10 Limestone Klippen Belt—Atypical Landforms in Flysch Uplands

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Abstract

The Pieniny Klippen Belt of the Western Carpathians is a peculiar tectonic and geomorphological zone that is only a few km wide, but up to 600 km long. It separates the External Western Carpathians from the Central Western Carpathians. The Pieniny Klippen Belt is exceptional by its picturesque rugged landscape, being formed by numerous, and often isolated cliffy hills called "klippen" surrounded by a smooth relief composing the "klippen mantle". The majority of klippen is composed of comparatively hard, Middle Jurassic to Lower Cretaceous limestones, surrounded by softer in places Lower Jurassic, but mostly Upper Cretaceous to Middle Eocene shales, marls and flysch deposits. In these geological settings, the selective erosion created a very contrasting mosaic of landforms in a relatively small area. In the Pieniny Mts., it has the form of a mountain range with relatively high rock peaks and deep river gorges. The Middle Ages enriched some klippen with castles, which have been preserved to the present, especially in the form of mysterious ruins. All these attributes make the Pieniny Klippen Belt one of the most valuable and interesting landforms in Slovakia, with significant geotouristic potential.

Keywords

Western Carpathians • Pieniny Klippen Belt • Tectonic mélange • Limestone klippen • Rock control • Selective erosion

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10.1 Introduction

The Pieniny Klippen Belt (PKB) of the Western Carpathians is a peculiar tectonic and geomorphological zone that is only a few km wide, but up to 600 km long. Forming a backbone of the Western Carpathian orogen (Fig. 10.1), it separates the Cenozoic accretionary prism of the External Western Carpathians (EWC, Flysch Belt) from the Cretaceous basement/cover thrust stack of the Central Western Carpathians (CWC; cf. Froitzheim et al. 2008; Plašienka 2018a). The PKB is exceptional by its picturesque rugged landscape, being formed by numerous, often isolated cliffy hills called "klippen" surrounded by a smooth relief composing the "klippen mantle". The majority of klippen is composed of comparatively hard, Middle Jurassic to Lower Cretaceous limestones, surrounded by softer shales, marls and flysch deposits, which are locally of Lower Jurassic, but mostly represent Upper Cretaceous to Middle Eocene succession.

Besides composition, the extraordinary complex PKB structure resulted from a long-termed deformation in a backstop position between the EWC accretionary wedge and the bulldozing CWC thick-skinned thrust stack (e.g. Plašienka and Soták 2015; Plašienka et al. 2020). As a result, some parts of the PKB show a disorganized, in part nearly chaotic block-in-matrix structure that has been often described as a megabreccia or mélange, interpreted as either tectonic or sedimentary, or both. In general, the PKB was formed by the latest Cretaceous to Middle Eocene thrust stacking of several independent nappe units and by superimposed Late Eocene–Early Miocene out-of-sequence thrusting and wrenching that caused extensive fragmentation of sedimentary successions.

Klippen may have various sizes, from a few metres to several hundred metres long. Uhlig (1904) estimated the number of klippen up to five thousand, Mahel' (1989) to more than two thousand, and Andrusov (1938) counted 125 klippen in the Orava segment of PKB. The term "klippe" has

M. Lehotský and M. Boltižiar (eds.), *Landscapes and Landforms of Slovakia*, World Geomorphological Landscapes,
https://doi.org/10.1007/978-3-030-89293-7_10

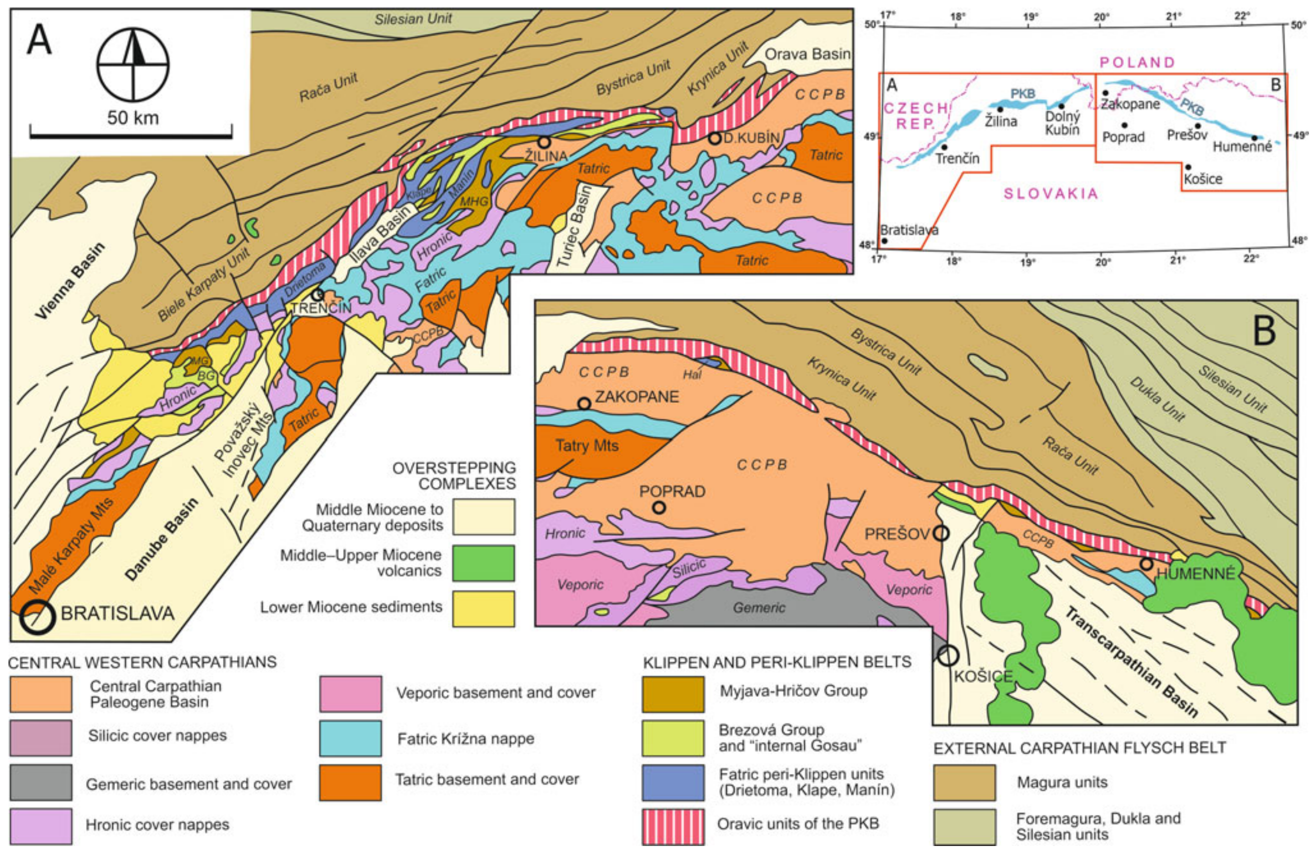

Fig. 10.1 Schematic map showing position of the Pieniny Klippen Belt in the tectonic framework of the Western Carpathians. Abbreviations: CCPB—Central Carpathian Paleogene Basin; BG—Brezová Group (Senonian); MHG—Myjava-Hričov Group (Paleocene–Middle Eocene); Hal—Haligovce Unit

become to be widely used starting from the first half of nineteenth century and the zone of klippen was designated as the "Klippenkalkzug" or "Klippenkalk-Gruppe" (e.g. Stur 1860). Afterwards, Neumayr (1871) introduced the term "Pieninische Klippenzug", i.e. the "Pieniny Klippen Belt" as it is commonly used in the current English-written texts (for the historical overviews see Andrusov 1938, 1964; Scheibner 1968; Birkenmajer 1977, 1986; or Plašienka 2018b).

10.2 Composition and Geological Structure of the Klippen Belt

The PKB as perhaps the most outstanding regional tectonic zone of the Western Carpathians has attracted the attention of geologists for a long time. It was marked like a "tectonic megabreccia", "raisins in cake", "chaotic mélange" or "wonder of nature", which names pertinently express the character of this extremely complex zone. Despite the comparatively small areal extent, a great number of tectonic units, nappes, sedimentary series, successions, developments, formations or morphological klippen types have been distinguished and innumerable opinions about their palaeogeographic settings and tectonic affiliations have been expressed (milestone works of Stur 1860; Neumayr 1871; Uhlig 1890, 1903, 1904, 1907; Andrusov 1931, 1938, 1965, 1968, 1974; Scheibner 1968; Birkenmajer 1977, 1986; Marschalko 1986; Mišík et al. 1996; Mišík 1997). These and numerous other authors provided a range of stratigraphical, lithological and sedimentological observations that are mostly still valid.

The extraordinary tectonic style and rugged surface relief of the PKB are largely conditioned by the material heterogeneity of the various klippen sedimentary successions (Fig. 10.2). Well-bedded basinal Jurassic to Lower Cretaceous successions of the Peri-Klippen Fatric units (Manín, Drietoma) and of the Oravic Pieniny Unit are prone to upright folding, therefore they form "immature" klippen. These are in fact projecting cores of large-scale anticlines—often periclines, particularly in the Manín Unit (Plašienka et al. 2018). In contrast, the thick strong layer of mostly massive Middle Jurassic to Lower Cretaceous limestones of the Oravic Subpieniny Unit (Czorsztyn-type successions;

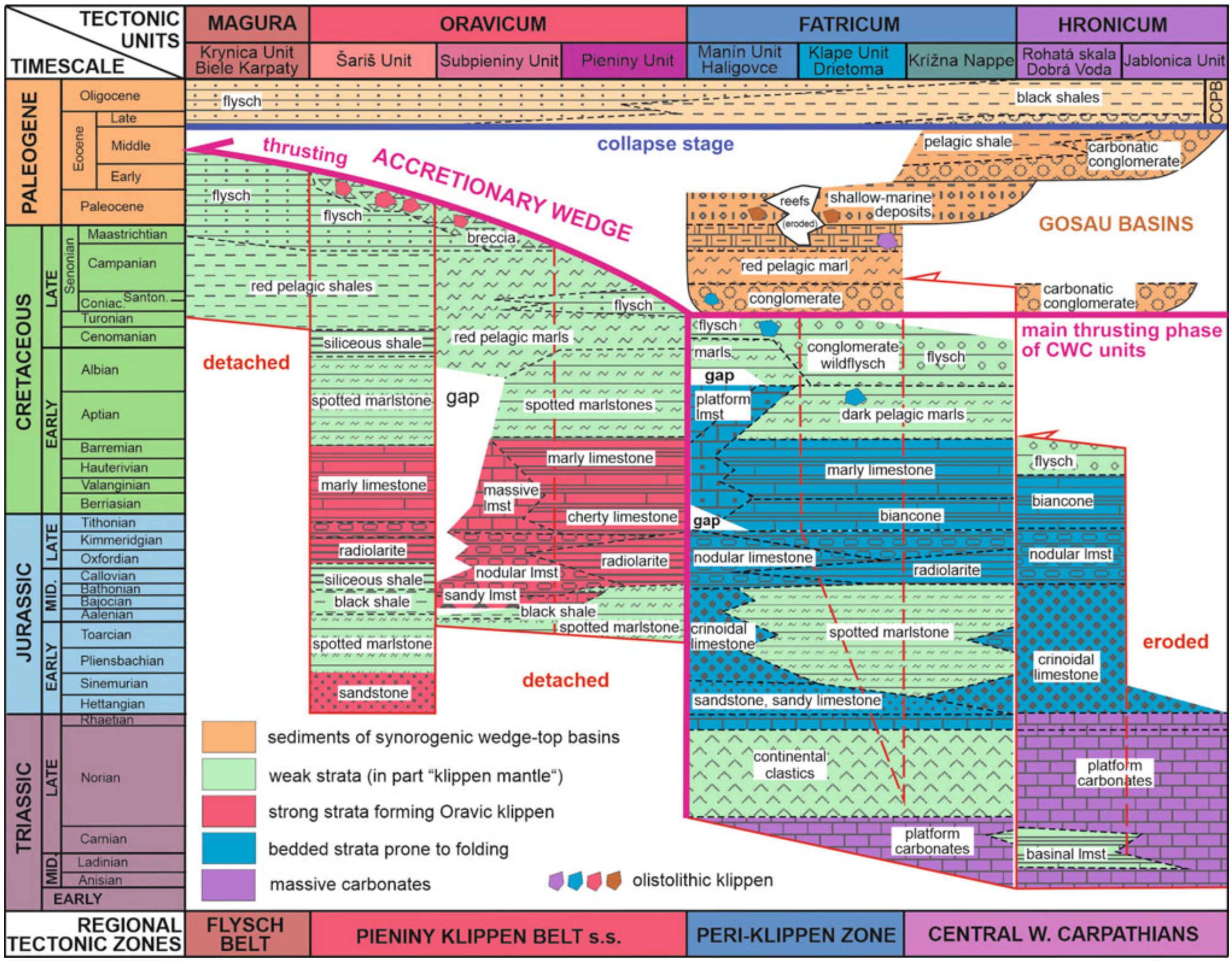

Fig. 10.2 Lithostratigraphic outline of the PKB and contiguous zones showing the material heterogeneity and competence contrasts in principal sedimentary successions and their formations

Fig. 10.2) tends to form nearly isometric blocky klippen—either tectonically separated, or as sedimentary olistoliths.

It is evident that lithology, biostratigraphy and sedimentology of the various klippen formations and successions have been very well studied and are known to great details. However, views on the PKB structure were and remain to be very diverging. In the next text, we shall follow the recent concepts of Plašienka and his co-workers (Plašienka and Mikuš 2010; Plašienka 2012a, b, 2018a, b, 2019; Plašienka and Soták 2015; Plašienka et al. 2012, 2018, 2020), which in part renew the original Uhlig's (1907) ideas and tectonic terminology. Accordingly, PKB in a broader sense (Figs. 10.1 and 10.2) entails units of two groups—Oravic Superunit (PKB s.s.) and Central Carpathian units forming the inner Peri-Klippen zone (Mahel' 1980, 1981). Three Oravic thrust units include the lowermost Šariš Unit (deep-water Jurassic–Middle Eocene succession) overridden by the Subpieniny Nappe (Jurassic–Cretaceous intra-oceanic ridge and slope successions like Czorsztyn, Niedzica, Czertezik, Pruské, e.g. Birkenmajer 1977)) and by the Pieniny Nappe (Jurassic–Cretaceous deep-marine successions of Pieniny, Kysuca, Branisko). The palaeogeographic and tectonic evolution of the PKB progressed in several main stages:

(i) The Oravic sedimentary basin originated by rifting of the European continental lithosphere during the earliest Jurassic, followed by Middle Jurassic breakup of the South Pennine oceanic zone (Piemont–Váh Ocean), with uplift of the Czorsztyn ridge as the rift shoulder. The Pieniny–Kysuca Basin neighboured the ridge from the southern side as a margin of the expanding Váh Ocean.

(ii) Individualization of the Czorsztyn ridge as an intra-oceanic continental ribbon was completed by the Early Cretaceous uplift of the rift shoulder during oceanic rifting of the North Pennine Valais–Rhenodanubian–Magura Ocean to the north.

(iii) Sequential shortening, detachment and nappe emplacement of Oravic units is recorded by syn-thrusting, coarse-grained wildflysch deposits containing material from the overriding nappe (Fig. 10.2)—latest Cretaceous in the Subpieniny Unit, and Paleocene–Early Eocene in the Šariš Unit.

(iv) The Central Carpathian ("non-Oravic") units consist of the frontal Fatric (Krížna) nappe units—Drietoma, Manín and Klape in western and Haligovce in eastern Slovakia (Fig. 10.1), which were emplaced during the Late Cretaceous over the inner Oravic zones and subsequently incorporated into the PKB structure.

(v) During the early Paleogene (Paleocene–Lutetian), the detached PKB units formed an accretionary wedge growing by frontal accretion and experienced alternating contractional and extensional events that controlled sedimentation in both the foreland trench and wedge-top, Gosau-type piggyback basins.

(vi) Throughout the Paleogene, the western PKB branch (Fig. 10.1) was affected by NW–SE compression and gradual transfer of Oravic units from the front to the rear of the wedge (Fig. 10.2), where their original nappe structure was disintegrated by forward out-of-sequence thrusting, then backtilting and backthrusting, whereas extensive dextral transpression affected the eastern segment during the Late Eocene.

(vii) Further important deformation occurred in the Early Miocene, when the SW–NE compression lead to the narrowing of the eastern segment and sinistral transtension in the western one (Fig. 10.1).

(viii) By the Early–Middle Miocene, the PKB became welded to both the Central and External Carpathian zones, which rotated as a unity by some 50° CCW relative to Europe (Márton et al. 2013). As a result, the PKB occupies a positions of an ancient backstop boundary at the transition from the CWC rigid block to the EWC accretionary wedge (Plašienka et al. 2020).

10.3 Earlier Classifications of Klippen Forms

Several authors attempted categorization of klippen forms, types and subtypes (Birkenmajer 1958; Andrusov and Scheibner 1968; Scheibner 1968; Andrusov 1968, 1974), using both tectonic and morphologic criteria. Although differing in details, these classifications are very similar. In general, they distinguished klippen of non-tectonic and tectonic origin. The non-tectonic sedimentary klippen are either autochthonous, like reef bodies uncovered by erosion of the surrounding sediments, or allochthonous such as older bioherms emplaced in younger deposits by submarine slides, extremely big boulders in conglomerates, olistoliths in slump bodies and blocks in recent landslides, and various "pseudoklippen" like selectively eroded massive sandstone and conglomerate bodies within continuous flysch successions.

Klippen related to tectonic processes can be in situ, tectonically predisposed forms like projecting cores of anticlines with continuous sedimentary successions (the "immature klippen style" of Mahel' 1980), or remnants of cordilleras and horsts inherited from the rifting stage. The proper tectonic klippen are morphologically positive forms, which are tectonically fully individualized from the surrounding sediments (Andrusov 1974). Klippen of the Pieniny type include several subtypes—the Rudín, Vršatec and Pieniny proper, differing in relationships between the klippen and surrounding rocks. In addition, Andrusov (1974) distinguished the diapiric Czerwona skala subtype (relying on the diapiric concept of Birkenmajer 1959) and several types of compound, mainly fold-related klippen.

Based on descriptive morphostructural criteria, Plašienka (2012b) differentiated between the so-called blocky and ribbon klippen in the eastern Slovakian PKB segment. Blocky klippen are more-or-less isometric bodies formed by predominantly Jurassic massive limestones of the Czorsztyn-type successions. They occur in two considerably different settings—as tectonically constricted lenses or boudins within continuous sedimentary successions of the Subpieniny nappe (Fig. 10.3B1), or as olistoliths embedded in mass-flow breccias of the synorogenic flysch of the Šariš Unit (Fig. 10.3B3). In the first case, the internal foliations (bedding and cleavage) show attitudes generally consistent with the surrounding sediments, whereas in the second case they are randomly oriented. The ribbon klippen of the lens-like or lozenge shape are typical for the Pieniny Unit, where they are formed by well-bedded, in places folded Jurassic to Lower Cretaceous limestone and radiolarite formations preserving the structural trends for longer distances. As such, the blocky klippen correspond to the Gruppentypus, and ribbon klippen to the Reihentypus of Uhlig (Uhlig 1890, 1903). The marly-shaly klippen matrix encompassing the blocky or ribbon tectonic klippen has often penetrative scaly fabrics, while the blocky olistoliths are enclosed by more competent and weakly deformed breccias and sandstones.

Despite the current klippen morphology is largely an erosional feature, and the relationships of klippen to the enclosing strata can be rarely examined in outcrops, the main factors controlling the klippen structures have recently been tentatively defined by Plašienka (2018b). The emphasis is

A: separation modes / foliation tilt		foliation missing or unimportant	
		gentle dips <45°	steep dips >45°
		areal klippen groups	linear klippen groups
primary	TECTONIC	isolated blocks in matrix	
		plateaus	rhomboidal blocks
		carapaces	dragon backs
	SEDIMENTARY	olistoliths, slides	
		olistostromes, mass-flows	
secondary	EROSIONAL	periclines and ribs	
		table mts, monadnocks	rock needles and towers
		rugged mosaics	goat backs – cuestas
	GRAVITATIONAL	separate downslope moving blocks	
		chaotic blocks accumulated at landslide toes	
	ANTHROPOGENIC	quarries, carved crags	

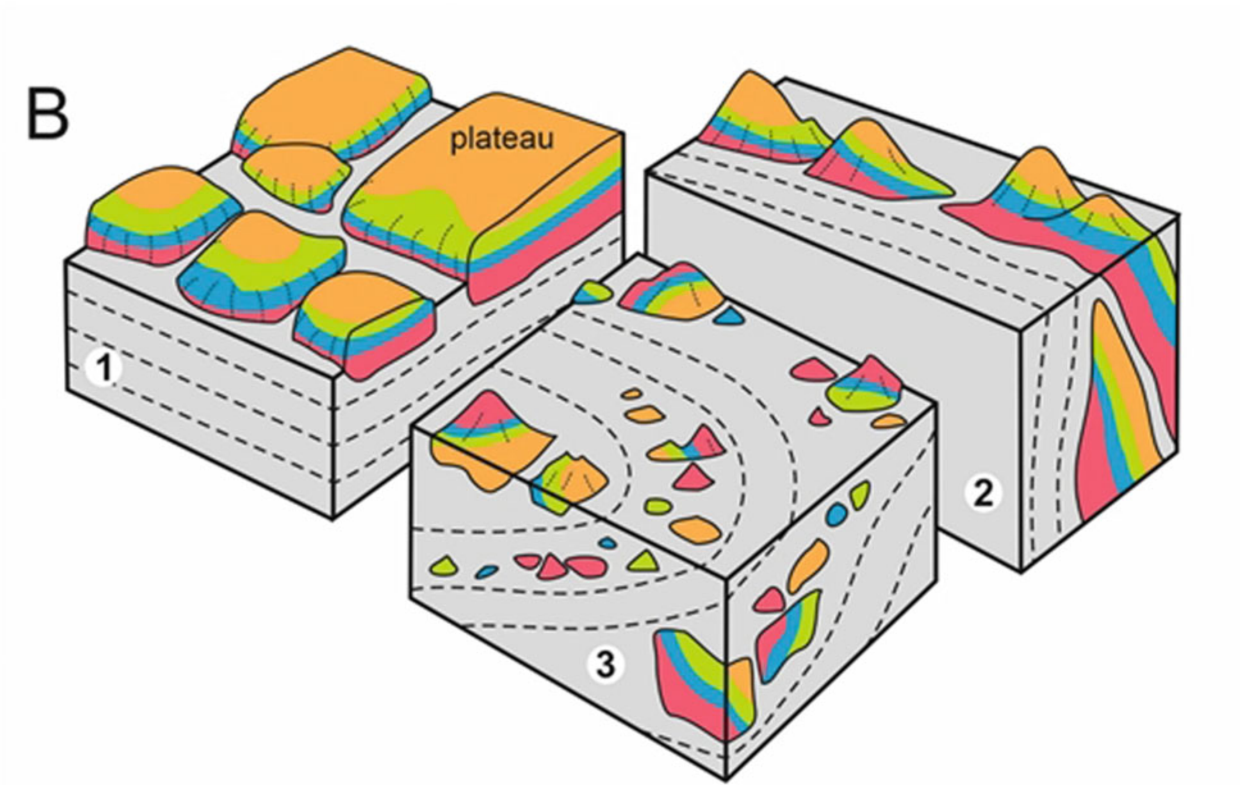

Fig. 10.3 A—Classification of the basic klippen types and forms. Modified after Plašienka (2018b). For details see that work. B—Blockdiagrams illustrating the basic types of primarily separated klippen. Klippen formations are coloured, their matrix is shown grey: 1—plateaus and their carapace-type arrangement in a subhorizontally lying succession; 2—lozenge-shaped blocks and coulisse array (dragon back) in a steeply dipping succession; 3—random distribution of blocky olistoliths and slides embedded in flysch sediments

given on the genetic factors that limited the primary klippen types, i.e. forms that originated before having been affected by surface processes. Nevertheless, the primary characteristics of klippen controlled also the secondary klippen forms shaped by the exogenous modifications, i.e. those that rule the present surface klippen forms and landscape of the PKB.

10.4 Factors Controlling the Klippen Forms

In his classification of the klippen types and forms, Plašienka (2018b) defined the main factors that controlled the klippen origin and shaping. These are the mode of klippen separation (genetic factor), their bedding attitudes and inclination of long klippen axes with respect to horizontal (structural factor), and exogenous processes modifying the klippen forms like erosion, redistribution by gravitational movements and anthropogenic impacts. The influence of these factors on the final klippen forms is schematically classified in Fig. 10.3A. There are also distinguished individual morphological klippen varieties and their mutually related groups, usually various types of short "hogbacks".

In general, there are two main ways how the klippen could be individualized—the primary mode, whereby klippen originated before being exposed at the Earth's surface, and secondary when klippen formed or were strongly modified by superimposed surface processes. The primary separation includes either sedimentary (i.e. exogenous) or tectonic (endogenous) modes of separation, while the secondary mode refers to post-origin processes.

10.4.1 Sedimentary Klippen—Olistoliths

There are two types of sedimentary klippen: (i) solitary olistoliths, usually large (many hundreds to several thousand cubic metres), emplaced amidst much younger hemipelagic or flysch deposits; (ii) variously sized olistoliths embedded in younger coarse-grained sandstones or breccia bodies and olistostromes associated with turbiditic flysch sequences.

The occurrences of olistostromes and olistoliths in the PKB were reviewed by Plašienka et al. (2017) in their discussion of the paper by Golonka et al. (2015). They distinguished five basic types, which differ in their tectonic position, genesis, sources and age. From structurally higher to lower and from younger to older, these are: (1) blocks of Thanetian algal-coral reefs embedded in contemporaneous or slightly younger calcareous sandstones and marls associated with tempestites, turbidites and slump bodies (Paleocene–Lutetian Myjava–Hričov Group, cf. Buček and Köhler 2017; Figs. 10.1 and 10.2). They can be regarded as intra-formational olistoliths originated from coeval rim and patch reefs. Type (2) olistoliths are similar to type (1), but older–Upper Cretaceous (Coniacian–Santonian and Maastrichtian). These are formed by re-deposited bioherms associated with conglomerates, allodapic limestones, tempestites and marlstones of nearly the same age (intra-olistoliths), as well as with extra-olistoliths of Lower Cretaceous Urgonian and Middle Triassic Wetterstein platform limestones (Fig. 10.2). Type (1) and (2) olistoliths originated probably in synorogenic wedge-top depressions in a piggyback position, above the deforming accretionary wedge and are affiliated with the Gosau Supergroup (Plašienka and Soták 2015). In the Middle Váh Valley and in the Pieniny Mts, the Gosau sediments form the post-thrusting cover overstepping the Fatric (Klape, Manín, Haligovce and Krížna; Figs. 10.1 and 10.2) and Hronic nappes of the Central Carpathian origin in the so-called Peri-Klippen zone (Mahel' 1980).

The third olistolith type (3) is represented by the Kostolec group of limestone klippen resting within the Albian–Cenomanian hemipelagic and turbiditic deposits of the southernmost partial subunit of the Manín Unit (Fig. 10.2). The most spectacular olistoliths of type (4) occur in the Klape Unit of the Peri-Klippen zone. These are solitary slide blocks measuring tens to hundreds of metres in diameter, the distinctive Mt. Klapy klippe being the largest one (e.g. Marschalko 1986). The Klape olistoliths are embedded in hemipelagic and distal turbiditic sediments of Aptian–Early Albian age. The provenance of olistoliths in the Manín and Klape units was interpreted by Plašienka (2019).

Genesis and structural settings of type (5) olistostromes and olistoliths in the Oravic units of the PKB that originated in a contractional regime were described by Marschalko et al. (1979), Nemčok et al. (1989), Plašienka and Mikuš (2010), Plašienka et al. (2012, 2017), Plašienka (2012a), Plašienka and Soták (2015). These were formed by fragmentation of the advancing nappe fronts and downslope transportation of discharged debris and olistoliths into the foreland depressions. The Paleocene olistostromes of the Šariš Unit and Maastrichtian olistostromes of the Subpieniny Unit represent syn-thrusting mass-flow deposits composed of material released from destructive frontal edges of overriding Subpieniny and Pieniny thrust sheets, respectively. Olistostromes of the Šariš Unit carry also huge sedimentary klippen of Jurassic–Lower Cretaceous formations derived from the Subpieniny nappe, including the Czorsztyn-type and also Czertezik and/or Niedzica successions (Fig. 10.3B3).

Very rarely, the Paleocene flysch deposits of the Šariš Unit contain olistoliths of massive Lower Cretaceous basalts (Birkenmajer and Lorenc 2008; Spišiak and Sýkora 2009), possibly derived from the Czorsztyn ridge (Spišiak et al. 2011).

10.4.2 Tectonic Klippen

The proper tectonic klippen, which are prevailing in the PKB, originated by tectonic processes in the higher levels of the Earth's crust, as revealed by the essentially brittle deformation mechanisms resulting in individualization of klippen. The klippen are characterized by numerous joints and slickensides, while the enclosing klippen matrix usually shows signs of a semi-ductile scaly fabric. The competence contrast between the klippen and their matrix substantially influenced the shape of the klippen. In the case the contrast was high, e.g. between the massive Jurassic limestones and surrounding shales and marls of the Subpieniny Unit (Fig. 10.2), the klippen form prismatic blocks, often nearly isometric and klippen are always bounded by fault surfaces. Lenticular klippen developed if the competence contrast was low and the klippen strata at least partly retain the stratigraphic continuity with the matrix.

Since bedding is the most common planar anisotropy in the sedimentary rocks, it represents the weakest planar structural grain, along which a klippe can break and separate. Therefore, the surface klippen shapes are largely controlled by their bedding attitude, as the long axes of klippen are usually parallel to bedding. Origin of variously shaped tectonic klippen was characterized in works of Plašienka and Mikuš (2010), Plašienka (2012a, b), and Plašienka et al. (2012).

10.5 Landscape of the Pieniny Klippen Belt

Despite being formed by the same systems of the Oravic tectonic units and sedimentary successions, individual sectors of the PKB differ by the representation of these units and succession and by the internal structure reflecting in part distinct tectonic evolution, for instance, between the western, SW–NE trending, and the eastern, NW–SE striking branches (see Fig. 10.1, e.g. Plašienka et al. 2020). The substantial part of the western branch is characterized by the Peri-Klippen zone composed of the Fatric units that provide a transition to the CWC areas with dominantly mountainous topography. Exceptions are the westernmost PKB sector, where the PKB neighbours the Myjava Uplands composed of the comparatively soft Gosau deposits (in SE), and short sectors in the Váh River Valley adjoining small Neogene pull-apart basins (flatland Trenčín and Ilava depressions; Fig. 10.1). The outer north-western boundary against the Magura units of the Flysch Belt is then usually morphologically distinct.

The eastern branch forms a straight, narrow zone composed exclusively of the Oravic units (except the Haligovce klippe in the Pieniny Mts), which is surrounded from the SW by the flysch deposits of the Central Carpathian Paleogene Basin (CCPB), and from the NE by similar flysch deposits of the Krynica Unit of the Magura nappe system of the EWC Flysch Belt (Fig. 10.1). There, the PKB is morphologically very distinctly expressed by rugged topography, surrounded by a smooth relief of the flysch complexes.

Compared to the geological understanding, the Slovak geomorphological literature devoted to the PKB is relatively poor. Lukniš (1972) in his encyclopaedic work provides the description of the Pieniny Klippen Belt relief of the whole Slovakia. It does not appear as the independent geomorphologic unit, with the exception of the Pieniny Mts; it is mostly delimited as the taxonomic unit of lower hierarchic level with distinctly different relief type within geomorphic units of the Outer Carpathians. Morphologically, it appears as depression in contrast to surrounding morphostructures.

Most of geomorphological contributions are of older date and thus reflect older geological views of the extent and structure of the PKB. Generally, authors treated this landscape as a typical example of the passive morphostructure characterized by selective erosion of the limestone klippen embedded in a weak shaley-marly matrix.

Drdoš (1960), in the study of the relief of the Pieniny Mts., distinguished between two different types of rocks. Sharply cut peaks bind to resistant limestone complexes. Less resistant sandstone and slate formations create a rounded surface or depressions. In addition to differences in rock resistance, Drdoš (1960) emphasized the importance of the system of fissures to which the river network is connected. Directions of streams are thus influenced by both lithology and tectonic structures. In some places, watercourses encircle the resistant rocks of the ridges, while elsewhere they create gorges through them. In addition to epigenetic valleys, Drdoš also admitted signs of antecedence. The relief of the Pieniny Mts. was similarly characterized by Košťálik (1970).

Mazúr (1963) described the relief of the PKB in the Manínská vrchovina Upland, the Kysucká vrchovina Upland and in the Javorníky Mts. According to the resistance of the rocks, he set aside three typical groups of forms—klippen s. s. of hogback type, corresponding to tectonic lens of resistant carbonatic rocks; klippe monadnocks, which are more common than klippen s. s. and built of moderately resistant formations of sandstones and conglomerates; and erosive basins and furrows formed in soft fissile-shale rocks.

Stankoviansky (1983) described the development of the PKB relief in the area of the Myjavská pahorkatina Upland and the Biele Karpaty Mts. according to the morphoclimatic conditions. Older and bigger monadnocks were thought to have formed in a warm humid climate by a combination of fluvial and gravitational processes. Later, in the colder Pleistocene period, smaller klippen formed, whereas the older ones were remodelled. In conditions of periglacial climate, relief was modelled mainly by cryogenic processes.

A decade later, Stankoviansky (1994) followed a newer view of the geological structure of the PKB, which is understood more restrictively than originally. Most sandstone and conglomerate monadnocks (e.g. the Manín Unit) are no longer part of the PKB s. s. Therefore, Stankoviansky (1994) did not classify structural elevations based on rock type, but distinguished monadnocks (largest and most prominent sharp elevations) and periglacial hills (structural elevations of smaller dimensions) according to their size. The third type of landforms is structurally conditioned depressions.

In this way, it is possible to describe the relief of the PKB in most of Slovakia. The boundaries between landforms are significant in the field and they mostly coincide with the boundaries of rock outcrops of different resistance and therefore they are essentially fixed and the significance of current morphogenetic processes is smaller (Urbánek 1986; Stankoviansky 1994).

This description is fully valid mainly in the eastern PKB branch, where the resistant tectonic or sedimentary klippen blocks are distinctly individualized by erosional removal of surrounding sediments and other secondary exogenous processes, such as river abrasion and carving by incised epigenetic valleys (e.g. the Dunajec River Gorge in the Pieniny Mountains). A similar situation occurs in the north-eastern part of the western branch in the Orava region.

However, some parts of the western branch are also influenced by the active neotectonic processes, especially by uplift tendencies of some PKB segments. This was indicated, for example, by the morphostructural analysis of the Kysucké vrchy Mountains in north-western Slovakia (north of Žilina in Fig. 10.1; cf. Mazúr 1963; Novotný 2002, 2003, 2005, 2006).

Massive hogback klippen are cut through by narrow valleys. The higher lifted blocks are more strongly divided and the directions of the valleys are linked to the system of transverse faults. Neotectonic uplift of this area as well as sinking of neighbouring basins (the Žilinská kotlina Basin and the Kysucká kotlina Basin) has been proved (Maglay ed. 1999). This led to intensive headward erosion of streams mouthing in the basins. River piracy (e.g. Lacika 2002) is responsible for the transformation of the valley network (Fig. 10.4).

Secondary factors (Fig. 10.3) that modify the klippen forms and may cause their individualization involve first of all various erosional processes like mechanical abrasion by river flows, chemical dissolution of limestone rocks, exfoliation, etc. Equally important is disintegration and downslope transport of klippen blocks, triggered by gravitational forces. Gravity-driven processes include breakdown of steep cliffs and ridges along vertical fissures, tilting of released blocks, rock falls and avalanches, and sliding, slumping or creeping dependent on the slope inclination and rheology of the underlying or encircling material.

Since typical klippen are built mainly of limestone, the karst phenomenon is also a relatively important element of their modelling. There are mainly tectonic caves, enlarged by corrosion, as well as surface karst phenomena (Hochmuth 2008). Hochmuth (2008) distinguished nine karst areas within the PKB in Slovakia. The most important are the Haligovské skaly in the Pieniny Mts., with the Aksamitka Cave (total length of the corridors 335 m), and the Bošácké bradlá in the Biele Karpaty Mts., with the Landrovská jaskyňa Cave (315 m).

Klippen shapes have also been often modelled by human activities (anthropogenic factor)—from small excavations and local exploitations of raw materials for various purposes to large quarries in which mostly limestones for cement and lime factories are mined (Fig. 10.3). The database of the State Geological Institute of Dionýz Štúr (ŠGÚDŠ 2020) contains more than 20 localities within the PKB registered as mineral deposits.

10.6 Natural and Cultural Value of the PKB

The elevations of the PKB are strongly contrasting forms of relief that contribute to increase the heterogeneity and stability of the landscape. The structure of land cover and land use is very strongly limited by the properties of relief. Although the PKB covers only about 2–3% of Slovakia's territory, it is a very valuable and unique part of the landscape. In addition to the exceptional geological and geomorphological structure, specific calciphile vegetation is also subject to protection.

From the nature protection point of view, the most important area is the Pieninský národný park National Park, which was declared in 1967. It is a continuation of a national park existing in the Polish part of the Pieniny Mts. since 1932. The most valuable part of the park is the Dunajec River Gorge that is 9 km long (Fig. 10.5). The river has created a deep valley across the limestone massif, with steep 200–300 m-high rock walls and meanders. Specific natural conditions are favourable for the occurrence of rare endemic plant species (Lacika and Ondrejka 2009).

The protection of other localities within the PKB is implemented within small-scale protected areas. Most of the major klippen have the status of a Natural monument (a total of 15 objects). Larger groups of klippen form Nature

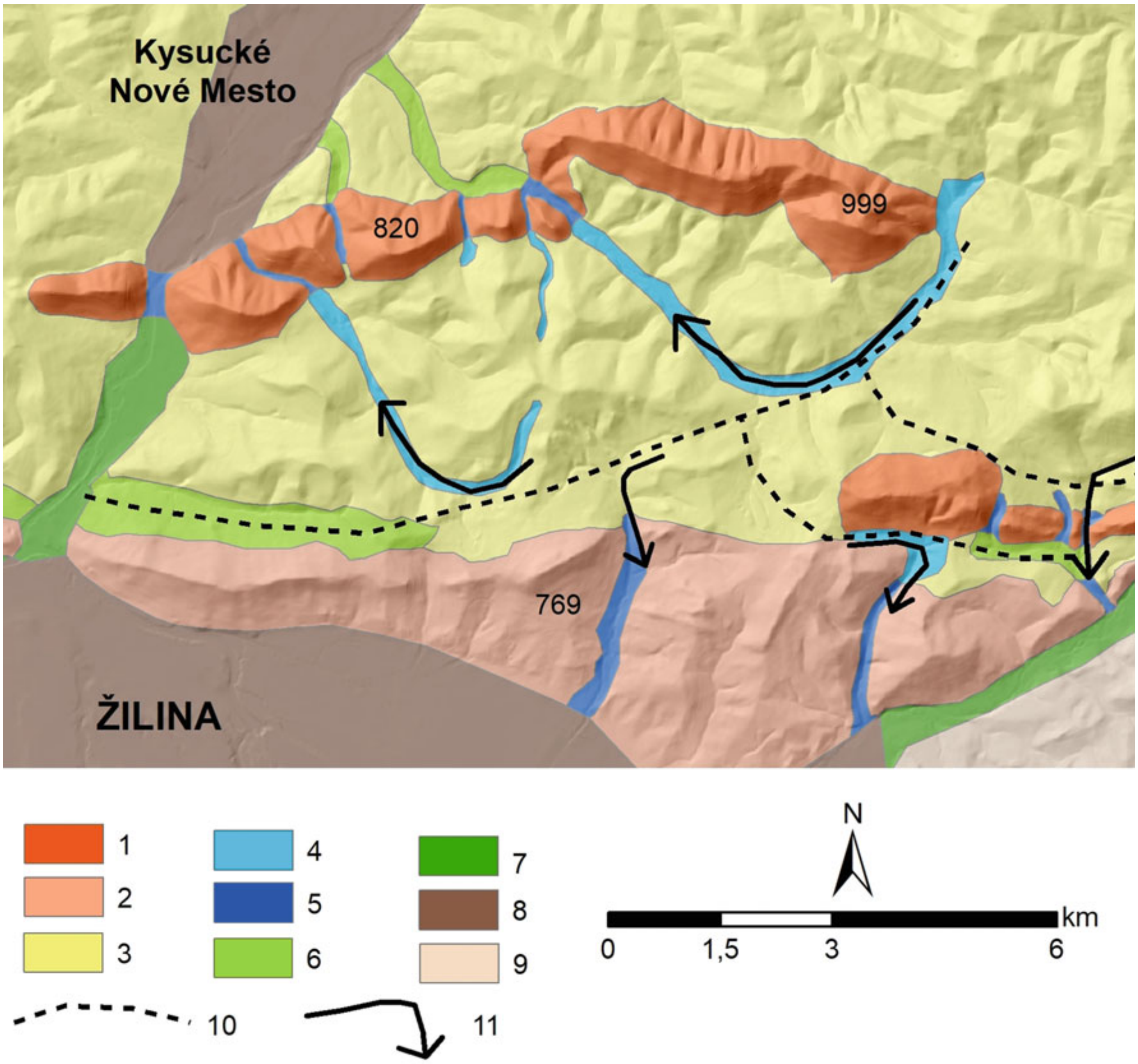

Fig. 10.4 The Kysucké bradlá Klippen, north of the town of Žilina. The case of neotectonic valley network transformation due to river piracy. 1—klippen s.s. (mainly Jurassic to Cretaceous limestones); 2—klippen monadnocks (mostly Cretaceous sandstones); 3—less dissected surface (mostly Cretaceous to Eocene shales, marls and flysch deposits); 4—upper wider parts of valleys of the small streams, locally with the elbow of capture; 5—narrow valley parts cutting through resistant rocks; 6—lower wider valley parts, locally misfit streams; 7—valleys of main rivers; 8—subsiding basins; 9—foothills of the Malá Fatra Mts; 10—presumed previous valley directions; 11—suspected sites of captures

reserves (10). The most important are the Oravské hradné bralo National Natural Monument (Fig. 10.6), the Bielska skala National Nature Reserve and the Manínska tiesňava National Nature Reserve (SAŽP 2007).

The PKB sites are also of undeniable scientific and educational significance. Many geological outcrops could be found which, due to their structure and position, can be used as reference stratigraphic profiles, suitable for calibration of sediment dating within the entire Western Carpathians (Michalík et al. 1997).

Individual klippen also played an important role in the history of human settlement. Significant rocky ridges, sharply contrasting within the surrounding smoothly modelled environment, are often located near the migration routes, which led mainly through the river valleys. They were thus more accessible than similarly formed rock formations located in remote parts of the mountains. Many of klippen have therefore become natural refuges and cult places, provided a strategic location on elevated and more easily defended places, as well as building material for the

Fig. 10.5 The Dunajec River Gorge in the Pieninský National Park (*Photo* J. Lacika)

construction of fortifications. Archaeological findings document more than 20 Slavic hillforts and fortified settlements of ancient age (Slovanské hradiská 2020) within the PKB, especially in the Váh River and the Orava River Valleys.

In the Middle Ages, castles were built on several klippen, which were the centres of administrative and military power at that time. Lacika (2016) registered 11 castles within the PKB. Only the Oravský hrad Castle has been preserved, the others are currently in ruins (Fig. 10.7).

10.7 Touristic Promotion

Klippen significantly increase the natural and aesthetic value of the landscape. From the point of view of international tourism, the already mentioned Pieninský NP has the highest potential. In addition to the exceptional natural environment, it also offers elements of traditional Goral culture, which are reflected in the local cuisine, architecture and folk art. One of the biggest attractions of the Pieniny Mts. is a rafting trip

Fig. 10.6 The Oravské hradné bralo National Natural Monument with the Oravský hrad Castle (*Photo* J. Lacika)

across the Dunajec Gorge (Fig. 10.8), during which visitors can admire the beauty of Pieniny's ridges from a special perspective. Every year, more than 80,000 visitors (PIENAP 2020) take part in these cruises on the Slovak side.

The Oravský hrad Castle is also an important destination. It rises on a massive limestone ridge above the Orava River. The castle dates from the thirteenth century and is visited annually by about 200,000 visitors (Oravské múzeum 2020). Several well-known films were made in the castle, the most famous of which is probably the silent German Expressionist horror film "Nosferatu: A Symphony of Horror" from 1922, inspired by Bram Stoker's Novel Dracula (Oravské múzeum 2020).

Other localities within the PKB have regional or local tourist potential. The most attractive are the Vršatské bradlá Klippen, the Manínska tiesňava Gorge and the ruins of the Vršatec Castle, the Lednica Castle (Fig. 10.9) or the Kamenica Castle. Most sites are accessible by educational hiking trails.

10.8 Conclusion

The Pieniny Klippen Belt is a testament to the complicated development of the Western Carpathians. Tectonic processes dispelled, compressed and tore the sedimentary rock formations deposited in the Mesozoic seas with fascinating force. This created a narrow zone of limestone cliffs, which, as a wall, separate the Inner and Outer Carpathians.

The unique character of the relief of the PKB results from its overall spatial composition. The complicated geological structure caused that selective erosion created a very contrasting mosaic of landforms in a small area. Meanwhile, the mosaic in individual localities is always somewhat different. It is determined by the facts that the geological structure of the PKB is not homogeneous and that the position of the PKB is always different regarding the neighbouring morphostructures (Novotný 2006).

Fig. 10.7 The ruins of the Vršatec Castle (*Photo* J. Lacika)

Fig. 10.8 Rafting in the Dunajec River Gorge in the Pieninský National Park (*Photo* J. Lacika)

Fig. 10.9 The Lednica Castle ruins, standing on the "dragon back" klippe in the Vršatské bradlá Klippen (*Photo* J. Lacika)

Fig. 10.10 Panoramic view of the Pieniny Mts. (*Photo* J. Lacika)

In the Pieniny Mts., it has the form of a mountain range with relatively high rock peaks (Fig. 10.10) and deep river gorges (Fig. 10.11). In the valley of the Orava River, it creates steep rock towers, reflected on the water surface. In the Biele Karpaty Mts., the Vršatské bradlá Klippen form an impressive rock town (Fig. 10.12). In the vicinity of the town of Žilina, it has the character of wooded hills. Elsewhere, they form small ridges, isolated or clustered, scattered across the surrounding country (Fig. 10.13). The Middle Ages enriched some klippen with castles, which have been preserved to the present, especially in the form of mysterious ruins. Others were used for the extraction of mineral resources, mainly limestone for cement production and construction purposes. Thanks to this, it is possible to find rock outcrops, allowing to study the geological history of this area.

All these attributes, in conjunction with the relatively easy access resulting from its location, confirm that the Pieniny Klippen Belt is one of the most valuable and

Fig. 10.11 The Dunajec River Gorge in the Pieniny Mts. (*Photo* J. Lacika)

Fig. 10.12 The Vršatské bradlá Klippen (*Photo* J. Lacika)

Fig. 10.13 The Kyjovské bradlá Klippen in the eastern part of the Pieniny Klippen Belt (*Photo* J. Lacika)

interesting landforms in Slovakia, with significant geo-touristic potential.

Acknowledgements The authors are thankful for the financial support of the PKB research from the Slovak Research and Development Agency (project APVV-17-0170) and Slovak VEGA Grant Agency (project no. 2/0052/21). We also wish to thank Dr. Ján Lacika for kindly providing the photos and to an anonymous reviewer for the thorough and constructive review.

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