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MÉLANGES AGAINST THE BACKGROUND OF THE GEODYNAMIC DEVELOPMENT OF THE PIENINY KLIPPEN BELT

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Abstract: Both tectonic and sedimentary processes (undersea mass movements) contributed to the formation of mélanges in the Pieniny Klippen Belt (PKB). The name Klippen Belt comes from the presence of "Klippen" (German for "cliffs") in this structure, i.e., elements that contrast in elevation with the surroundings. The "klippen" that are harder and more resistant to erosion are located among less resistant clastic formations, i.e., sandstones, mudstones, and marls. These klippen are composed of limestone and siliceous rocks, deposited on the ridge and slope parts of the PKB basins. In contrast, the flysch complexes, containing sandstones, mudstones, and marls, were deposited in the deeper parts of these basins. Some of the klippen are olistoliths, i.e., homogeneous or complex rock blocks of various sizes that were moved by gravity to the deeper zones of flysch basins. Other klippen entered the flysch formations as a result of tectonic deformations that took place during orogenic movements. Collisions and relative shifting of lithospheric plates resulted in the formation of the structure of the PKB, the western segment of which takes the form of a flower structure, bounded on both sides by deep faults. After uplift, the PKB was subjected to erosion processes, which led to the removal of the less durable complexes to reveal the shallower limestone blocks, which today form the klippen, clearly visible in the landscape.

Key words: Olistolith, Carpathians, Alpine Tethys, regional geology, plate tectonics, palaeogeography.

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INTRODUCTION

"Mélange" is a French word, meaning "mixture". Greenly (1919) introduced it into geology to describe chaotic rock formations. The term was characterized and popularized in the 1960s by Hsü (1968). Mélanges describe accumulations of rock fragments that differ in lithology, age, and mode of origin (Festa *et al*., 2012, 2019, 2020). Mélanges have various forms, but in general they consist of varying sizes of clasts, including large clasts measuring ten of meters and hundreds of meters. Usually, mélanges are characterized by a lack of visible order in their internal structure, and they are commonly called chaotic deposits. Their internal structure is disordered and deformational, with varying degrees of continuous and discontinuous types of deformation.

This structure is a result of mélange formation, which involves rock fragmentation and displacement of the debris (e.g., Abbate *et al*., 1970; Lucente and Pini, 2003; Neuendorf *et al*., 2005; Cieszkowski *et al*., 2012; Festa *et al*., 2012; Golonka *et al*., 2015). Many geological processes generate mélanges, including tectonics, mass transportation, diapir formation and fluid extrusion, glaciotectonics, and gas and hydrate generation (e.g., Hsü, 1968, 1974; Abbate *et al*., 1970; Elter and Trevisan, 1973; Naylor, 1981; Pini, 1999; Trümpy, 2006; Camerlenghi and Pini, 2009; Cieszkowski *et al*., 2009, 2012; Festa *et al*., 2012, 2019, 2020). The widespread occurrence of these processes causes mélanges to be a common component of the Earth, particularly in orogens. They are also an important component of the Carpathians (e.g., Nowak, 1964; Unrug, 1968; Słomka, 1986, 2001; Malik and Olszewska, 1984; Cieszkowski *et al*., 2009, 2012, 2017; Ślączka *et al*., 2012; Waśkowska and Cieszkowski, 2014; Golonka *et al*., 2015, 2022; Hnylko and Hnylko, 2016, 2019; Strzeboński *et al*., 2017; Bubík *et al*., 2020; Siemińska *et al*., 2020; Hnylko *et al*., 2021; Woyda *et al*., 2023). The Pieniny Klippen Belt (PKB) occupies a special position in the Carpathians because of its comparatively high proportion of mélanges.

GEOLOGICAL SETTING

The Carpathians, which stretch from the Vienna Basin to the Iron Gate on the Danube, form an orogenic arc over 1,300 km in length (Fig. 1). To the west, they border the Alps, while to the east, they connect with the Balkans (Książkiewicz, 1977; Oszczypko, 2004, 2006; Golonka *et al*., 2019a, b, 2021 and references therein). In terms of longitudinal division, the Carpathians are divided into the Western, Eastern and Southern Carpathians. The Western Carpathians encompass the orogenic area from the western end of the arc and extend eastward through the territory of the Czech Republic, Slovakia, and Poland to the Polish-Ukrainian border region (Hnylko and Hnylko, 2016), where the boundary is set at the Uzhok Pass, in the Bieszczady Mountains (Golonka *et al*., 2019b).

The Western Carpathians consist of the Inner and Outer Western Carpathians (Książkiewicz, 1977; Biely, 1989; Bezák *et al*., 2004; Ślączka *et al*., 2006; Golonka *et al*., 2019a, b, 2021 and references therein; Figs 1, 2). The Inner Carpathians are located in the south and are the older part of the range. They are an Alpine nappe system, which originated from the Cretaceous to the Neogene. The more northerly Outer Western Carpathians are composed of a series of nappes, formed in the Neogene (e.g., Książkiewicz, 1977; Ślączka *et al*., 2006; Golonka, 2011; Golonka *et al*., 2019a). Along the boundary of the Inner and Outer Western Carpathians is the narrow and highly elongated zone of the Pieniny Klippen Belt, which extends for a distance of about 600 km from near Vienna to Romania (Fig. 1).

The PKB consists of lithological elements of varying age and characteristics (e.g., Birkenmajer, 1977, 1983, 1986; Golonka and Krobicki, 2004; Wierzbowski *et al*., 2006, 2009, 2021; Golonka *et al*., 2015, 2018a, b; 2022; Jurewicz, 2018). Its complex structure refers to a mélange, in which it is difficult to distinguish individual tectonic units, and this sets the PKB apart from other structural units of the Carpathians. This complex structure also is reflected in the landscape. It is marked by significant morphological diversity and the irregular distribution of limestone klippen along the PKB (e.g., Andrusov, 1965; Birkenmajer, 1977, 1986, 1988; 2017; Mišík, 1994; Wierzbowski *et al*., 2006, 2009; Plašienka *et al*., 2018a, 2020; Cichostępski *et al*., 2024; Łój *et al*., 2024). This feature is distinctive for the PKB. It is highlighted in its name, where the term 'Klippen Belt' is combined with the geographical identifier "Pieniny".

The lithological inventory of the PKB includes mostly marine deposits that originated from the Jurassic to the Neogene within the Alpine Tethys (Fig. 3; e.g., Andrusov *et al*., 1965; Birkenmajer, 1977, 2017; Wierzbowski *et al*., 2006; Birkenmajer and Gedl, 2017; Golonka *et al*., 2018a; Watycha *et al*., 2019a, b; Watycha and Boratyn, 2022a, b and references therein). These deposits are characterized by a high facies and lithological diversity, which has resulted from the wide spectrum of sedimentary environments, formed during the evolution of this realm.

From the Pliensbachian to the Bajocian, the deposition of dark marl-limestone sediments predominated. The Szopka, Krempachy, Skrzypne, and Harcygund formations originated during these times (Birkenmajer, 1977, 2017; Tyszka, 1991, 1994; Wierzbowski *et al*., 2006; Górniak *et al*., 2008;

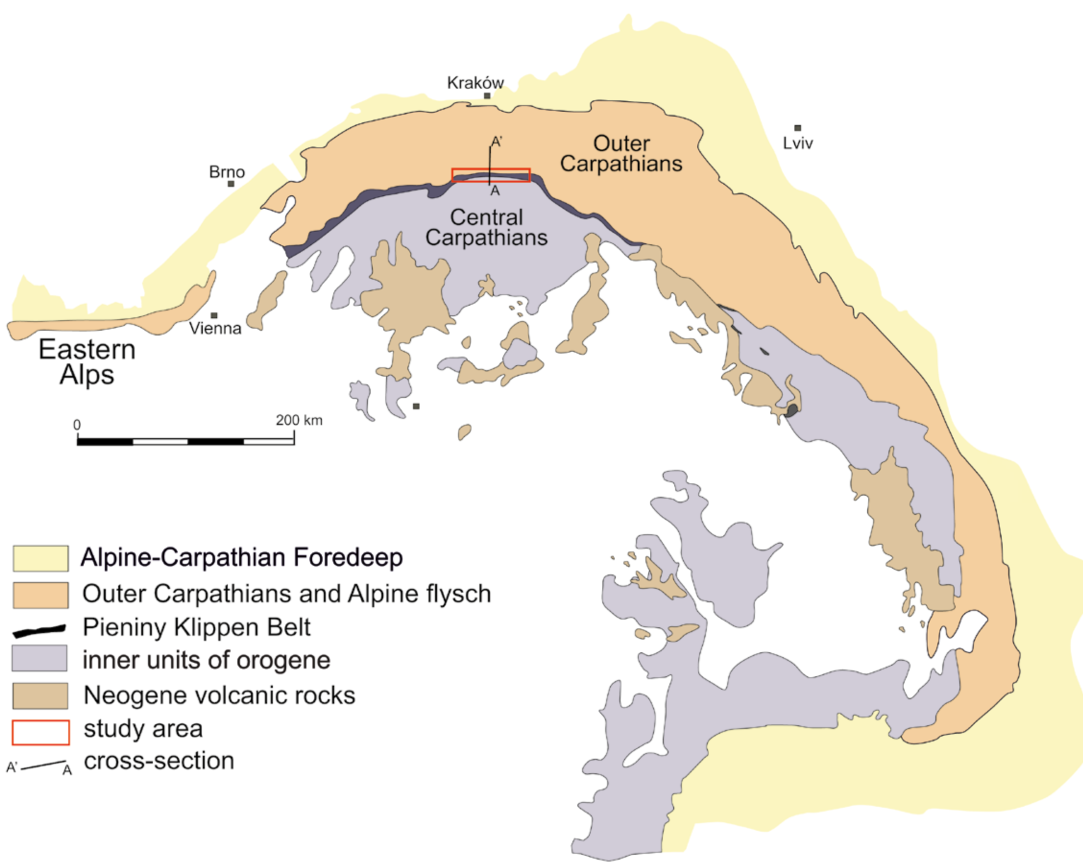

Fig. 1. Pieniny Klippen Belt in the Carpathians (after Kováč *et al*., 1998, modified).

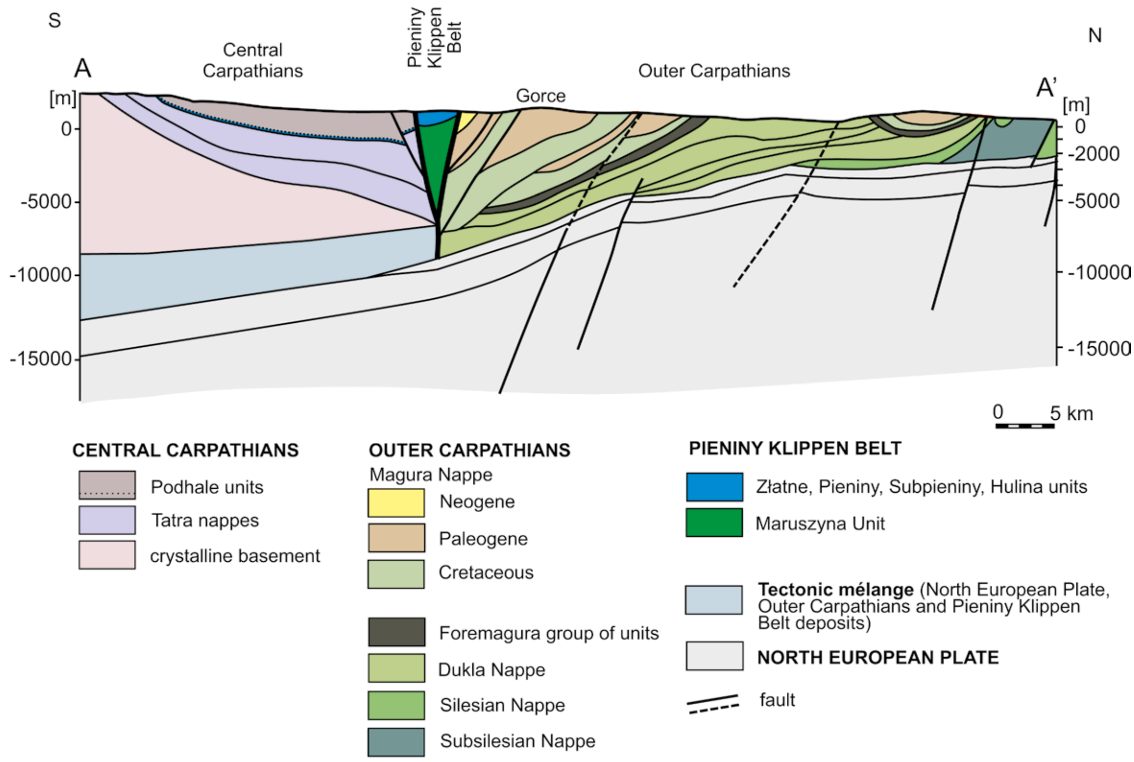

Fig. 2. Cross-section through the structure of the Carpathians in the Bukowina–Gorce–Wiśniowa area (for cross-section position see Figure 1; after Golonka *et al.*, 2019a, modified).

Golonka *et al.*, 2009; 2018a; Watycha *et al.*, 2019a, b; Watycha and Boratyn, 2022a, b). Then, during the Middle Jurassic, a significant facies differentiation occurred. This was the result of the geotectonic reorganization of the Alpine Tethys, marked by the uplift of the Czorsztyn Ridge in the central part of this realm. This ridge separated the southern (Złatne Basin) and northern (Magura Basin) areas. This reorganization led to modifications in the basin morphology and the formation of areas with different sedimentation conditions, both shallow and deep-water. Therefore, in the Alpine Tethys, a few successions are distinguished according to the specific zones, to which they correspond. The Czorsztyn succession covers the top parts of the ridge, the Niedzica and Czertezik successions include the upper slope areas, while the lower slope and adjacent areas belong to the Branisko and Pieniny successions. The Hulina (Grajcarek) succession originated in the northern (Magura) basinal area. The southern basinal area is characterized by the Złatne succession (e.g., Birkenmajer, 1977, 1986; Golonka and Sikora, 1981; Krobicki and Wierzbowski, 2004; Krobicki *et al.*, 2006, 2010 and references therein; Krobicki, 2018, 2023). The upper ridge areas were covered by carbonate sediments, while on the lower slopes and in the surrounding areas, carbonate-siliceous sedimentation occurred. In the Jurassic, the Smolegowa, Krupianka, Niedzica, Dursztyn and Czorsztyn formations were deposited on the upper slope, and Flaki, Sokolica and Czajakowa formations in the deeper areas.

In the Cretaceous, the carbonate and carbonate-siliceous rocks of the Pieniny, Kapuśnica and Jaworki formations were deposited in the slope areas, while mostly carbonate deposits of the Łysa, Spisz, Chmielowa, and Pomiedznik formations originated on the ridge (Birkenmajer, 1963, 1977, 2017; Golonka and Sikora, 1981; Widz, 1991, 1992; Widz and De Wever, 1993; Krobicki and Wierzbowski, 1996; Aubrecht *et al.*, 2006; Birkenmajer and Gedl, 2017; Golonka *et al.*, 2018a; Watycha *et al.*, 2019a, b; Watycha and Boratyn, 2022a, b).

During the Albian–Late Cretaceous, the deposition of clastic sediments from gravity-driven clastic flows began in the Alpine Tethys. Turbidites were generated, with deposition initially occurring in the southern part of the Alpine Tethys (Złatne Basin), and later, in the Late Cretaceous and Paleogene, also in its northern (Magura Basin) part (Sikora, 1962, 1971; Birkenmajer, 1977, 2017; Golonka, 1981; Golonka and Sikora, 1981; Gasiński, 1983; Cieszkowski and Olszewska, 1986; Birkenmajer and Oszczypko, 1989; Ślączka *et al.*, 2006; Oszczypko and Oszczypko-Clowes, 2010, 2014; Golonka *et al.*, 2015, 2022; Oszczypko *et al.*, 2015; Kaczmarek *et al.*, 2016). In the Złatne Basin, clastic sedimentation started with the Albian Trawne Formation, followed by the Upper Cretaceous Maruszyna, Sromowce, and Snežnica formations, the Paleogene Žilina and Złatne, and the Neogene Kremna formations. In the Magura Basin, this type of deposit began with the Upper Cretaceous Malinowa, and Cretaceous–Paleocene Jarmuta and Szczawnica formations, followed by the younger Zarzecze, Magura, Maľcov, Stare Bystre, and Kremna formations (Birkenmajer, 1977, 2017; Cieszkowski and Olszewska, 1986; Birkenmajer and Oszczypko, 1989; Oszczypko *et al.*, 2015; Kaczmarek *et al.*, 2016; Golonka *et al.*, 2018a, 2022; Madzin *et al.*, 2019). Clastic sedimentation continued until the Neogene, until the closure of the Alpine Tethys, and the uplift of the mountain range in the Miocene.

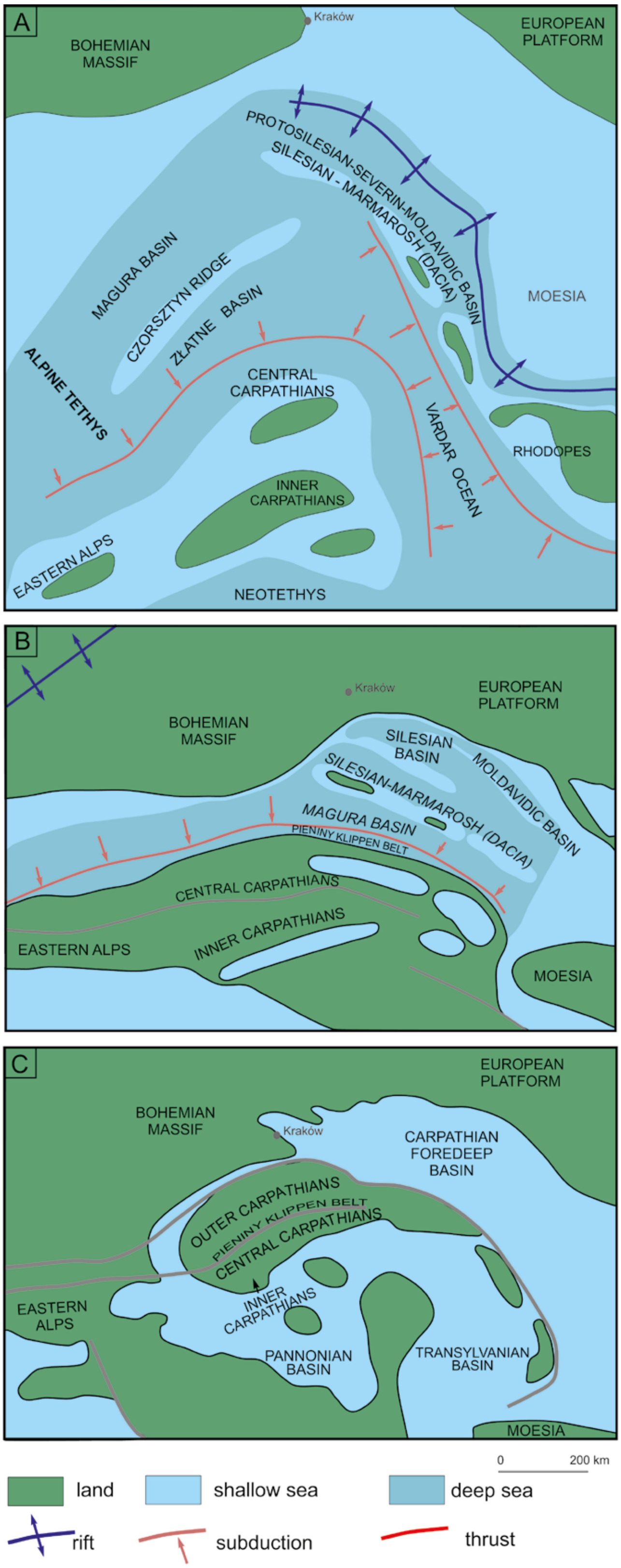

Fig. 3. Geotectonic evolution of the Alpine Tethys and adjacent regions (after Golonka *et al.,* 2021, modified). **A.** Tithonian–Berriasian (140 Ma). **B.** Eocene. (45 Ma). **C.** Miocene (14 Ma).

DATA SOURCES

The geological, geomorphological, and stratigraphic field work was carried out, and supplemented by studies of the published data and archival materials, including geological and geophysical maps and profiles. The field geological works included mapping as well as sedimentological documentation. Lithostratigraphic and biostratigraphic studies were based on fieldwork and laboratory analysis, which included palaeontological, petrographic, geochemical and mineralogical studies. Special attention was given to the location of olistoliths and olistostromes.

The geophysical surveys complemented the geological observations. These surveys included seismic refraction tomography (SRT), gravity and geoelectrical mapping of mélanges (Porzucek *et al*., 2023; Bania *et al*., 2024; Cichostępski *et al*., 2024). The results of previously made deep seismic reflection surveys were also utilized (Golonka *et al*., 2019b; Marzec *et al*., 2020, 2021). The construction of palaeogeographic maps utilized computer software PLATES UT Austin and GPLATES. Integration of all the methods mentioned was used to reconstruct the sedimentary processes, stratigraphy framework, palaeogeography and tectonic evolution of the PKB.

SEDIMENTARY MÉLANGES IN THE PIENINY KLIPPEN BELT IN POLAND AND THE ADJACENT PART OF SLOVAKIA

The sedimentary mélanges that originated within the Alpine Tethys form two belts. Olistostromes, formed along southern margins of the Złatne Basin, occur in the southern part of the Złatne Unit (Figs 3–5) and are well exposed in the vicinity of Haligovce village in Slovakia. The blocks of the Triassic, Cretaceous, Paleocene, and Eocene carbonate-siliceous succession originated on the Central Carpathian Plate and were redeposited into the turbiditic Upper Cretaceous Snežnica Formation (Horwitz and Rabowski, 1930; Birkenmajer, 1953, 1959, 1977, 1986, 1988; Matějka, 1961; Potfaj, 2002; Golonka *et al*., 2015). The Paleocene Kambühel-type limestones (Fig. 5C), representing reef facies of coral-algal type, and Eocene nummulitic limestones (Fig. 5D), found among the Paleocene–Eocene flysch deposits of the Žilina Formation (Potfaj, 2002; Cieszkowski *et al*., 2009; Golonka *et al*., 2015), are evidence of later mass movements. The olistostrome mélanges, connected with the southern Złatne Basin, contain clasts of hard rocks as well as large amounts of softer rock associations, particularly marls with numerous clasts of the Upper Cretaceous Jaworki Formation, widely distributed in the Late Cretaceous in central part of the Alpine Tethys (Golonka *et al*., 2015, 2022).

The second belt contains mélanges, deposited along the southern margin of the Magura Basin, which originated on the northern slopes of the Czorsztyn Ridge (Figs 3, 4). These mélanges occur in the Hulina Unit within the flysch rocks of the Upper Cretaceous–Lower Eocene Jarmuta and Szczawnica formations, composed of sandstone and sandstone-shale (marl or mudstone) turbidites (Chrustek *et al*.,

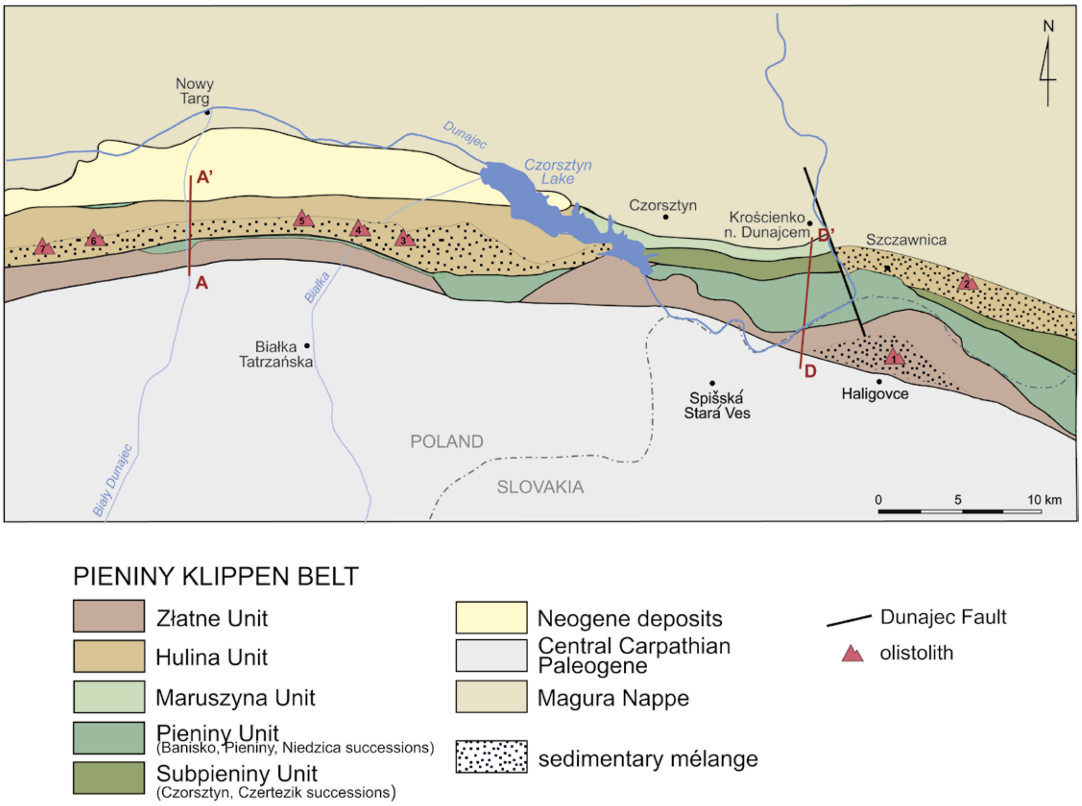

Fig. 4. Tectonic sketch of the Pieniny Klippen Belt in Poland and adjacent part of Slovakia with the location of selected olistoliths and olistostromes (after Cichostepski *et al*., 2024, supplemented). 1 – Haligovce, 2 – Homole-Biała Woda, 3 – Korowa Skała and Lorencowe Skałki, 4 – Obłazowa and Kramnica, 5 – Cisowa Skała, 6 – Rogoźnik, 7 – Stare Bystre.

2005; Cieszkowski *et al*., 2009; Szczęch and Cieszkowski, 2021; Szczęch and Waśkowska, 2023). They contain material of varying competence, including both rigid limestone blocks and more deformable mudstone-marl packages. One of the largest olistoliths is the olistoplaque, known as the Homole-Biała Woda Block, located in Jaworki, representing the Jurassic–Cretaceous shallow-water Czorsztyn succession (Fig. 5A; Birkenmajer, 1959, 2017; Wierzbowski *et al*., 2006; Cieszkowski *et al*., 2009; Golonka *et al*., 2015, 2018a). A spectacular olistolith is a block of volcanic rocks of Cretaceous olivine basalt (Fig. 5B), located within the clastic Upper Cretaceous–Paleocene Jarmuta Formation in Jaworki (Golonka and Rączkowski, 1984; Birkenmajer and Lorenc, 2008; Oszczypko *et al*., 2012; Golonka *et al*., 2015).

In the PKB, in the Spiskie Pieniny Mts. region, several olistoliths form "klippes" containing rocks of the Czorsztyn succession, surrounded by a matrix representing mainly the Upper Cretaceous Jarmuta, Jaworki, and Malinowa formations. The more competent rocks of the Obłazowa, Kramnica, Cisowa Skała, and Lorencowe Skałki represent the most numerous klippes (Bartuś *et al*., 2012). West of Bialy Dunajec River, the Rogoźnik coquina (Fig. 5E), belonging to both the uppermost part of the Czorsztyn Limestone Formation and the Dursztyn Limestone Formation of the Czorsztyn Succession, represents an olistolith, surrounded by a matrix that is well exposed in the nearby Trawne Stream (Golonka and Sikora, 1981). The Stare Bystre olistolith (Fig. 5F) contains rocks of the Branisko Succession, surrounded by a matrix, represented mainly by the Jarmuta Formation.

DEVELOPMENT OF THE OF PIENINY KLIPPEN BELT MÉLANGES IN THE FRAMEWORK OF REGIONAL PLATE TECTONICS

The Carpathians are the final structure that formed as a result of the evolution of the western Tethys. The origin of the PKB is connected with geological processes that were responsible for the formation and functioning of the sedimentary basins, followed by their closuring and folding, which lasted from the Jurassic to the Miocene. Within the evolution of the PKB, a stage of expansion related to rifting processes is distinguished, next to the closure of the basin, associated with subduction and subsequent folding and uplift (Birkenmajer, 1983, 1986, 2017; Golonka *et al*., 2019a, b, 2021). The stages of development of the PKB are connected with the processes that generated mélanges.

Extension (synrift and postrift) phase (Opening and expansion of marine basin)

The basin area of the Outer Carpathians was formed in the Jurassic. It consisted of two palaeogeographic units – the Alpine Tethys and the Proto-Silesian Basin (Fig. 3A). The Alpine Tethys was an extension of the Central Atlantic system (Golonka *et al*., 2005, 2006, 2018a, b, 2019a, b, 2021, 2022; Waśkowska *et al*., 2014), which was bounded from the northeastern site by the Silesian Ridge (e.g., Unrug, 1968; Książkiewicz, 1977; Golonka *et al*., 2013, 2019a, b,

Fig. 5. Selected olistoliths in the Pieniny Klippen Belt in Poland and adjacent part of Slovakia. **A.** Homole–Biała Woda block; Jaworki-Biała Woda, Małe Pieniny Mts. **B.** Cretaceous basalt (olistolith); Jaworki, Biała Woda, Małe Pieniny Mts. **C.** Haligovce Klippen olistoliths; Paleocene coral-algal reefal Kambühel Limestone in the foreground, Triassic–Cretaceous limestones in the background; Haligovce, Małe Pieniny Mts. **D.** Eocene nummulitic limestone; Aksamitka Mountain, Haligovce, Małe Pieniny Mts. **E.** Rogoźnik coquina; Rogoźnik. Photo by Michał Krobicki. **F.** Stare Bystre olistolith; Stare Bystre.

2021; Fig. 3A). It was an elongated basin, oriented SW–NE, in which marl and dark mudstone sedimentation took place (Birkenmajer, 1977, 1986; Tyszka, 1994, 2001; Golonka *et al.*, 2018a). An intra-basin elevation of the Czorsztyn Ridge formed in the central part of the Alpine Tethys in the Bajocian (Birkenmajer, 1977, 1986; Golonka and Sikora, 1981; Golonka *et al.*, 2000, 2006, 2008, 2018a, b; Golonka and Krobicki, 2004, 2023; Krobicki and Wierzbowski, 2004; Krobicki *et al.*, 2006, 2010; Krobicki, 2018). Its origin caused the division of the Alpine Tethys into two parts:

one on the south side of the Złatne Basin (known as the Pieniny Basin), and the other to the north, the Magura Basin (Fig. 3A).

The morphology of the Alpine Tethys changed and influenced the diversification of sedimentary environments. On the basis of facies differences, several zones corresponding to individual sedimentary regimes were distinguished in the Złatne Basin (Birkenmajer, 1977, 2017; Wierzbowski *et al*., 2006; Golonka *et al*., 2022; Golonka and Krobicki, 2023). Generally, this area was under the influence of autogenic sedimentation, containing shallow-marine with carbonate and marl deposits and deep-water with carbonate-siliceous deposits (Andrusov, 1945; Birkenmajer, 1977, 2017; Wierzbowski *et al*., 2006; Golonka *et al*., 2018a; Golonka and Krobicki, 2023 and references therein). On the top of the Czorsztyn Ridge, the production of organo-detrital material took place, forming crinoidal limestones (Birkenmajer, 1963, 1977, 2017; Wierzbowski *et al*., 1999; Golonka and Krobicki, 2004; Krobicki and Wierzbowski, 2004). In the Middle Jurassic, the Czorsztyn Ridge began to subside (Krobicki and Wierzbowski, 2004; Golonka *et al*., 2005, 2018a, b, 2022; Wierzbowski *et al*., 2006) and lost its significance as a source area for the Alpine Tethys. Due to the complex structure of the PKB and the limited direct access to rock material, the activity of the zone bordering the Złatne Basin to the south is not known precisely.

Synorogenic phase (Contraction and partial closure of oceanic basins)

In the Middle Cretaceous, the gradual closure of the Alpine Tethys basin began. A convergent zone developed in the Złatne Basin and started the subduction of the Alpine Tethys Plate beneath the Central Carpathian Plate. The activation of an accretionary wedge, on which piggy-back basins formed, and flysch basins originated. Evidence of the synorogenic stage is flysch sedimentation, which was marked in the Złatne and Magura basins during the Albian (Sikora, 1971; Golonka and Sikora, 1981). The sedimentary regime changed, and autogenic deposits were gradually replaced by flysch deposits, consisting of interbedded sandstones and mudstones or clays, as well as marls and conglomerates with the main supply from southern areas (Madzin *et al*., 2019). These are well-developed in the Złatne Zone and take the form of turbidites (Sikora, 1971; Golonka and Sikora, 1981).

The formation of the convergent zone caused instability-related disturbances on the northern slopes of the Inner Carpathians. They triggered mass material movements into the Złatne Basin. Since the Cretaceous, a piggy-back basin developed on the northward-migrating accretionary wedge, where mainly flysch deposits accumulated until the Miocene. From the Cretaceous to the Eocene, this turbiditic sedimentation was supplemented by mass movements deposits with an olistostrome character, consisting of carbonate rocks, redeposited from the shallower zones from the southern margin of the Złatne Basin (Köhler *et al*., 1993; Golonka *et al*., 2015, 2017; Buček and Köhler, 2017; Figs 3, 6).

During the Cretaceous, the wedge moved northward through the Alpine Tethys, serving as a significant source of clastic material for the contracting Złatne Basin. In the Late Cretaceous along the Magura Basin's southern margin another zone of mélange formation developed. It was a result of the collision of the accretionary wedge with the Czorsztyn Ridge, which though submerged was still a prominent morphological element of the Alpine Tethys (Golonka *et al*., 2015, 2018a, 2022). The processes were launched that led to the formation of tectonic units displaced along thrusts (Sikora, 1971; Birkenmajer, 1986, 1988, 2017; Jurewicz, 2005; Golonka *et al*., 2015, 2018a, b, 2021), as well as the deposition of sedimentary mélanges. Collision caused the destruction of the Czorsztyn Ridge, and clastic material created in this process was progressively pushed to the north to the Magura Basin, forming olistostrome mélanges (Fig. 6).

An effect of the collision of the wedge with the ridge was the formation of tectonic units, composed of Alpine Tethys deposits. The sedimentary succession of the Pieniny, Branisko, and Niedzica formations formed the Pieniny Unit, while the Czertezik and Czorsztyn series gave rise to the Subpieniny Unit (Figs 3, 4, 6; Birkenmajer, 1977, 1986, 2017). Part of the accretionary wedge was transformed into the Złatne Unit and was thrust over the ridge zone, partially covering the previously formed Pieniny and Subpieniny units. The processes that caused the reorganization of the basin structures, related to the formation of detachment zones, faults, fold deformations, and displacements, created a new generation of tectonic mélanges.

After crossing the structures of the Czorsztyn Ridge, the accretionary wedge progressively prograded in a north-westerly direction and entered the Magura Basin. The piggy-back basin operating behind it remained active until the Neogene (Figs 3B, 4, 6).

Collisional and post-collisional phase

In the Neogene (Fig. 3C), a collision between the Inner Carpathians and the Eastern European Platform caused the formation of the orogen. The crystalline basement of the Central Carpathian Plate was thrust onto the Eastern European Platform (Golonka *et al*., 2019a, b). This triggered a series of processes, such as thrusting, uplifting, and the formation of nappes, which led to the formation of the recent tectonic structure of the Western Carpathians. The rotation of the Eastern European Plate and associated strike-slip movements (Márton *et al*., 1999, 2004, 2013; Csontos and Vörös, 2004; Jurewicz, 2005; Plašienka, 2018b; Golonka *et al*., 2019a; Plašienka *et al*., 2020) caused a series of transpressional, transtensional, and translational processes. They resulted in the formation of fault zones, vertical arrangements and diapirs and other deformations (Ratschbacher *et al*., 1993; Nemčok and Nemčok, 1994; Jurewicz, 2005; Marko *et al*., 2017) and caused a significant reorganization of the PKB. The flower-like structure of the PKB developed with tectonic separation from the south by a sinistral fault, dipping to the north (Golonka *et al*., 2018a, b, 2019b; Ludwiniak, 2018), and a series of southward-vergent faults formed on the northern side. These faults originated between the Złatne and Hulina (Grajcarek) units, resulting in their vertical positioning in the Czorsztyn and Krościenko areas (Ślączka *et al*., 2006; Golonka *et al*., 2018b; Porzucek *et al*.,

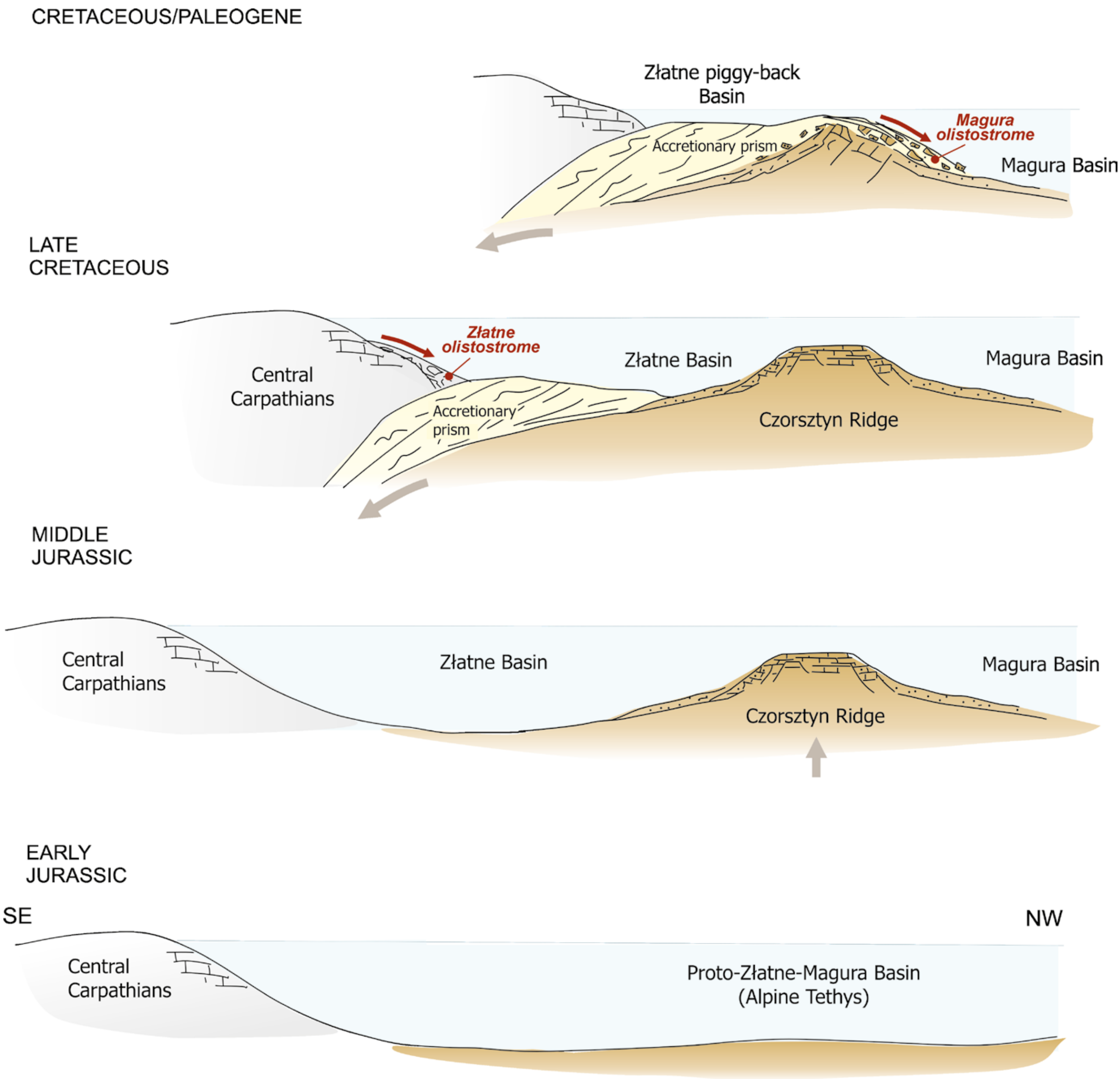

Fig. 6. Sedimentary mélange generation zones (olistostrome with olistoliths) in the Carpathian Tethys in the Mesozoic.

2023; Figs 4, 6, 7). This complicated the internal structure of the PKB and led to a new generation of tectonic mélanges. Such mélanges are visible in the Pieniny Mountains region (Golonka *et al*., 2022).

DISCUSSION

The PKB is composed of Alpine Tethys deposits. The Złatne and part of Magura basinal deposits belong to the PKB current structure, while the rest of the Magura Basin deposits have been incorporated into the Magura Nappe. The Pieniny, Subpieniny, and Złatne units originated within the Złatne Basin, while the Hulina (Grajcarek) and Maruszyna units were deposited within the Magura Basin (Figs 3, 6; Sikora, 1962; Golonka and Sikora, 1981; Birkenmajer, 1986, 1988; Golonka and Krobicki, 2004; Pieńkowski *et al*., 2008; Birkenmajer and Gedl, 2012, 2017; Plašienka, 2012; Oszczypko *et al*., 2015; Golonka *et al*., 2019a; Marzec *et al*., 2020, 2021).

In the PKB, mélanges play a significant role. They have a complex structure with the presence of individual packages in various configurations, previously described by Birkenmajer (1986) as a megabreccia. The term mélanges, in reference to PKB deposits, was used by Golonka *et al*. (2015), who focused mainly on sedimentary mélanges.

PKB mélanges were formed as a result of both sedimentary and tectonic processes. Sedimentary mélanges are connected with the synorogenic stage of Alpine Tethys development and take the form of olistostromes with olistoliths. They originated in two basin areas. One occurred along southern margins of the Złatne Basin during the

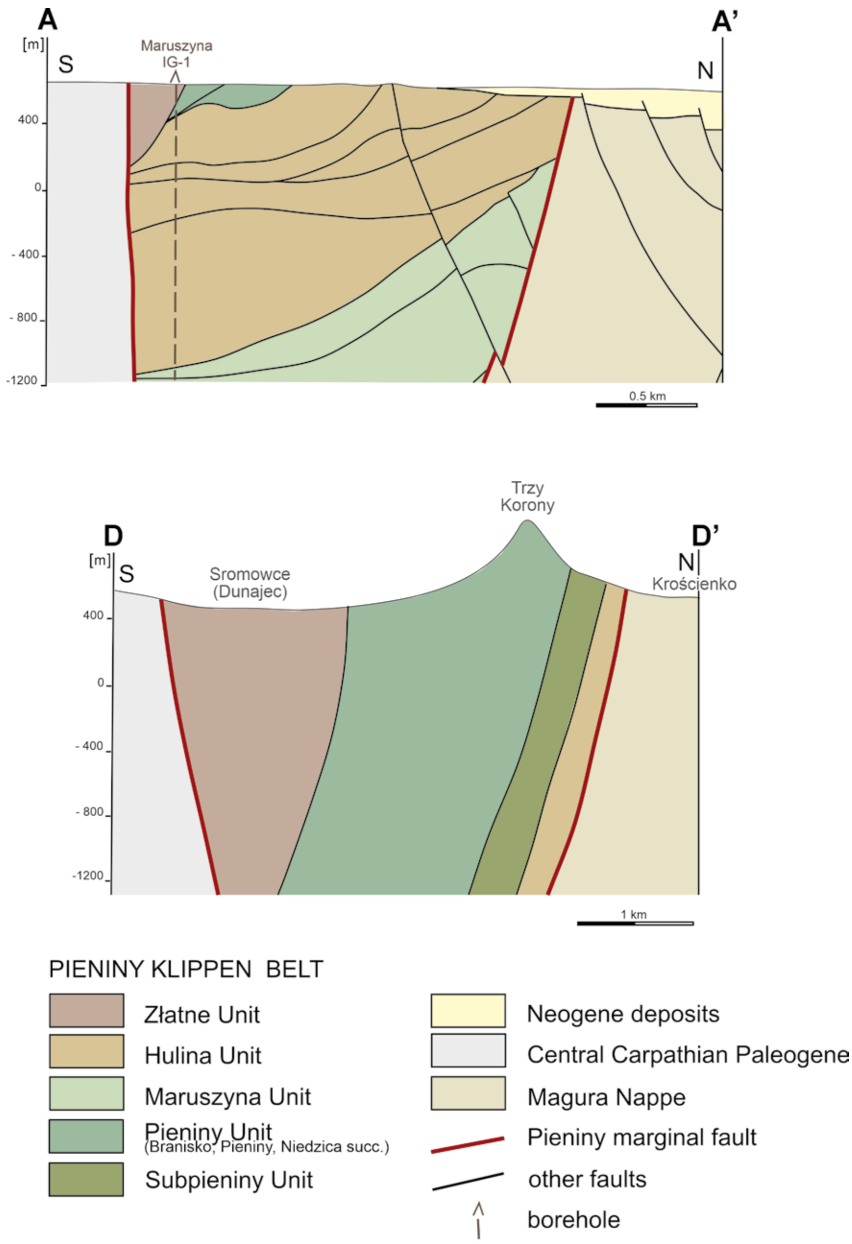

Fig. 7. Generalized geological cross-sections across the Pieniny Klippen Belt structure in the area south of Nowy Targ (A–A') and south of Krościenko n. Dunajcem (D–D') (for line of cross-section see Figure 4).

Cretaceous–Eocene and was a result of slope instability, caused by the movement of the Central Carpathian Plate and subduction processes (Fig. 6). The second area was connected with the southern slope of the Magura Basin, where material from the destruction of the Czorsztyn Ridge was deposited as a result of collision with the advancing accretionary prism. This area was active during the Late Cretaceous and Early Paleocene.

These mélanges formed independently and in different parts of the Alpine Tethys. Their detachment is marked in the current structure of the PKB, and they form two belts. In the Złatne Unit, the southern strip of mélanges formed along the edge of the Inner Carpathians (Golonka *et al*., 2015, 2017, 2018a, b), while along the southern boundary of the Magura Nappe, within the Hulina (Grajcarek) Unit, deposits from the destruction of the Czorsztyn Ridge are present (Golonka *et al*., 2015, 2017, 2018a, b; Figs 6, 8). These olistostromes also have been linked to tectonic activity, connected with the faulting (Chorowicz, 2016).

Another type is tectonic mélanges. These result from continuous and discontinuous deformation and displacement of fragmented material that occurred within the PKB structures during the formation of tectonic units, fault zones, and block displacements, which took place during the Late Cretaceous and Paleocene, and during the development of the flower-like structure in the Neogene (Figs 6, 8). Their presence is evident throughout the PKB structure, which is composed of a mosaic of often highly fragmented tectonic elements with internal disturbances.

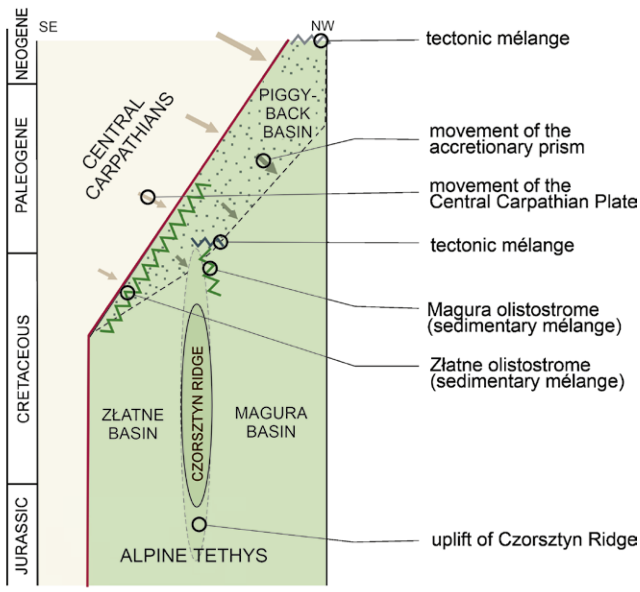

Fig. 8. Time distribution of mélange-generating processes.

CONCLUSIONS

The Pieniny Klippen Belt has a complex structure, with a mélange character that takes the form of a mixture of blocks. This mélange has both sedimentary and tectonic origins. It was formed from Cretaceous–Miocene as a result of folding, displacement, and uplift processes, as well as gravitational displacements.

Sedimentary mélanges are an effect of intrabasinal mass movements, linked to the subduction processes during the synorogenic stage of the evolution of the Alpine Tethys. They form extensive olistostromes with olistolith blocks and were deposited in two independent basin zones: along the southern margin of the Złatne Basin, and along the southern margin of the Magura Basin. The Złatne Basin olistostromes originated during Cretaceous–Eocene time and were a result of slope instability and material displacement in the subduction environment and the movement of the Central Carpathian Plate. The Magura olistostromes formed during the Late Cretaceous–Early Paleocene, developed as an effect of the collision of the accretionary prism with the Czorsztyn Ridge and the displacement of material in the prism foreland. These mélanges form two separate belts: the southern belt occurs in the Złatne Unit, and the northern (inner) belt is located in the Magura Unit.

Tectonic mélanges were formed during the Late Cretaceous–Early Paleocene and the Neogene. They are the result of the structural reorganization of the Pieniny Klippen Belt and the differentiation and deformation of structural units by the formation of fault zones, block displacements, folding, and uplifting. The mélanges originated in the Late Cretaceous and occur in the thrust zones and internal deformations of the Złatne, Pieniny, and Hulina (Grajcarek) units. They were re-deformed in the Neogene, owing to transpressional, transtensional, and translational processes that caused vertical arrangements and diapirs during the formation of the flower-like structure of the Pieniny Klippen Belt.

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