Pomiedznik, and Dursztyn, as well as Jaworki, Wronina, Hulina, Sokolica, and Flaki formations. The outcrops of the Branisko Succession form a thin belt, in which there are mainly cherty limestones of the Pieniny Limestone Formation of the maiolica facies. To the west of the Białka River (Fig. 2), the Branisko Succession occurs; deposits of the Branisko and Pieniny successions are also found in sedimentary mélanges.

THE MARUSZYNA IG-1 BOREHOLE AND REMARKS ON THE CRETACEOUS DEPOSITS OF THE MARUSZYNA UNIT

The sequence of PKB tectonic units is observed in its deep structure and is distinguished in the profile of the Maruszyna IG-1 deep borehole, which was located in the Złatne Nappe area (Figs 2, 8). Some controversy of an interpretative nature concerns the identification of the lithostratigraphic units and successions, to which particular rock associations belong.

Deposits of the Złatne Nappe occur to a depth of 564 m. They consist of Upper Cretaceous flysch rocks of the Złatne Succession, mainly represented by sandstones, shales and marls, including grey shales, as well as grey and variegated marls. Sikora (1971) and Golonka and Sikora (1981) pointed out that it is the variegated flysch of the Złatne Basin, which is located in the overburden of the Trawne Formation. They refer to the PKB surface outcrops in the nearby the Trawne, Skrzypny and Dursztyński (Kręty) stream sections, west of the Białka River (see above). Birkenmajer and Gedl (2012) and Chowaniec and Sokołowski (1985, 1986), incorporated these deposits into the Sromowce and Jaworki formations as ridge successions.

At depths of 564 m to 960 m, there are Jurassic-Upper Cretaceous formations of the Pieniny Unit, probably of the Branisko Succession. The lithological inventory distinguishes spotty marls of the Kapuśnica Formation, cherty limestones of the maiolica facies of the Pieniny Limestone Formation, radiolarites (found in drill cuttings) and limestones and spotty marls of the Podzamcze Limestone Formation (Chowaniec and Sokolowski, 1985, 1986; Birkenmajer and Gedl, 2012).

Below, to a depth of 2,000 m, there is a mixture of diverse Jurassic and Cretaceous rocks (Chowaniec and Sokołowski, 1985, 1986; Birkenmajer and Gedl, 2012). Distinguished here are deposits of the Jarmuta, Pieniny,

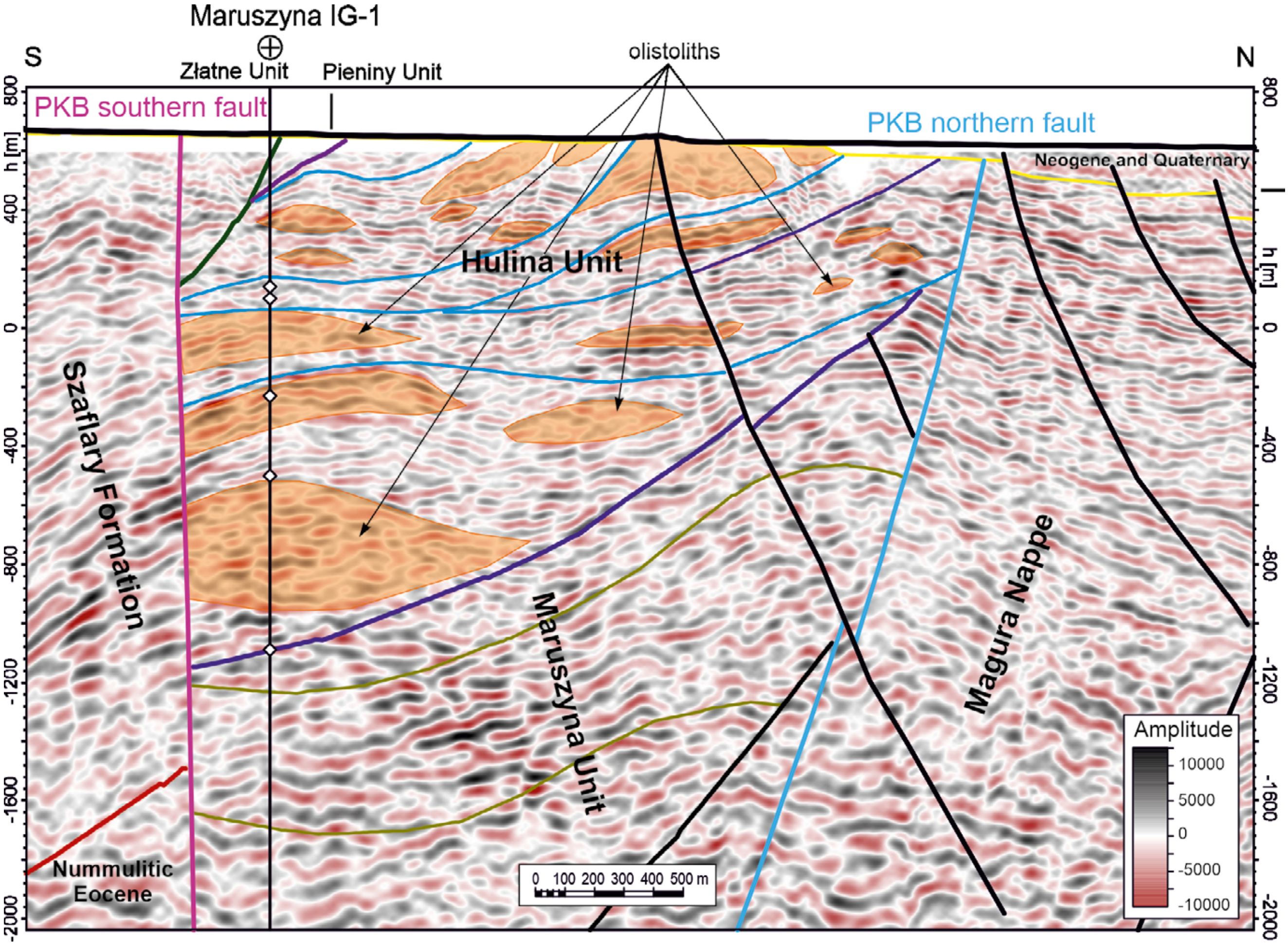

Fig. 8. Seismic profile, based on the processed seismic line 24-5-87K 1. The Maruszyna IG-1 borehole was projected on profile line (after Golonka *et al*., 2019b, modified).

Harcygrund, Podzamcze, Kapuśnica, Malinowa Sromowce, and Jaworki formations. For the most part, it is a sedimentary-tectonic mélange. In it, olistolithic blocks of Jurassic-Upper Cretaceous formations of the Branisko Succession are distinctive, including those from the Pieniny Limestone Formation, the Harcygrund Shale Formation, Sromowce Formation, the Podzamcze Limestone Formation, interbedded with the Jarmuta, Sromowce, and Jaworki formations, which constitute the matrix. This mélange has been incorporated into the Hulina Unit (cf. Golonka *et al*., 2018b, 2019a).

From 2,000 to 4,843 m, Upper Cretaceous flysch rocks, composed of sandstones, shales and marls, occur beneath the Hulina Nappe (Chowaniec and Sokołowski, 1985, 1986). Following the traditional division of the PKB into successions, Birkenmajer and Gedl (2012) assigned them to the Sromowce and the Jaworki Marl formations. However, owing to their stratigraphic position and lithologic characteristics, these deposits are closer to those of the adjacent Krynica Unit of the Magura Domain and related to the flysch Jarmuta, Malinowa and Szczawnica formations (Ślączka *et al*., 2006; Szczęch and Cieszkowski, 2021; Szczęch and Waśkowska, 2023). Apart from lithological similarities, they are characterized by a sizable thickness, which corresponds to the thickness of complexes observed in Magura Basin, not known from the Czorsztyn Ridge. The position of the unit, also important, is at the base of the overlying nappes, forming a sequence of successive units, containing the lithological inventory of PKB zones, located originally in the southern part of the Alpine Tethys. In terms of seismic imagery, these deposits have a similar structure to that of the Magura Nappe formations adjacent to the PKB and therefore were included in the separate Maruszyna Tectonic Unit (Figs 8, 9; Golonka *et al*., 2018b, 2019a; Marzec *et al*., 2020, 2021). The sequence of units in the Maruszyna IG-1 deep borehole corresponds to that observed in the western part of the Spisz Pieniny, where the Złatne Nappe overlaps the Pieniny Nappe, which in turn overlaps the Hulina Nappe. In the seismic imagery (Fig. 8), a separate Maruszyna Unit is clearly distinguished under the Hulina Unit (Golonka *et al*., 2019a; Marzec *et al*., 2020, 2021).

TECTONICS

The PKB is a narrow zone at the interface of the Central and Outer Carpathians. Its southern boundary in the study area is a subvertical fault, descending to the north (Golonka *et al*., 2018a, 2019a, b; Ludwiniak, 2018; cf. Waśkowska and Golonka, 2024); the northern boundary in the eastern part is covered by Neogene and Quaternary deposits.

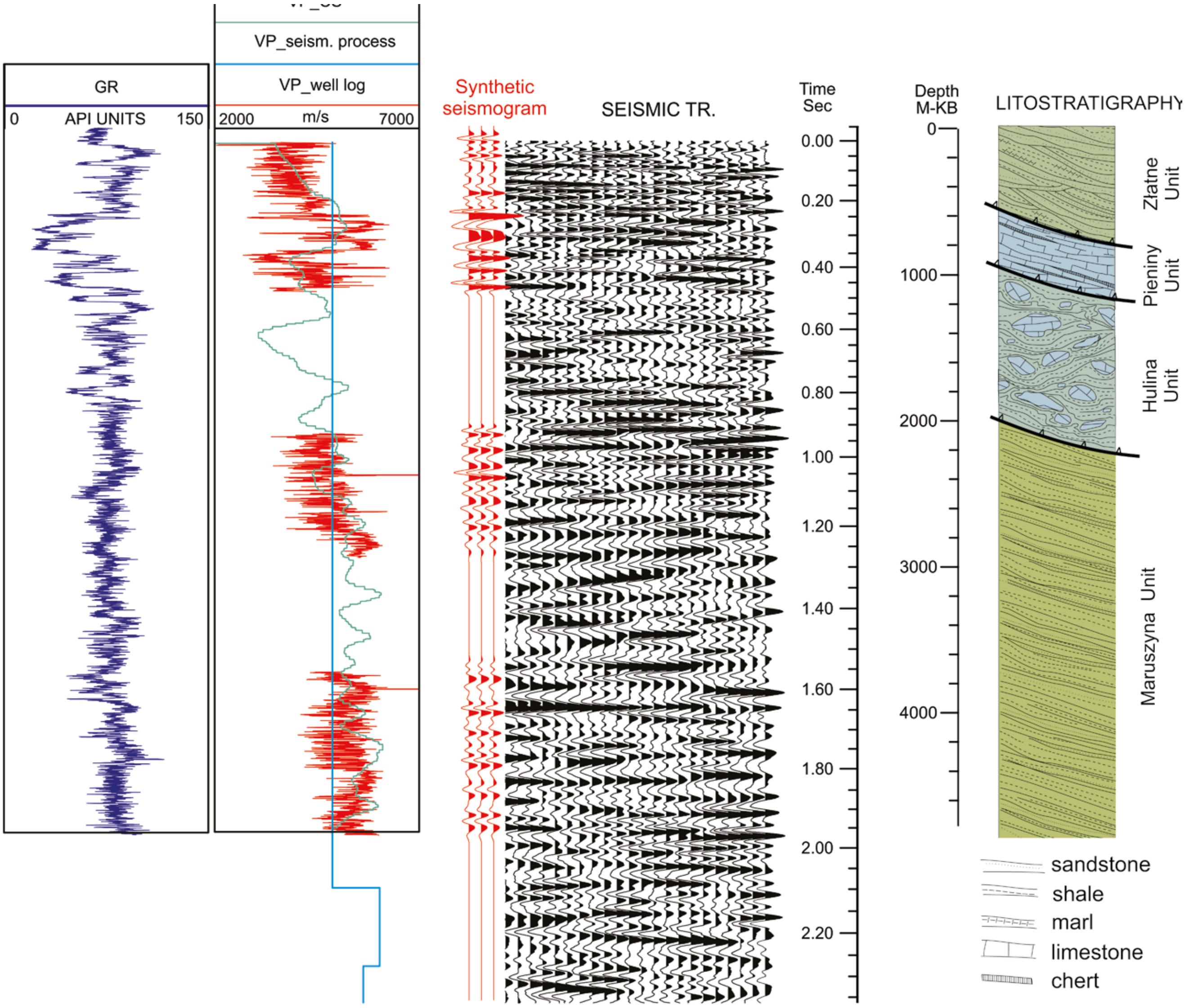

Fig. 9. Geophysical logs and simplified lithologies of the Maruszyna IG-1 borehole (after Golonka *et al*., 2019, modified). GR – gamma ray; VP_well log – acoustic log; VP_CS –interval velocities from check shot also used in migration velocity field calibration.

To the west of Białka River, four PKB nappes are exposed: the Złatne, Pieniny, Hulina, and Maruszyna nappes (Fig. 2). The southern Złatne Nappe overlaps the northern Hulina (Grajcarek) Nappe, and locally between them the Pieniny Nappe is exposed. The Maruszyna Nappe was encountered in the Maruszyna IG-1 borehole and in the area north of the Rogoźnik Klippen. Several secondary thrust sheets were distinguished in these units. These nappes are result of tectonics, caused by the collision of the prism with the Czorsztyn Ridge in the Late Cretaceous (Golonka *et al*., 2022).

In the study area, the Złatne Nappe is composed mainly of the Upper Cretaceous–Paleogene flysch deposits of the Trawne Formation and overlying it, the shaly flysch of the Žilina and Złatne formations. The Hulina Nappe, consists of two elements running parallel to the PKB boundaries: the outer belt, located on the north-western side and composed mainly of deposits of the Jarmuta Formation, and the inner belt, which is a mélange. In the mélange, there are flysch rocks of the Jarmuta and Malinowa formations, which are mixed with blocks of the Czorsztyn Succession of the olistolithic origin (Figs 3, 5). The largest olistoliths form the klippen of Stary Bystre, Rogoźnik, Szaflary (limestone quarry), Cisowa and Obłazowa (Fig. 2). The Pieniny Nappe is exposed only locally, and it forms a thin, in places absent belt of outcrops. This nappe comprises Jurassic-Lower Cretaceous rocks, mainly of the Pieniny Limestone Formation of the Branisko Succession. This nappe forms, *inter alia*, Ranisberg Mountain (Raniszberg) in Szaflary.

DISCUSSION

Geological analyses of the PKB have been carried out for more than two hundred years, since the time of Stanislaw Staszic (1815), Viennese geologists (e.g., Neumayr, 1871; Uhlig, 1890), and Horwitz and Birkenmajer (Krobicki, 2022) and have contributed to the recognition of its structure and interpretation of basin and its tectonic evolution (Birkenmajer, 2017; Golonka *et al*., 2018a, 2022; Plašienka, 2012, 2018); incoming new data allow the structure and evolution to be described in more detail and further modified. The lithostratigraphy of the Jurassic and Cretaceous deposits of the PKB presented above was developed by Birkenmajer (1977), with later additions (Birkenmajer, 2017). It remains in common use for the Polish part of the PKB and is also applied to the Slovak part (Plašienka, 2018). The complicated structure of the PKB is referred to as a mélange and is the result of sedimentary, and tectonic processes. The degree of its complexity means that some questions about the structure and lithostratigraphy are still being debated. Therefore, there are some difficulties in proper recognition of the formations and assigning them to relevant units. While the lithostratigraphy of the northern basin and the central parts comprising the Czorsztyn Ridge areas are recognized to a fairly good degree, the areas of the southern Złatne Basin, especially the early synorogenic sediments, are less well recognized. This sedimentation continued there from the Albian. In the first phase, up to the Cenomanian, the variegated marl-sandstone flysch included in the Trawne Formation was deposited. Sedimentation of the variegated deposits continued until the end of the Cretaceous. At the beginning of the Paleogene, these were replaced by flysch, with a significant proportion of sandstones and exotic material of the Żylina and Złatne formations (Figs 4, 6, 7). The variegated flysch was deposited from the Turonian; the foraminiferal Uvigerinammina jankoi Zone was determined. Foraminiferal assemblages in their upper part contain the upper Maastrichtian index taxa *Abathomphalus mayaroensis* (Bolli) (Birkenmajer and Jednorowska, 1983; Watycha *et al*., 2019a). However, there is a lack of more precise data on the continuity of this sedimentation. Similar deposits have been found in the Trawne Stream and Biały Dunajec River sections (Alexandrowicz and Birkenmajer, 1978; Sikora, 1980). Corresponding to these are the deposits of the variegated flysch in the Dursztyński Potok (Kręty) section, east of Białka River, and in the Maruszyna IG-1 borehole. Golonka and Sikora (1981) included these deposits in the Złatne Succession.

Several stratigraphic issues still await clarification, especially concerning the Cretaceous and Neogene basinal successions (Jurewicz, 2018; Jurewicz and Segit, 2018; Plašienka, 2018). One of them is the age of the so-called black flysch formations within the Hulina Succession (Grajcarek). These black turbidite sediments, belonging to the Albian-Cenomanian deposits of the Wronina, Sztolnia, and Hulina successions, are located between the Kapuśnica and Malinowa formations in the Małe Pieniny (Oszczypko and Oszczypko-Clowes, 2010; Oszczypko *et al*., 2004, 2010, 2015). Similar sediments have been described as the Toarcian-Bajocian Szlachtowa Formation (cf. Birkenmajer and Gedl, 2017 and references therein), being the oldest sediments of the Hulina Succession (Grajcarek). The present authors assume that the black flysch was deposited during both the Jurassic and Cretaceous periods.

The names of palaeogeographic and tectonic units were used according to the principle of priority. The name "Złatne (Ultrapieniny) Succession" to describe the basin facies of the southern part of Alpine Tethys was used first by Sikora (1971), later the term "Maruszyna Succession" was introduced (e.g., Birkenmajer and Jednorowska, 1983; Kostka, 1993; Birkenmajer, 2017). The Slovak equivalent of Złatne (Pieniny) is "Vahicum" and "Oravicum", terms later introduced by Maheľ (1981). Similarly, according to the principle of priority, the term 'Hulina Succession (Unit)' takes precedence over the term 'Grajcarek Succession (Unit)', which was introduced later. The Slovak equivalent of the Hulina (Grajcarek) Succession is the Šariš Succession (Jurewicz, 2018; Plašienka, 2018). Ridge successions have been defined and named by Birkenmajer (1977, 1986, 2017). The scheme of the tectonic structure of the PKB has been supplemented by the Maruszyna Unit, associated with the basinal Magura Zone, with an Upper Cretaceous sedimentary profile correlated with the Krynica Zone (Golonka *et al*., 2018b, 2019a, 2022; Marzec *et al*., 2020, 2021). The lithological inventory of this unit corresponds to the Upper Cretaceous deposits of the Jarmuta, Malinowa and Szczawnica formations. It is distinguished in the seismic survey and marked in the borehole record of Maruszyna IG-1 by a sedimentary profile with a thickness of more than 2,800 m (Fig. 9).

CONCLUSIONS

The Polish part of the Pieniny Klippen Belt represents a complex geological structure at the contact between the Central Carpathian and North European plates. It comprises rocks deposited from Jurassic to Miocene, reflecting successive phases in the Alpine Tethys during formation of the Pieniny Klippen Belt. In the initial phases of the synrift stage, clastic-carbonate sedimentation predominated. With the origin of the Czorsztyn Ridge and modification of the basin relief, this transformed into siliceous-calcareous sedimentation. From the Late Cretaceous, in the synorogenic stage of basin development, it was successively replaced by flysch sedimentation, associated with the progradation of the prism and the development of a piggy-back basin. This progradation is marked by the lateral distribution of facies in the Pieniny Klippen Belt successions, with occurrences of variegated deposits and sandy flysch deposits, first in the southern Złatne part, and next in the northern Magura part.

The Pieniny Klippen Belt nappe structure is made up of a system of units with a preserved sequence, corresponding to the order of occurrence in the sedimentary areas, where the uppermost Złatne Nappe consists of deposits from the southern part of the basin. Next there is a unit, corresponding to the ridge zones, and below it the succeeding Hulina and Maruszyna units correspond to the northern part of the basin.

Acknowledgements

This research was financially supported by the Polish National Science Centre Grant NCN – 2019/35/B/ST10/00241 and the AGH University of Krakow Subsidy Funds no. 16.16.140.315. Our paper was greatly improved, thanks to reviewers, Oleh Hnylko, Mateusz Szczęch and editors, Alfred Uchman, Ewa Malata and Frank Simpson, to whom we would like to extend our thanks.

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