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Outline of the geology of Slovakia (W. Carpathians)

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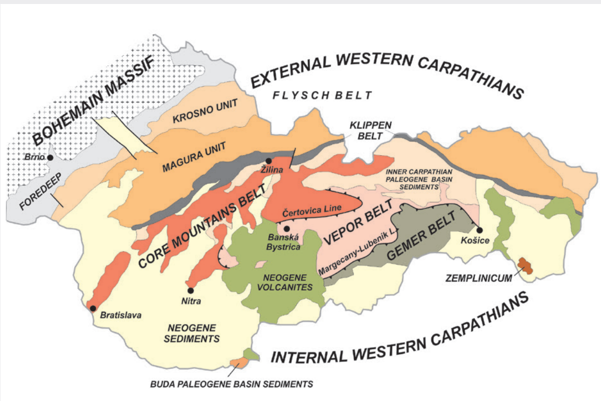
Abstract: The paper provides an overview of the main Alpine and earlier Hercynian (Variscan) tectonic units, as well as superimposed Cenozoic "post-nappe stacking" formations. Simplified localization maps of mentioned tectonic units, lithostratigraphic tables with emphasis on typical lithostratigraphic members and models of the assumed paleogeographical positions are included. References have been selected with an intention to provide more detailed information on a particular issue, resp. tectonic unit. Paper follows dual division of principal tectonic zones into the External (EWECA) and Internal Western Carpathians (IWECA), which reflects different rock composition as well as different time and mechanisms of their structuralization.

Key words: Western Carpathians, tectonics, lithostratigraphy, thrust belt

Graphical abstract



Highlights

- Dual division into External (EWECA) and Internal Western Carpatians (IWECA) is followed after earlier works
- The main Alpine tectonic units in Slovakia are described in the order: EWECA - Outer Group of Nappes (Krosno and Magura nappe systems and Oravicum), IWECA - Lower Group of Nappes (Vahicum and Tatricum), Middle Group of Nappes (Veporicum, Fatricum and Hronicum), Upper Group of Nappes (Gemericum, Turnaicum, Meliaticum and Silicicum), as well as the Zemplinicum with an exceptional status.
- The Upper Cretaceous–Cenozoic sequences are unconformably and transgressively overlying the nappe structures.

Introduction

Information about the geology of Slovakia was published by various authors (e.g. Andrusov, 1968; Maheľ & Buday, 1968; Maheľ, 1974, 1986; Mišík, 1997a; Plašienka et al., 1997; Kováč et al., 2003; Janočko et al., 2006; McCann, 2008; Bezák et al., 2011; Plašienka, 2018). Existing geological maps (Biely et al., 1996a, b; Lexa et al., 2000; Bezák et al., 2004, 2008, 2009; Geologická mapa Slovenska 1 : 50 000, 2013) mostly lack the relevant description of the geological structure of Slovak territory. This contribution provides concise information about tectonics and lithostratigraphy of the principal Alpine tectonic units of Slovakia in a comprehensible form to a foreign reader.

Principal tectonic units of the Western Carpathians – former division based on tectonic belts

The territory of Slovakia is formed by the Western Carpathians. Only southern regions of Slovakia represent a part of the Pannonian Basin system, which extends here from the area of Hungary. The present day geological structure of the W. Carpathians is generally a result of the Alpine orogenic stage, having preserved also remnants of earlier Hercynian (Variscan) evolution.

A tectonic unit is here considered as the three-dimensional rock body with defined borders, its own (unique) lithostratigraphic, metamorphic and structural content and defined tectonic evolution (Fig. 1). Since the second half of 20th century (Andrusov, 1973), the suffix -icum is used

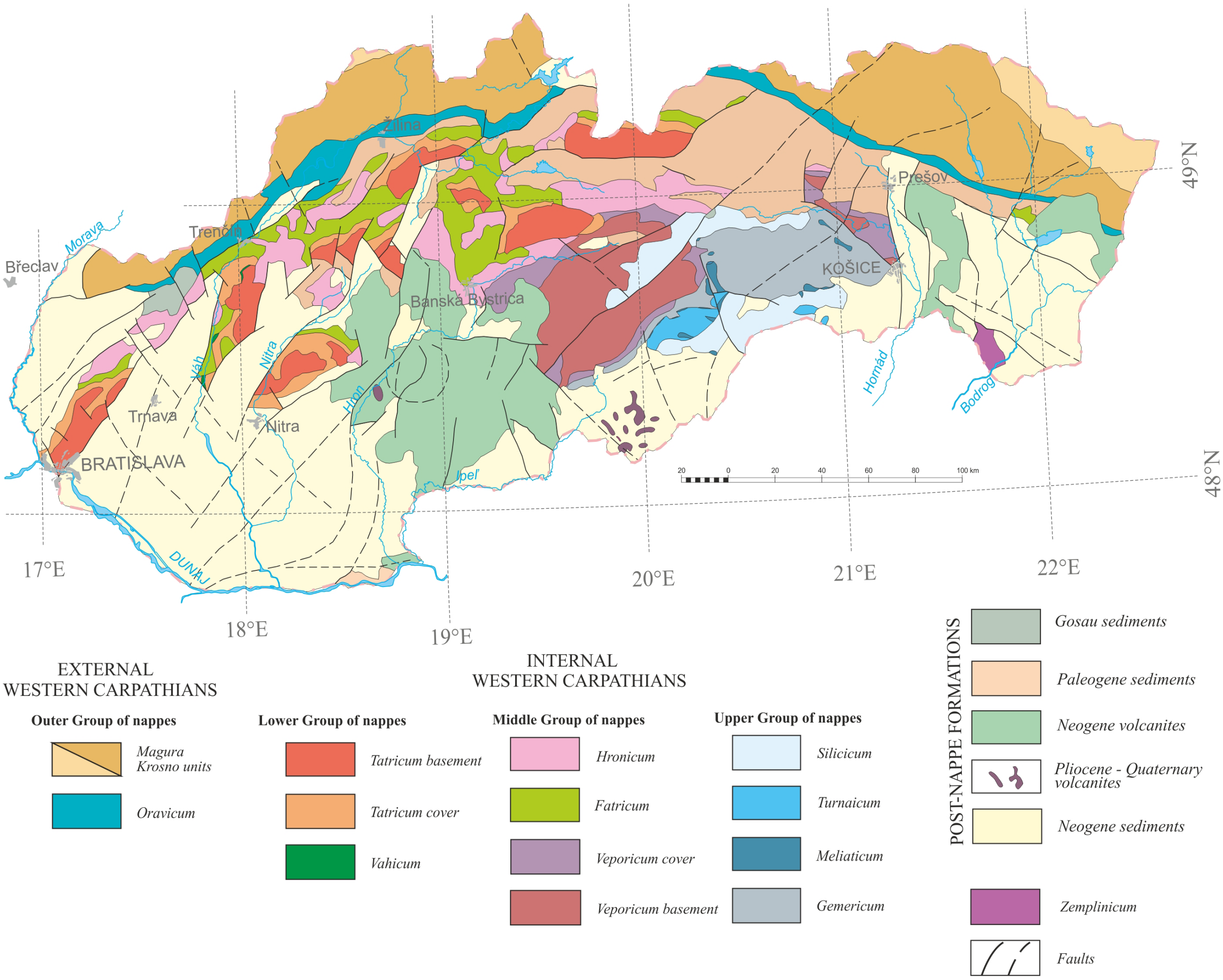


Fig. 1. Position of principal Alpine tectonic units and post-nappe formations in the territory of Slovakia (based on Hók et al., 2014).

for the names of the Western Carpathian Alpine tectonic units.

Tectonic units in the frame of the W. Carpathians are arranged in imbricated structures one above the other, generally thrust from the south to the north (i.e. having northern vergency; Fig. 2). The reason is that the Alpine orogenetic processes produced the horizontal crustal shortening and closed existing sedimentary basins. From the view of recent W. Carpathians it started in the southern - internal regions and proceeded generally to northern – external zones of W. Carpathian belt (Plašienka, 2018).

According to **timing and deformation mechanisms**, the orogenic zone of W. Carpathians is divided into **External Western Carpathians (EWECA)**, containing the Neo-Alpine (Miocene) nappes and the **Internal Western Carpathians (IWECA)** with Paleo-Alpine (Cretaceous) nappe stacking (Fig. 2). The boundary between them is represented by the Klippen Belt zone (Oravicum).

In the Alpine structure of the W. Carpathians, products of the **Hercynian (Variscan) orogenic phase** are preserved in relics, which either were not reworked by the Alpine deformation, or the degree of their Alpine overprint still allows to decipher older tectonic events. The Hercynian structural arrangement suggests the displacement of rock complexes generally from the north to south (or NNW to SSE; i.e. south-vergent). It means that Hercynian orogeny had generally opposite vergency than that of Alpine one (Bezák, 1994; Jacko et al., 1997; Németh, 2002). The main lithotectonic units of the Hercynian (Variscan) tectonic setting were formed due to the Meso-Hercynian lithospheric collision, which was accompanied with a thickening of the crust (380–340 Ma) and intrusion of granitic rocks. Later in the Neo-Hercynian stage (340–260 Ma) the compression was replaced by the extension (probably a post-orogenic relaxation), representing the second period of intrusions of granitic bodies (Broska et al., 2013; Uher et al., 2014). The oldest tectonic events, which for now can be reliably attributed to the Hercynian orogeny, took place during the Early Carboniferous (Mississippian; 360–330 Ma). On the contrary, the sediments of Late Carboniferous

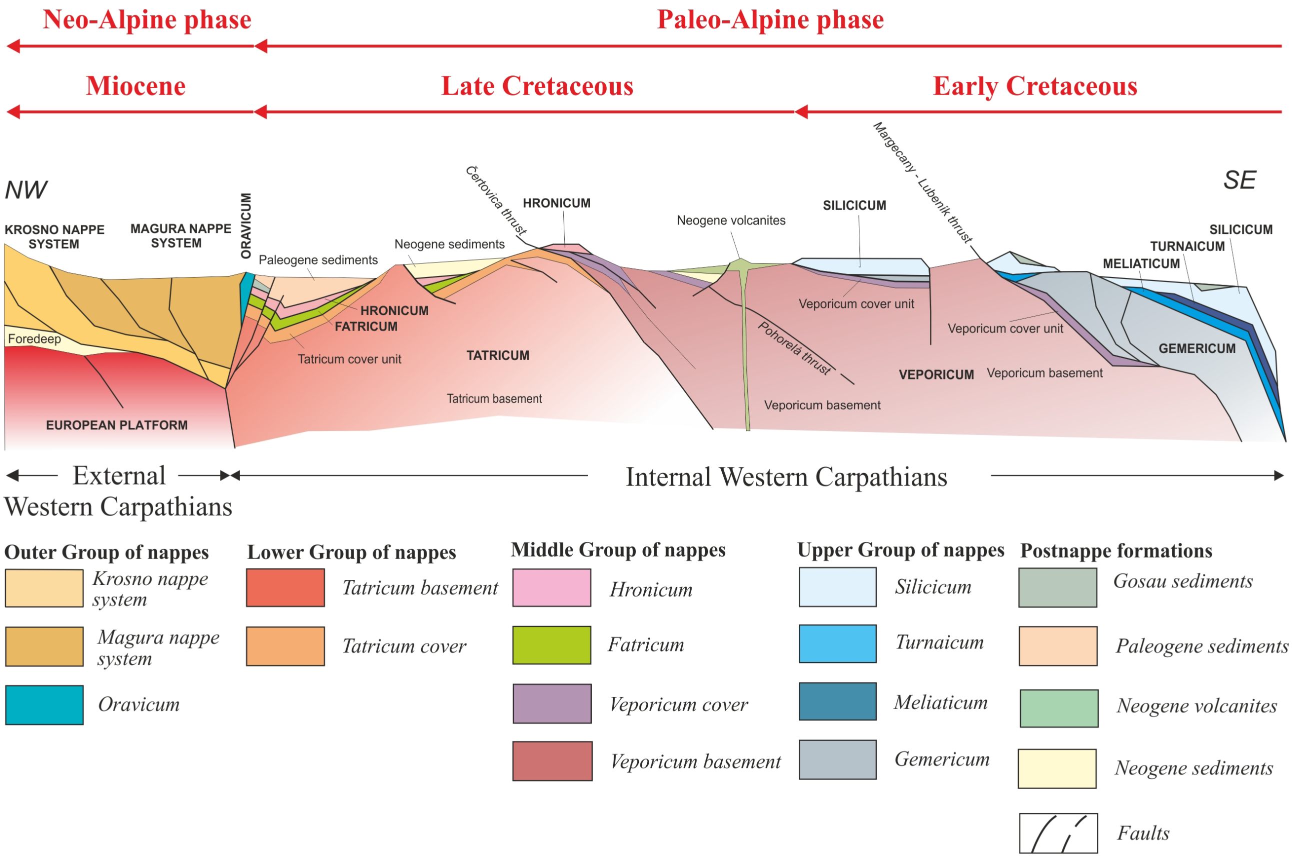


Fig. 2. Schematic cross-section showing the main tectonic units of the Western Carpathians in the territory of Slovakia with marked emplacement timing of particular group of nappes and the age of their tectonic individualization (based on Hók et al., 2014).

age (Pennsylvanian) represent the termination of the Hercynian orogeny in the territory of W. Carpathians. The degree of metamorphic transformation during the Hercynian orogeny can be generally considered to be higher (amphibolite-granulite facies) than during the Alpine tectono-metamorphic processes.

The **Alpine nappe emplacement** in the external zones of the W. Carpathians (EWECA) culminated during the **Neo-Alpine phase** in Neogene, resp. the Miocene. The EWECA include the Flysch Belt, consisting of the Krosno and Magura nappe systems (displaced Cretaceous and Paleogene sediments) as well as the independent Oravic (or Klippen Belt) tectonic units, built of Mesozoic sediments (Fig. 3).

The **Carpathian foredeep** is situated outside the territory of Slovakia (Fig. 3). It consists of autochthonous predominantly sandy and clayey sediments of the Neogene age, lying on their original basement - the European Platform (in their northern part) and Bohemian Massif (northwestern part). Assignment of the external Carpathian foredeep sediments into the W. Carpathian structure is disputable, because they represent autochthonous sedimentary cover of neighbouring basement units.

The **Flysch Belt** of EWECA represents massive accretionary wedge, a nappe stack composed of the Cretaceous and mainly the Paleogene formations in typical "flysch" development, with alternating clayey shales and sandstones, deposited in the deep-water environment by the gravity flows, mostly of the turbidity currents.

The Pieniny Klippen Belt (or the Klippen Belt, **Oravicum**) represents a narrow and intensively deformed belt. Name "Klippen Belt" is derived from their characteristic morphotectonic features – the steep cliffs – so-called klippen, towering above the surrounding soft relief. The "klippen" are composed of Jurassic and Early Cretaceous limestones that are more resistant to erosion than the surrounding Upper Cretaceous and Paleogene marlstones and clayey sediments.

The principal **Paleo-Alpine tectonic units**, internally (i.e. south) of the tectonic unit of Oravicum, are as follows: the Vahicum, Tatricum, Fatricum, Veporicum, Hronicum, Gemericum, Bôrka Nappe, Meliaticum, Turnaicum and Silicicum. These tectonic units, forming IWECA, are traditionally arranged in the higher order zones termed as "belts" (the Core mountains Belt, Vepor Belt and Gemer Belt, Fig. 3).

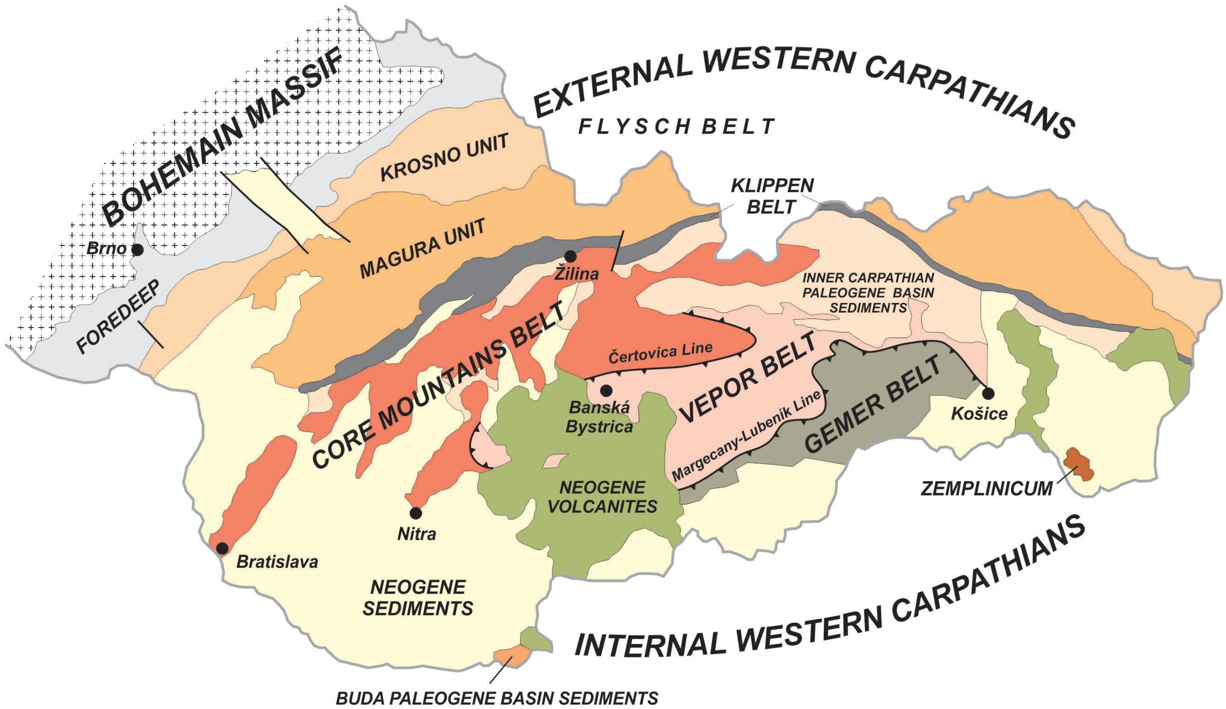


Fig. 3. Division of the Western Carpathians into separate sub-zones and belts (modified after Hók et al., 2001).

The **Core mountains Belt** represents northernmost and the most external tectonic unit of IWECA (Fig. 3). This belt is separated from the south located Vepor Belt by the Čertovica thrust on its southern (internal) margin. The Čertovica thrust is a product of Lower Cretaceous thrusting of Veporicum on Tatricum. The term *Core mountains* (originally Uhlig's (1903) *Kerngebirge*) is derived from the typical morphotectonic phenomenon, where the central part of the mountain range (core) is formed by the crystalline basement rocks (granites and crystalline schists) and these are overlain by the Late Paleozoic and mainly the Mesozoic sedimentary (cover) sequences, and often also directly by the Cenozoic sediments (e.g. in the Malé Karpaty Mts.). Besides Tatricum, tectonic units of the Vahicum, Fatricum and Hronicum are involved in the geological structure of the Core mountains. The Core mountains belt encompasses the Malé Karpaty Mts., Považský Inovec Mts., Žiar Mts., Strážovské vrchy Mts., Malá Fatra Mts., Veľká Fatra Mts., Tatry Mts., western part of the Nízke Tatry Mts. (so-called Ďumbierske Tatry Mts.) and the western part of the Tribeč Mts. (so-called Zobor part; Mazúr & Lukniš, 1986).

The largest part of the **Vepor Belt** is represented by the tectonic unit of Veporicum. Similarly as Tatricum, also the Veporicum is composed of Early Paleozoic crystalline basement and Late Paleozoic–Mesozoic sedimentary cover. Besides the Veporicum, other tectonic units participating in the structure of the Vepor Belt are represented by the Hronicum and Silicicum. The Vepor Belt is separated by the Čertovica thrust from the belt of Core mountains, located northwest, and the Margecany-Lubeník thrust divides it from the Gemer Belt, thrust above the Vepor Belt from the south (Fig. 3).

The Vepor Belt covers large areas of Central Slovakia (Fig. 5) - generally the Veporské vrchy Mts., Stolické vrchy Mts. and the Revúcka vrchovina Highland, eastern part of the Nízke Tatry Mts. (so-called Kráľovoholské Tatry), northeastern part of the Tribeč Mts. (so-called Rázdiel Part), Kozie chrbty Mts., Branisko and Čierna hora Mts. Apart from the aforementioned regions, the Vepor Belt, or the Veporicum, crops out from below the Neogene volcanites (traditionally named neovolcanites) in the form of so-called "islands" or horsts. The largest horsts are the Sklené Teplice Horst between the towns of Sklené Teplice and Vyhne, the Pliešovce Horst exposed directly in the Pliešovce and the Lieskovec Horst east of the Zvolen town.

The **Gemer Belt** represents the most internal and structurally highest belt in the Alpine nappe structure of the W. Carpathians (Fig. 3). It is located in the Volovské vrchy Mts. and the Slovenský kras Mts. and includes tectonic units of Gemericum, Bôrka Nappe, Meliaticum, Turnaicum and Silicicum.

New tectonic division of the Western Carpathians – combination of tectonic belts and groups of nappes

It is obvious that division of W. Carpathians to External (EWECA) and Internal (IWECA) does not encounter any contradiction, because the tectonic individualization of **External W. Carpathians (EWECA)** took place during the **Neo-Alpine phase in Neogene**, i.e. later than that of IWECA (Paleo-Alpine phase; Cretaceous). EWECA includes Krosno and Magura nappe system and Oravicum. These units are built of Mesozoic to Paleogene sediments, and particularly the Krosno and Magura nappe systems are represented by the "flysch" character deep-water sediments deposited by the gravity flows (turbidity currents). Aforementioned units represent the **Outer group of nappes**, which is present only in **External W. Carpathians (EWECA)** (Fig. 2).

The situation is however more complex internally (south) of the Klippen Belt (Oravicum), where the individualization of **IWECA** took place earlier - in **Cretaceous.** The vertical division, however, raises the question how to lead the boundary between the particular belts in a way not split the same tectonic unit being encompassed in several belts (cf. Andrusov et al., 1973; Maheľ, 1983; Mišík et al., 1985; Plašienka, 1999). The tectonic division based on tectonic stacking of the main elements of the nappe structure, being separated (individualized) at different times on subhorizontal (usually overthrust) contacts, allows to allocate four main groups of nappes (Outer, Lower, Middle and Upper) with different mutual structural superposition and the age of tectonic individualization (Hók et al., 2014; Fig. 1). The subhorizontal division in this case is dominating over the vertical division into belts.

The **Lower group of nappes** of **Internal W. Carpathians** (IWECA) is represented by the tectonic unit of Tatricum, composed of crystalline basement rocks and Late Paleozoic/Mesozoic sedimentary cover, as well as tectonic unit of Vahicum. The Lower group of nappes was structuralized in the late Cretaceous to Paleogene (Figs. 1 and 2).

The **Tatricum** is generally regarded as the lowermost and sub-autochthonous unit of the IWECA. In tectonic superposition above Tatricum there are present several allochthonous tectonic units: the lower unit, or nappe, is called Fatricum, the structurally higher unit is represented by Hronicum. Both tectonic units, Fatricum and Hronicum are ranging here from to the Middle group of nappes, where they belong together with Veporicum.

The **Vahicum** is hypothetical tectonic and paleogeographic unit (Maheľ, 1981). The Belice Unit (Plašienka et al., 1994) in the Považský Inovec Mts. was considered as the main representative of the Vahicum in the present surface occurrences. Structural position of the Belice Unit is, however, in contradiction with previous interpretations (Pelech et al., 2016).

The **IWECA Middle group of nappes** was structuralized during the Late Cretaceous (Cenomanian–Campanian) and is formed by the tectonic units of Veporicum, Fatricum and Hronicum.

The **Veporicum** is predominantly composed of crystalline basement (granitoids, gneisses and mica schists). Based on lithostratigraphy of autochthonous Late Paleozoic and Mesozoic sediments, the Veporicum is divided into Northern and Southern Veporicum, separated by the Pohorelá thrust (Fig. 2).

The **Fatricum** is a tectonic unit of nappe character, transferred from the former position on the contact of the present Veporicum and Tatricum. Synonymously it is often referred as the **Krížna Nappe**. It occurs in allochthonous position in the Core mountains Belt and overlies the Tatricum. Stratigraphic range is very variable, especially in lower members. It is a result of closing of its former sedimentary basin and related decollement with movement of the Fatricum thrust sheet on its stratigraphic members with suitable rheology. Sedimentary sequence usually terminates with the earliest Upper Cretaceous (Cenomanian) "flysch"-like sediments (Poruba Fm.).

The **Hronicum** represents, similarly as the Fatricum, a stack of partial nappe bodies structuralized during Late Cretaceous from the facially subdivided sedimentary basin. Synonymously it is designated as the **Choč Nappe**. It occurs in the Core mountains Belt as well as in the Vepor Belt and overlies the Fatricum and Veporicum. Unlike the Fatricum, the original root area of the nappe is not known, although it is evident that it comes from southerly (more internal) paleogeographic zones than the Fatricum. The Hronicum sedimentary basin was formerly assumed between the Vepor Belt and Gemer Belt. Stratigraphic range of Hronicum is from Carboniferous to the Early Cretaceous. The complete sedimentary sequence is however nowhere preserved. The most typical sequences of Hronicum are composed mainly of Triassic carbonates (limestones and dolomites). Carboniferous and Permian volcanites and sediments represent very characteristic lithostratigraphic members of Hronicum, forming thick rock sequence of the Ipoltica Group.

The **IWECA Upper group of nappes** is located southernmost or most internal, representing tectonically the highest group of nappes of IWECA. It is composed of Paleozoic rock sequences of Gemericum and mostly Mesozoic complexes of the Bôrka Nappe, Meliaticum, Turnaicum and Silicicum as the Early Cretaceous nappe structures (Fig. 2).

The **Gemericum** is exposed in a largescale anticlinal dome – anticlinorium, which forms the region of Volovské vrchy Mts. (the Spišsko-gemerské rudohorie Mts., resp. Spiš-Gemer Ore Mts.). It substantially differs from the other basic W. Carpathian tectonic units by different rock composition, age and metamorphism. Unlike the Tatricum and Veporicum it is composed mainly of the low-grade metamorphic rocks with dominating Paleozoic age – the Early Paleozoic basement and its mostly Late Paleozoic sedimentary cover.

The **Bôrka Nappe** contains rock sequences of Permian to Middle Jurassic age. They are characterized by higher-grade metamorphic overprint, reaching in Mesozoic members the subduction related high-pressure and low-temperature (HP-LT) blueschists facies. The parallelization of the protolith of metamorphites with the cover sequences of southern Gemericum indicates that they are most probably derived from the zone between the Gemericum and Meliaticum (e.g. Németh, 1996, Fig. 4 ibid.).

The **Meliaticum** is a tectonic unit of nappe character, known in present day surface only in relics, cropping out from below the nappes of Turnaicum and Silicicum (Fig. 2). It represents a tectonic melange of Triassic carbonates, radiolarites and volcanites, occurring as blocks in the dark and black Jurassic shales and radiolarites. Sedimentary sequences indicate that it represents former zone of oceanic character. During the convergence, the Bôrka Nappe rocks were subducted and exhumed. Subduction of oceanic crust and the gradual closure of the Meliaticum basin caused the displacement of rock complexes originally deposited at the southern margin of this basin (in today's geographical coordinates) and forming the tectonic units of Turnaicum and Silicicum. Decollement and emplacement of the Meliaticum, Turnaicum and Silicicum nappe units represent the beginning of the shortening of the Internal W. Carpathians. Related thrusting and nappe displacements maintained its polarity from the south (internal areas) to the north since Early Cretaceous (in Gemer Belt) to the Late Cretaceous (in the Core mountains Belt).

The **Turnaicum** represents another nappe unit, cropping out from below the Silicicum (Fig. 2) and occurring in the southern part of the Gemer Belt, mainly in the Slovenský kras Karst plateau. Its Late Carboniferous to Late Triassic rock sequence bears characteristic metamorphic overprint. It differs from the Silicicum by the occurrence of the Triassic pelagic carbonate facies, by this way forming the transitional member between Meliaticum and Silicicum during the basin evolution.

The **Silicicum,** often referred as the **Silica nappe,** is structurally the highest tectonic unit of the IWECA Alpine nappe structure. It occurs as a relatively flat lying nappe body in the region of Slovenský kras Mts., Slovenský raj Mts., Galmus Mts. and Muránska planina Mts. (Fig. 2). The sedimentary sequence of the Silicicum ranges from the latest Permian–Early Triassic to the Late Jurassic (Callovian to Oxfordian). A substantial part of the Silicicum is built by the Middle and Upper Triassic shallow water limestones (e.g. Wetterstein limestones), often containing abundant fossil remains.

Description of the principal tectonic units

The **External Western Carpathians (EWECA)** encompass the Flysch Belt and Klippen Belt (Fig. 4). The sediments of the **Carpathian Foredeep** represent autochthonous Miocene–Pliocene sedimentary cover of the European Platform as well as Bohemian massif and are generally situated below the Krosno nappe system. Re-

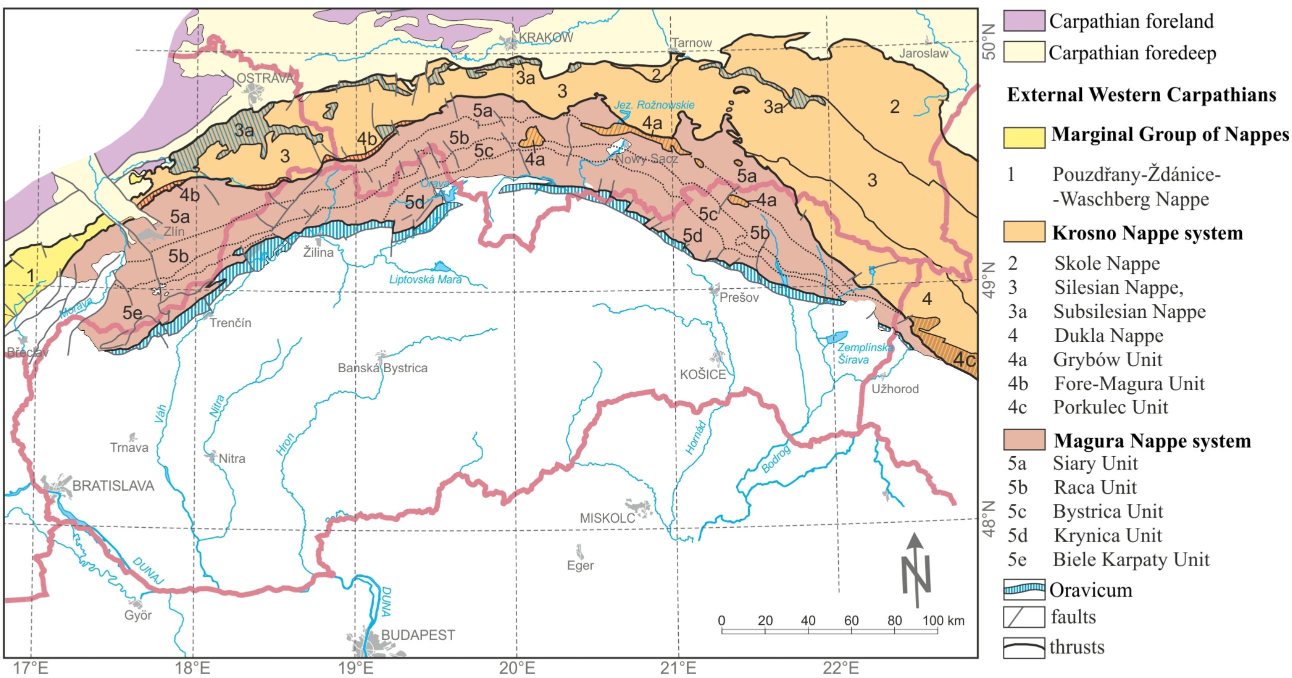


Fig. 4. Map of the External Western Carpathian nappes.

garding its position, the Carpathian foredeep should not to be assigned to the Carpathian system.

Flysch Belt – Krosno and Magura nappe system

EWECA are mostly formed by the Cretaceous to Paleogene deep-sea "flysch" deposits. Original flysch basins were bordered by continental crust ridges, which provided a clastic material to the basins. The Flysch Belt is one of the few zones being continuous across the whole Carpathian arc.

EWECA represents a system of rootless nappes amputated from their former basement and transported to the foreland represented by the European platform and the sediments of Carpathian foredeep.

Flysch Belt consists of several nappe systems arranged in imbricated style - the internal units are thrust over the external ones. Mostly the Magura nappe system occurs in Slovakia, and represents the southernmost part of the Flysch Belt. The underlying Krosno nappe system includes the Dukla, Silesian, Skole and other smaller nappes (see Fig. 4). The lithostratigraphic units within nappe systems are shown in Fig. 5. The Krosno nappe system is generally characterized by variegated claystones, the Magura nappe system by prevailing sandstones.

The sedimentary basins were situated in the area between the IWECA block and the European Platform. Similarly, as the area of the Carpathian foredeep, also the Magura Basin was connected to the west with the flysch foreland of the Eastern Alps (Rhenodanubian Flysch) and similarly to the north and east to the flysch nappes in present Poland and Ukraine (in the Eastern Carpathians). The oldest preserved EWECA sediments are represented by the Upper Jurassic limestones, marls and carbonate flysch. However, it can be assumed that the formation of future Flysch Belt basins is related to the regional extension period in the area of the W. Carpathians, which took place in the Middle Jurassic (Plašienka, 2018). The former sedimentary area of the EWECA was gradually closed since the end of middle Eocene (the Biele Karpaty Unit) up to the early Miocene (the Krosno nappe system). The youngest sediments are represented by the locally preserved Miocene deposits (Karpatian).

Marginal nappe system

The outermost (most external) EWECA unit is Pouzdřany-Ždánice-Waschberg Nappe, not reaching the territory of Slovakia (Fig. 4) and representing the allochthonous body (nappe) over the Bohemian Massif margin.

Krosno nappe system

Several tectono-lithofacial nappes (or units) north of the Magura nappe system form the Krosno nappe system. They are arranged from outer to inner as follows: Skole, Sub-Silesian, Silesian and Dukla (Grybów, Fore-Magura) nappes. Only Silesian and Dukla (Grybów) nappes reach the territory of Slovakia (Lexa et al., 2000).

The Skole Nappe is situated NE in the foreland of Sub-Silesian Nappe on Polish territory, not reaching the territory of Slovakia. The Sub-Silesian Nappe crops out as a thin body on the border of Skole and Silesian nappes. The Silesian Nappe is found in a limited extent in the northern Kysuce region (Potfaj et al., 2002, 2003), where only the Godula succession is present. Sandstone-rich Istebna Fm., Sub-Menilite Fm. with spherically disintegrating Ciężkowice sandstones, Menilite Fm. and Krosno Fm. are typical.

The Dukla Nappe reaches the NE edge of Slovakia. Its sedimentation area was initially associated with the Magura Basin. Younger deposits have affinity rather with the Silesian Nappe. To the west, Dukla Nappe passes into thin bodies of Grybów and Fore-Magura nappes, which underlie the Magura Nappe and crop out in the Smilno tectonic window.

The most characteristic for the Krosno nappe system are the menilite shales or Menilite Formation, composed of brown claystones with bodies of sandstones and black cherts which were formed from diatoms tests during the late Eocene to early Oligocene. Another very characteristic lithostratigraphic unit is the Sub-Menilite Formation of Eocene age, being composed of variegated (red, green and grey) claystones and sandstones. The menilite shales are known as the main oil-bearing horizon across the EWECA.

Magura nappe system

The Magura nappe system is the largest tectonic unit of the EWECA, and represents the main part of the EWECA on the Slovak territory (Cieszkowski, 1992; Lexa et al., 2000; Oszczypko et al., 2015; Kaczmarek et al., 2016). The Magura nappe system is divided into the partial tectono-lithofacial units. In ordering from the north (external units) to south (internal ones) these are the Siary, Rača, Bystrica, Krynica and Biele Karpaty units. Together with the Biele Karpaty Unit, which occurs only in the western part of the zone and has a special status, the Magura nappe system forms tectonically the highest part of EWECA. Moreover, the Krynica Unit was as well backthrust southward over the Klippen Belt (Oravicum) in the Orava region (Pešková et al., 2012).

The rocks of the Magura nappe system have deposited in a few hundred kilometers wide Magura Basin having 2,000 to 4,000 meters depth. The time, when the Magura Basin started to open, has not been reliably confirmed yet, because the nappe is completely detached from its substratum. There is assumed the Upper Jurassic time of its opening (Pícha et al., 2006; Hrouda et al., 2009; Golonka et al., 2013; Oszczypko et al., 2015). Pelagic claystones and thin-bedded "flysch" deposits (Ropianka Fm. and Beloveža Fm.) deposited in the deep-sea environment on the bottom formed probably by oceanic or distal continental crust. Along with thin-bedded deposits the red and green (variegated) claystones, mudstones or marls have deposited especially during the Upper Cretaceous and lower Eocene (Cebula Fm., Ondrášovec Mb. and Lower Beloveža Mb.). Sandy fans and lobes penetrated into the basin and partly also on the slopes of the basin. Clastic turbidity sedimentation dominated since Maastrichtian. Each fan deposited hundreds of meters of sandstones (less conglomerates).

According to petrographic and sedimentological properties, we can distinguish several major types of sandstones in the Magura nappe system: Soláň (Mutne), Szczawina, quartz-carbonate, Riečky, Skawce, glauconitic and Magura type sandstones. The petrographic composition of the sandstones reflects the nature of the source area (ridges/cordilleras). Its sedimentary structures are determined by the nature of the current transport, global temperature and sea-level changes. The Malcov Fm. represents the fill of smaller piggy-back sub-basins. The north-vergent thrusting by the end of Oligocene and in early Miocene until Badenian caused the spatial reduction and the origin of the fold and thrust setting. The boundary of the Krosno and Magura nappe systems in the Moravia is characterized by the occurrence of Jurassic limestones (olistoliths, formerly known as the so-called External Klippen Belt). Dozens of lithostratigraphic units have been determined by the combination of mentioned lithotypes and lithofacies (Fig. 5).

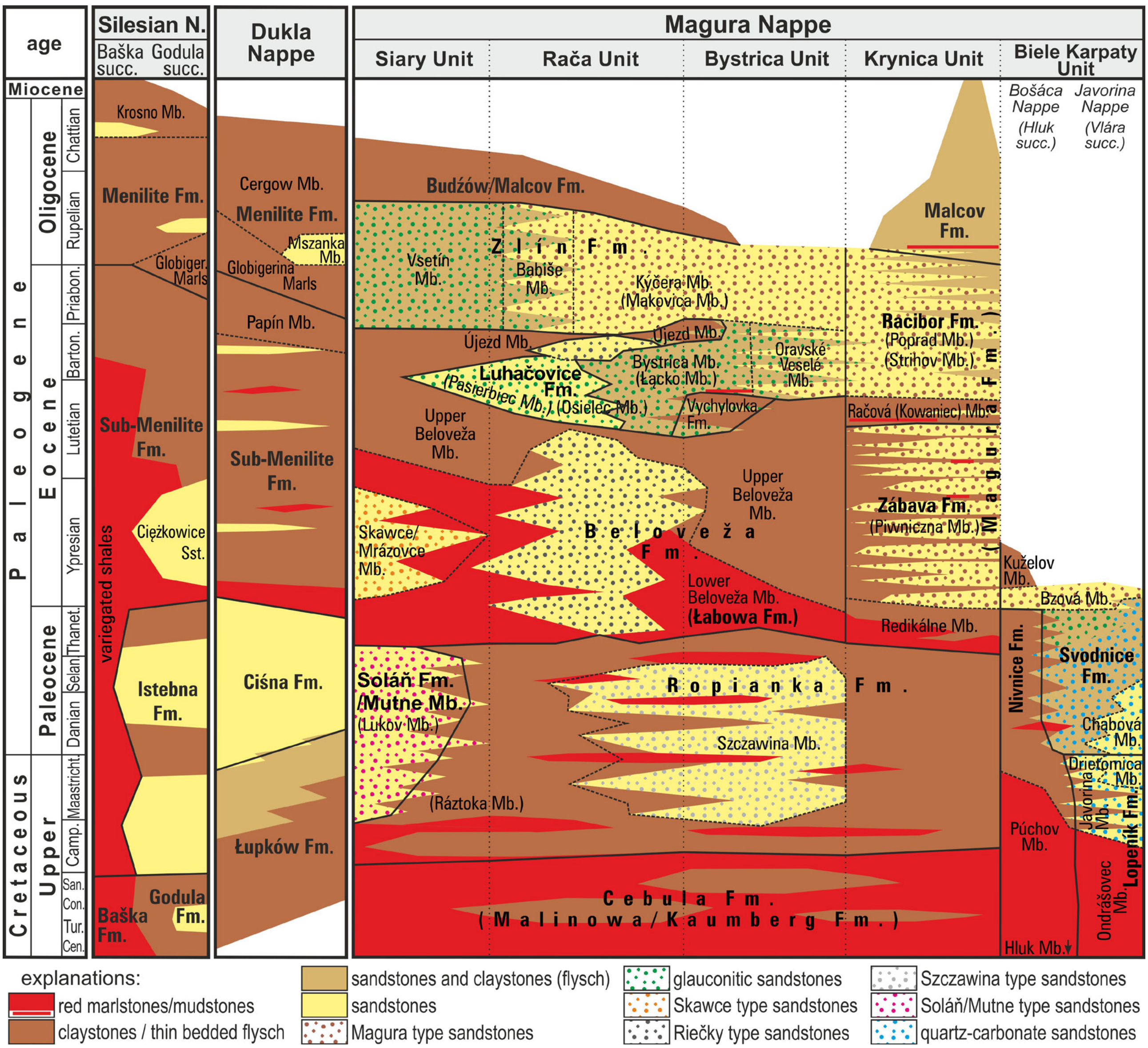


Fig. 5. Simplified lithostratigraphic scheme of the Flysch Belt in the Slovak territory (modified after Potfaj, 1993; Lexa et al., 2000; Teťák et al., 2016).

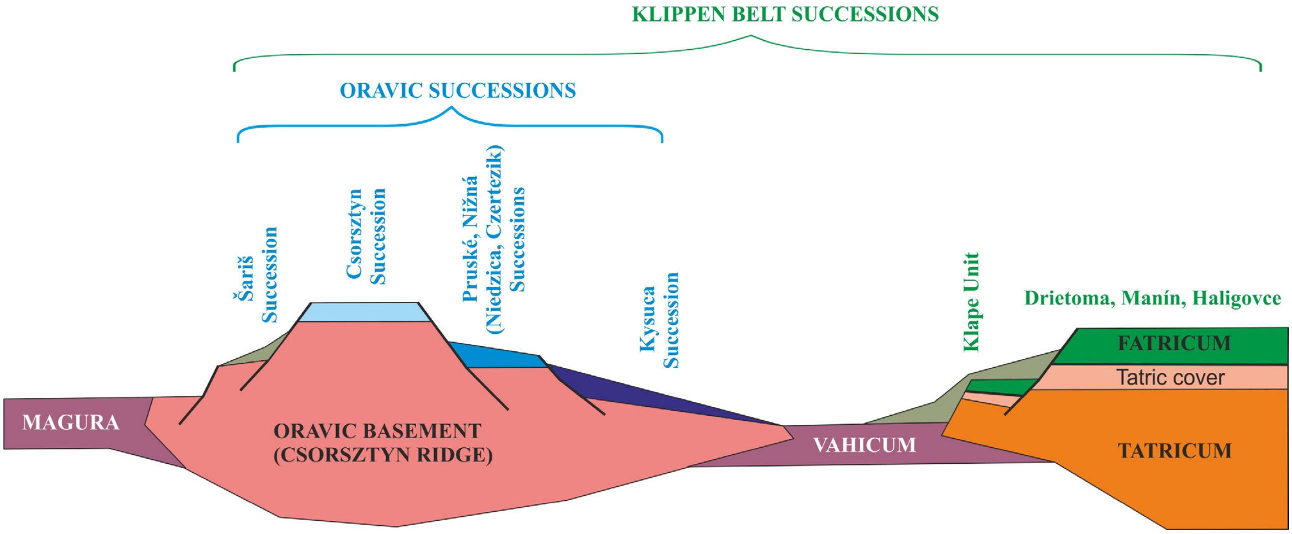


Fig. 6. Supposed paleogeographic position of the Oravic and Klippen Belt sensu lato successions during Jurassic period.

Klippen Belt – Oravicum

The Klippen Belt represents narrow (max. 15 km wide) and more than 600 km long morphotectonic structure on the boundary between the Internal and External W. Carpathians (Figs. 1 and 4). The Klippen Belt contains the Oravic rock successions as well as successions derived from the IWECA (Fig. 5).

The exceptional tectonic complexity and numerous identified rock successions (Mišík, 1997b) and formations (e.g. Birkenmajer, 1977) of the Klippen Belt are related to the fact that it suffered multiphase deformation: for the first time together with the Internal Western Carpathians and for the second time after the Paleogene with the Flysch Belt. Structure was additionally complicated by the strike-slip faults longitudinally segmenting its units. The essential segmentation of sedimentary basins of the future Klippen Belt, similarly as in the case of other W. Carpathian tectonic units, occurred in the Jurassic.

The Oravic units were during the Jurrasic situated in the paleogeographical position surrounding the hypothetical continental ribbon known as the Czorsztyn ridge (Fig. 6). The Czorstyn ridge was separated from the European platform by the oceanic domain of the Northern Penninicum or the Magura ocean in the north, and from the Internal Western Carpathian block by the oceanic domain of the Southern Pennicum or the Vahicum (Plašienka, 2012; Plašienka & Soták, 2015). According to its different facial character, resulting from differing paleogeographic areas, several sedimentary successions were distinguished, incl. the Czorsztyn and Kysuca, as well as the Niedzica/Pruské and Czertezik successions termed as the **Oravicum**.

The most widespread are the Czorsztyn and Kysuca (also Kysuca-Pieniny) successions. They are tectonically amputated and displaced from their former substratum, therefore their sedimentary sequence starts with Lower Jurassic rocks.

The Czorsztyn succession is characterized by generally shallow water sediments. The most typical member is represented by the Czorstyn Limestones (Middle to Late Jurassic) - the red nodular limestones with abundant fossils, especially ammonites. Another typical member is a sandy-crinoidal limestone (Middle Jurassic). The Czorsztyn sequence occurs in the outer – northern margin of the Oravicum/Klippen Belt and represents most externally located sequence among the Klippen Belt units.

The Kysuca succession is typical by Jurassic deep-water sediments - the Allgäu Formation, green and red radiolarites and Pieniny Limestone.

The Czorsztyn and Kysuca successions are typical with variegated (red, green and grey) marlstones (or calcareous claystones) and marly limestones mostly of the Late Cretaceous age. They are known under various local names (e.g. Púchov Marls) and often collectively they are referred as the “Couches Rouges”.

The Klape Unit is present in the Považie (Middle Váh Valley) and Orava regions in the frame of Klippen Belt. The most typical is the flysch formation predominantly of the Late Cretaceous age, containing several characteristic members with exotic material (Orlové Sandstone, Spherosiderite Beds, Upohlav Conglomerates). The Klape sequence is folded together with Klippen Belt main sequences (Czorstyn and Kysuca) and in the majority of occurrences the strata are in an overturned position.

The Manín Unit, known only in the Middle Váh Valley (name is derived from the Manínska tiesňava Gorge), is most internal sequence of the Klippen Belt. The paleogeographic position of the former sedimentary basin is problematic and placed on the northern margin of the Tatricum, as well as on the northern margin of the Fatricum (i.e. southern edge of Tatricum). The most characteristic part of this Early Jurassic to Middle Cretaceous sequence is the Urgonian Limestone (Manín Fm.) - the organodetritic limestone with abundant macrofossils (algae, corals, rudists). With the Manín Unit in the eastern part of the Klippen Belt **the Haligovce Unit** is correlated (Mišík, 1997b).

The Drietoma Unit is a structural element derived from the Fatric nappe system incorporated into the western segment of the Klippen Belt. Typical lithostratigraphic members of the Upper Triassic (Norian) – Lower Cretaceous (Berriasian) Drietoma Unit are the Carpathian Keuper and Allgäu Fm.

The **Internal Western Carpathians (IWECA)** encompass following tectonic units, individualized in the Cretaceous: Vahicum, Tatricum, Fatricum, Hronicum, Veporicum, Gemericum, Bôrka Nappe, Meliaticum, Turnaicum and Silicicum. These units are present in the Core mountains Belt, Vepor Belt as well as the Gemer Belt (Figs. 1 and 3). In the subhorizontal division of W. Carpathians into the separate Alpine groups of nappes, the Vahicum and Tatricum represent the Lower Group of Nappes, the Fatricum, Hronicum and Veporicum represent the Middle Group of Nappes and the Gemericum, Bôrka Nappe, Meliaticum, Turnaicum and Silicicum represent the Upper Group of Nappes (Fig. 1).

The Lower Group of Nappes

The rock complexes of the Lower Group of Nappes (Vahicum and Tatricum), crop out mainly in the Core mountains Belt (Figs. 2 and 7).

Vahicum

The Vahicum is a hypothetical tectonic unit paleogeographicaly situated in the frontal part of the IWECA (Fig. 6) and considered as an equivalent of the Alpine Penninicum (Maheľ, 1981). Supposed oceanic crust of the Vahicum is unknown from the surface presence. Some authors parallelize Vahicum with occurrences of Upper Cretaceous Horné Belice Group (Belice Unit) in the Považský Inovec Mts. (Plašienka et al., 1994). Substantial part of the Horné Belice Group is represented by the Late Cretaceous (Turonian–Maastrichtian) turbidites ("flysch"), with occurrences of olistoliths of crystalline basement, and Early Triassic to Upper Cretaceous sediments (Rakús in Ivanička et al., 2011; Pelech et al., 2016). Similar formations also occur in the borehole SBM-1 Soblahov east of Trenčín (Maheľ, 1985), as well as above Tatric sedimentary cover east of Piešťany (Pelech et al., 2017). The sediments of the Horné Belice Group in the Považský Inovec Mts. are therefore of unclear tectonic affiliation and probably represent a remnant of larger sedimentary wedge-top basin adjacent to the IWECA area (Pelech et al., 2016).

Tatricum

Tectonic unit of Tatricum contains Hercynian crystalline basement rocks (granitoids, gneisses and mica schists), covered by the Late Paleozoic (rarely Carboniferous, more often Permian) and Mesozoic rocks, deposited directly on the basement.

The crystalline basement rocks of the Tatricum were formed by the Hercynian magmatic and tectono-metamorphic processes. Concerning the Hercynian structure, it is not possible to distinguish between the Tatricum and Veporicum crystalline basements, forming during Hercynian orogeny the uniform stabilized unit, later overlapped by cover sequences. The Hercynian tectonics

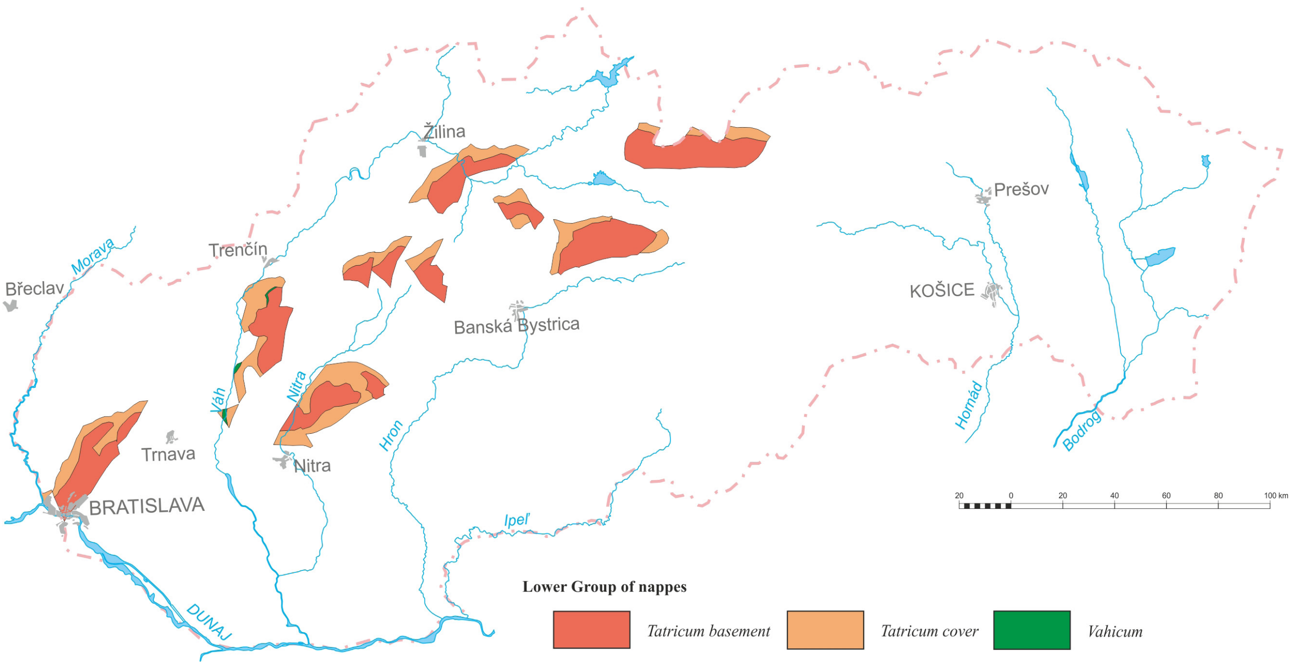


Fig. 7. Position of rock complexes of tectonic units of Vahicum and Tatricum of the Lower Group of Nappes (based on Hók et al., 2014).

had the opposite polarity (south-vergent) than the Alpine one – so being thrust generally from the north to south, the high grade metamorphic rocks were structurally the highest and their relics are today found in the northernmost (most external) part of this unit and *vice versa* – the low grade metamorphic rocks are the lowest and their relics are preserved in the south (Bezák, 1994). The Alpine north-vergent nappes overprinted the pre-existing structure, making the reconstruction of the original position of the Hercynian tectonic units rather complicated (Hrouda et al., 2002). Based on the present state of knowledge, it is possible to reconstruct the Hercynian structure into the following three units (Bezák, 1994):

Upper Lithotectonic Unit (ULU) – composed of high-grade metamorphic rocks (gneisses, migmatites, granitoids and amphibolites) it is present predominantly in the Core mountains;

Middle Lithotectonic Unit (MLU) – forms the substantial part of the Veporicum crystalline basement and consists of gneisses, mica schists and relicts of low-grade metamorphic rocks;

Lower Lithotectonic Unit (LLU) – is present in southernmost zones of the Veporicum and consists of low grade metamorphic crystalline schists.

Lithological composition of the aforementioned units is even more complicated in detail. Lower-grade metamorphic sequences occur within each lithotectonic unit and paragneisses are intruded by granitoid rocks of different ages (Bezák et al., 2004). The Upper Lithotectonic Unit is overlain by a separate complex with characteristic low-grade metamorphic rocks known as the Upper Epizonal Complex (e.g. the Pernek Group in the Malé Karpaty Mts.).

Upper Lithotectonic Unit

Protolith of the ULU metamorphites was represented mainly by greywackes with smaller proportion of sandstones and basic volcanic rocks. These complexes were partly intruded by granitoids, later transformed to orthogneisses.

The reconstruction of the tectonic relationships indicates that these complexes in the highest position are usually overlying the medium-grade metamorphic rocks. It is best seen in the Západné Tatry Mts. (Janák, 1994) and in the eastern Nízke Tatry Mts. The ULU occurs mainly in the Core mountains Belt (Tatry, Nízke Tatry, Branisko a Čierna hora, Malá Fatra, Strážovské vrchy and Považský Inovec Mts.).

The ULU contains also probably Early Paleozoic low-grade metamorphic complexes (greenschist facies; so-called upper epizonal complexes) occurring in isolated occurrences within the higher metamorphic crystalline basement rocks of the Tatricum and Veporicum, having local names according their regional distribution. Locally they overlie the older granites (Klinisko Phyllites on the northern slopes of the Ďumbierske Tatry Mts), or they are affected by the contact metamorphism of nearby granitoids (i.e. being metamorphosed by the heat rising from the granite magma, e.g. Harmónia Series or Pezinok Group in the Malé Karpaty Mts). Other occurrences encompass the metasediments in the Bukovecká dolina Valley on the southern slopes of the Ďumbierske Tatry Mts. and occurrences in the Veporicum crystalline basement – the Jánov grúň Complex, Predná hoľa Complex and the Krakľová Fm.

Middle Lithotectonic Unit

The Middle Lithotectonic Unit is known mainly from the Veporicum (Putiš et al., 1997), however occurs also in several Core mountains as the Malé Karpaty Mts., Považský Inovec Mts. and Tribeč Mts. MLU is built of mica schist to gneiss complexes with amphibolites, locally orthogneisses and minor metaquartzites, graphitic gneisses and metamorphosed sedimentary Fe-ores. Several complexes of the MLU are described from the Northern Veporicum (Hron, Čierny Balog and Kráľova hoľa complexes).

Lower Lithotectonic Unit

The low-grade metamorphic complexes with variegated lithology, assigned to the LLU, occur in the Southern Veporicum (e.g. Ostrá, Klenovec and Sinec complexes), as well as within the Pezinok-Pernek Series (Pernek Group) in the Malé Karpaty Mts.

The vast majority of the Tatricum granitoid rocks are Carboniferous in age. The youngest granitoid rocks are known in the area of Rochovce (Rochovce granite). They are however known only in the sub-surface position, originally due to their contact metamorphism of the surrounding rocks. The 80 Ma age of intrusion was based on radiometric dating (Hraško et al., 1999).

Tatricum sedimentary cover sequences

The crystalline basement was deeply eroded after the end of the Hercynian tectogenesis and the evolving depressions were gradually filled with the Late Paleozoic continental sediments. Carboniferous sediments are known only in the northern Považský Inovec Mts. (Novianska dolina Fm.). The Permian sediments occur in a limited extent in the Malé Karpaty Mts. (Devín Fm.), Považský Inovec Mts. (Kálnica Group), Tribeč Mts. (Skýcov Fm. and Slopňa Fm.), Malá Fatra Mts. (Stráňanský potok Fm.), Tatry Mts. (Meďodoly Fm.) and Ďumbier part of the Nízke Tatry Mts. (Vážna Fm.). They consist of greywackes, arkoses, sandstones and shales of generally variegated colours (red, purple, green). The composition of the sediments and their weak sorting reflects the proximity of the source area (consisting of granites and crystalline schists clasts) and generally short transport (Vozárová & Vozár, 1988).

The Mesozoic sedimentary sequence starts in the Early Triassic and continues with several gaps up to the Late Cretaceous (Cenomanian) with exception of the

Považský Inovec Mts. (Campanian), Tatry and Veľká Fatra Mts., where the sedimentary record ends in the middle Turonian (Pelech et al., 2017 and references herein). The Lower Triassic rocks in the whole Tatricum region are characterized by the quartzites and shales (Lúžna Fm.), which are discordantly overlying the Permian rocks or more often directly the crystalline basement. The quartzites represent the continental sedimentation, being in the Middle Triassic replaced by the marine carbonate sedimentation (Gutenstein Limestone and Ramsau Dolomite). During the Late Triassic the sedimentation continued in shallower lagoonar and continental (terrestrial) conditions. Succession of versicolour sediments (red, violet, yellow sandstones, shales and dolomites) is referred to as the Carpathian Keuper. The latest Triassic (Rhaetian) in the Tatricum region is characterized by a discontinuity in sedimentation. The continental sediments of the Late Triassic are preserved in the Tichá dolina Valley in the Tatry Mts. (Tomanová Fm.), where the footprints of dinosaur were found (see Niedźwiedzki, 2011). Non-deposition and often a significant erosion occurred in the Early Jurassic due to major paleogeographyc changes in the Tethyan region (Plašienka, 2018). In the Middle Jurassic the sedimentation in the Tatricum was divided into two contrasting facies - the deep-water type facies (Fatra type or synonymously Šiprúň type), containing a Middle Jurassic radiolarites, radiolarian limestones and

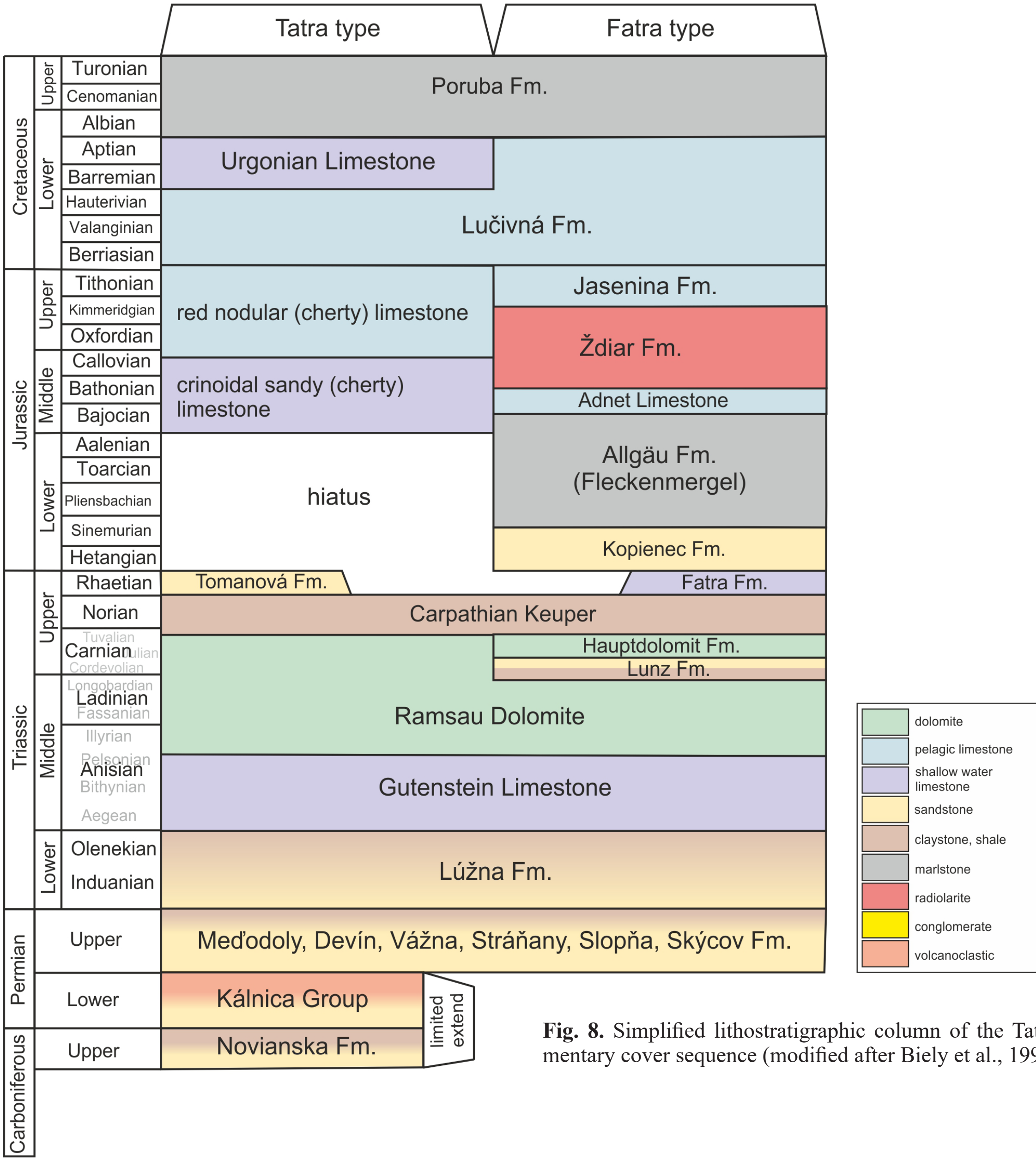


Fig. 8. Simplified lithostratigraphic column of the Tatric sedimentary cover sequence (modified after Biely et al., 1996a).

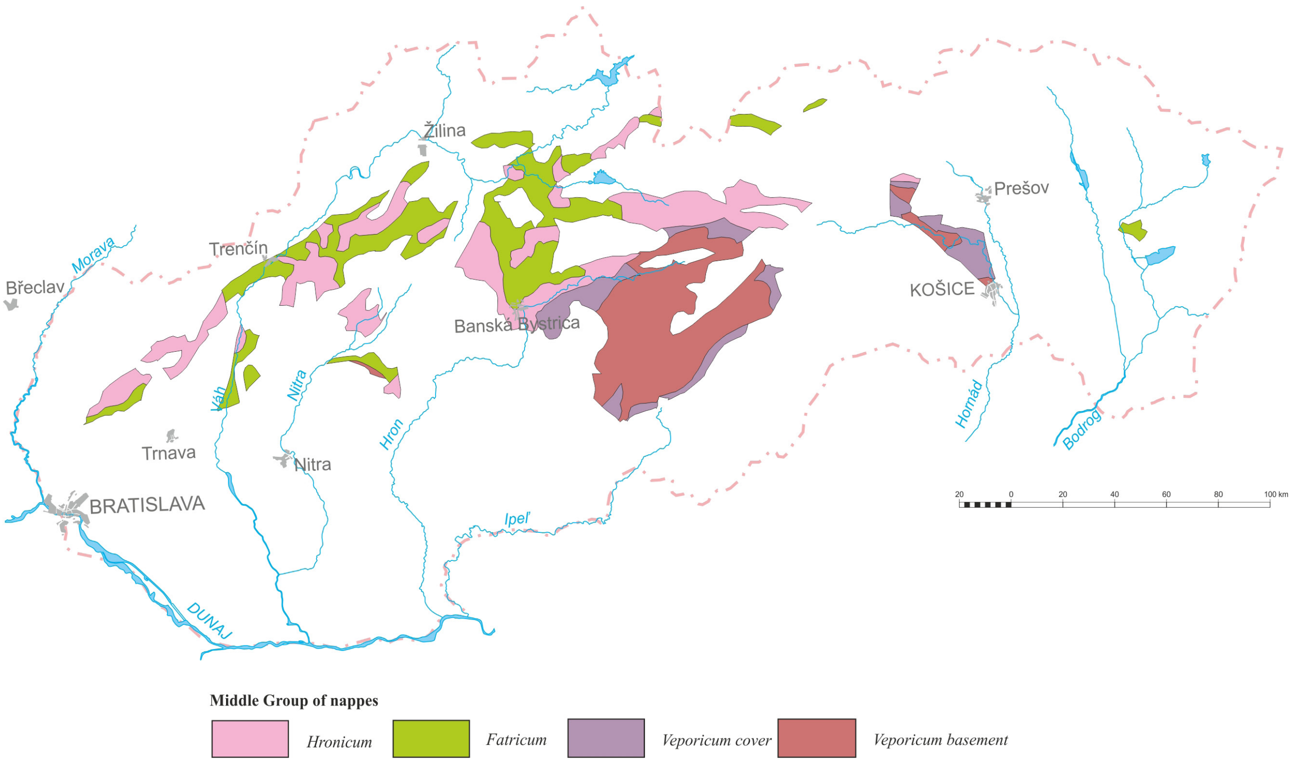


Fig. 9. Position of the tectonic units of Middle Group of Nappes (based on Hók et al., 2014). Dark-red colour indicates position of Veporicum, depicted in Fig. 10 below.

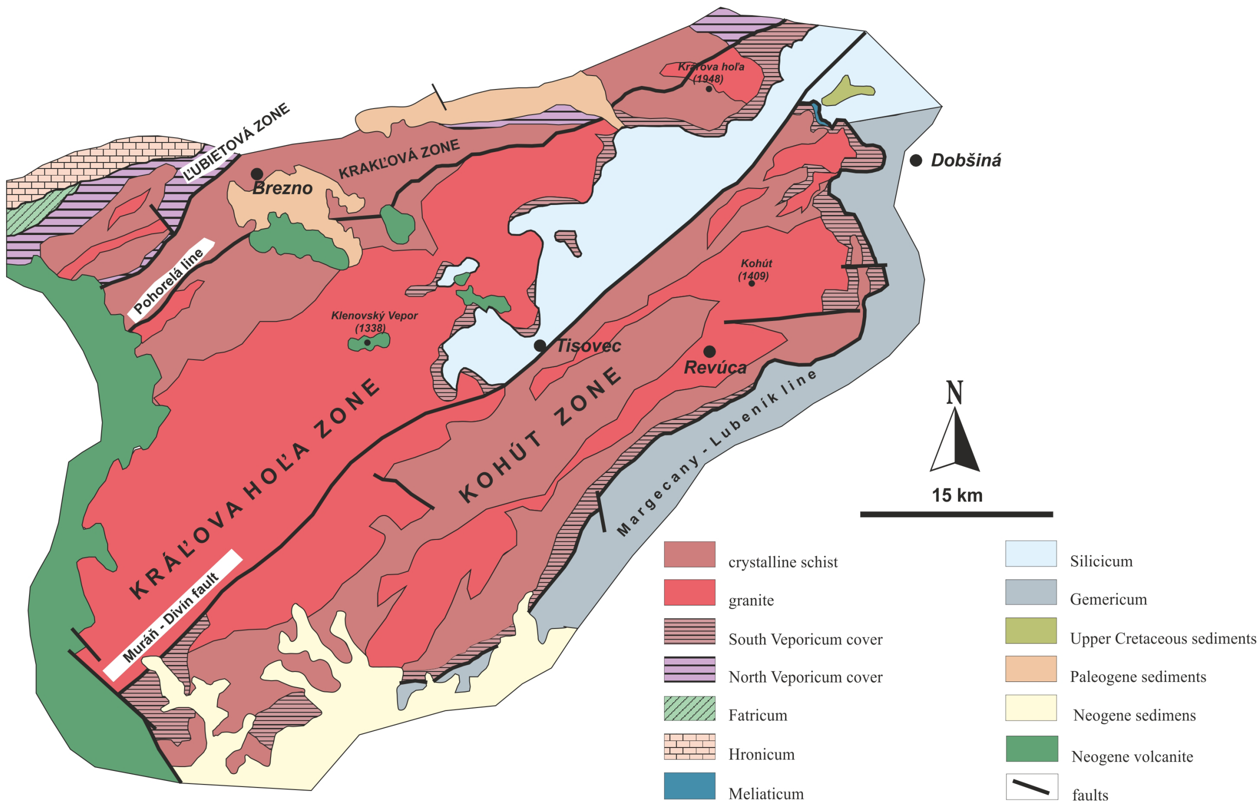


Fig. 10. Tectonic scheme of essential portion of the Veporicum, present in the Veporské vrchy Mts., Stolické vrchy Mts. and Revúcka vrchovina Mts. (modified after Hók et al., 2001).

spotted marly limestones and shales ("Fleckenmergel" – Allgäu Fm.), and the shallow water facies (Tatra type), characterized by the crinoid and sandy limestones (Hierlatz Limestone).

The **Fatra type** of the sedimentary cover sequences occurs in the Veľká Fatra Mts., Malá Fatra Mts., Považský Inovec Mts. and Strážovské vrchy Mts. The **Tatra type** occurs in the Tatry, Nízke Tatry Mts. and Tribeč Mts. Beside the aforementioned basic facial types a number of specific successions occurs in the particular Core mountains. Typical example represent the cover sequences in the Malé Karpaty Mts., among which the Borinka succession exhibits a contrasting difference from all other sedimentary cover sequences (Plašienka, 2012).

The Tatricum was considered structurally as the lowermost tectonic unit in the frame of Alpine setting of Internal Western Carpathians, which is overridden by other tectonic units, forming large-scale nappe structures. The internal structure of the Tatricum itself is however considerably complicated with a wide range of partial thrusts, duplexes in the sedimentary cover sequences, as well as crystalline basement, e.g. fold of Giewont and Červené vrchy in the Tatry Mts., fold of Tlstá in the Nízke Tatry Mts., Žibrica duplex in the Tribeč Mts. The allochthonity (nappe position) of the granitoid rocks forming the Bratislava and Modra bodies was documented in the Malé Karpaty Mts. The granitoid bodies are thrust over the Borinka cover succession. The Borinka sequence is due to its facial difference and the allochthonous position of granitoids considered to be even lower tectonic element than Tatricum (i.e. Infratatricum; Plašienka et al., 1997).

Middle Group of Nappes

The Middle Group of Nappes is represented by Veporicum (crystalline basement and sedimentary cover sequences), which occurs in the Vepor Belt (Fig. 9) and thin-skinned nappes of Fatricum and Hronicum that overlie tectonic units of Tatricum and Veporicum in the Core mountains Belt and the Vepor Belt (Fig. 1).

Veporicum

Veporicum covers significant part of Central Slovakia (Figs. 1, 9 and 10). The Vepor Belt is divided from the Core mountains Belt (Tatricum) by the **Čertovica thrust** and from the Gemer Belt (Gemericum) by the **Margecany-Lubeník thrust**. The Gemer Belt is thrust over the Vepor Belt. The largest part of the Vepor Belt is built by the Veporicum. Other tectonic units involved in the geological structure of the Vepor Belt are represented by the Silicicum and Hronicum. As in the case of the Tatricum, the Veporicum is composed of a crystalline basement and sedimentary cover sequences of the late Paleozoic to Mesozoic age.

Veporicum crystalline basement

The crystalline basement of Veporicum is predominantly composed of specific types of granitic rocks (e.g. Vepor type, Sihla type, Hrončok granite, Čierťaž granite, etc.) and various grade metamorphic rocks (migmatites, gneisses, mica schists and phyllites), which similarly as granites, are designated by local names (Muráň orthogneiss, Klenovec gneiss, Brezina mica schist, etc.). The Veporicum crystalline basement contains relatively well-preserved relics of Hercynian structure. The prevailing part of the crystalline basement is composed of the Middle lithotectonic unit and, contrary to the Tatricum, also the Lower lithotectonic unit with the lower grade metamorphic rocks is present. The geological and tectonic structure of the crystalline basement is very complicated. It is mainly due to the considerable share of Hercynian tectonics and its subsequent significant Alpine overprint. This fact has led in the past to various interpretations of the geological setting, reflecting different levels of knowledge and geological information about the region. Differing interpretations are still widely used today.

Vertical division of the Veporicum was based upon the differing proportion of the individual types of the crystalline rocks and sedimentary cover sequences (Zoubek, 1957). According to this principle the Veporicum was divided (from the south to the north) to the Kohút Zone, Kráľova hoľa Zone, Kraklová Zone and Ľubietová Zone (Fig. 10). The individual zones were thrust above each other or separated by the subvertical faults (e.g. Muráň-Divín Fault, Pohorelá Line). Later on (Klinec, 1966, 1971), revealing the Alpine nappe position of the crystalline complexes, a horizontal division into the Kráľova hoľa and Hron complexes became predominant. The **Kráľová hoľa Complex,** composed predominantly of granitic rocks and high-grade metamorphic rocks (migmatites, gneisses and amphibolites) is lying in the nappe position above the **Hron Complex,** consisting of lower grade metamorphic rocks (mica schists, phyllites).

Veporicum sedimentary cover sequences

It is possible to divide the sedimentary sequences of Veporicum into two distinct successions: the Southern Veporicum sedimentary cover unit (Federáta Unit) and the Northern Veporicum sedimentary cover unit (Veľký bok Unit). The Federáta Unit is present in the Kohút and Kráľova hoľa zones. It covers the southeastern margin of the Veporicum and dips under the Gemericum along the Lubeník thrust and at the same time it forms the substratum of the Muráň Nappe (Silicicum) in the Muránska planina Plateau. The contact zone with corresponding kinematics (thrusting and subsequent unroofing) was proved also in the eastern margin of the Gemer Belt – along the Margecany part of the Lubeník-Margecany thrust zone, forming the mutual contact of the Spiš-Gemer Ore Mts. and Čierna hora Mts. (cf. Németh et al., 2012). The Veľký Bok Unit is present mainly in the Kráľovohoľské Tatry (eastern part of the Nízke Tatry Mts.).

The **Federáta Unit** represents complicated system of thrust slices affected by the low-grade metamorphic overprint. The Mesozoic sedimentary sequence ranges from the Lower to Upper Triassic. However, also the Upper Carboniferous and Permian rocks (Revúca Group) are its integral part, often representing tectonically independent thrust slice. The dolomites of the Late Triassic age (Norian) represent the youngest lithostratigraphic member, substituting the rocks of Carpathian Keuper, which represents the most significant difference with regard to the sedimentary sequence of the Northern Veporicum.

The **Veľký bok Unit** is characterized by close linkage to the crystalline basement, lithostratigraphic and tectonic affinity to the Fatricum and sedimentary sequence ranging from Permian to the earliest Lower Cretaceous (Albian). Tectonic position of the Veľký bok Unit, confined to the Fatricum, similarly as paleogeographic location relates to southern margin of former sedimentary basin of Fatricum. During Alpine tectogenesis it was displaced, together with the underlying Veporic crystalline basement above the Tatricum. Its autochthonous position above the northern zones of Veporicum (as the sedimentary cover) was preserved. The Veľký bok Unit is exposed in the zone of direct contact of Tatricum and Veporicum (so-called *root zones of the Krížna Nappe*), for example in the Nízke Tatry Mts. (the Veľký bok sequence), Branisko Mts., Čierna hora Mts. and Tribeč Mts. (Veľké Pole sequence).

Fatricum

The Fatricum (other names: Krížna Nappe, Krížna sequence/series) is an (allochthonous) nappe unit present in the Core mountains Belt above the Tatricum and below the Hronicum nappe. The Fatricum, unlike other thin-skinned nappes, is well identifiable from its root zones to its foreland. The westernmost surface occurrences of the

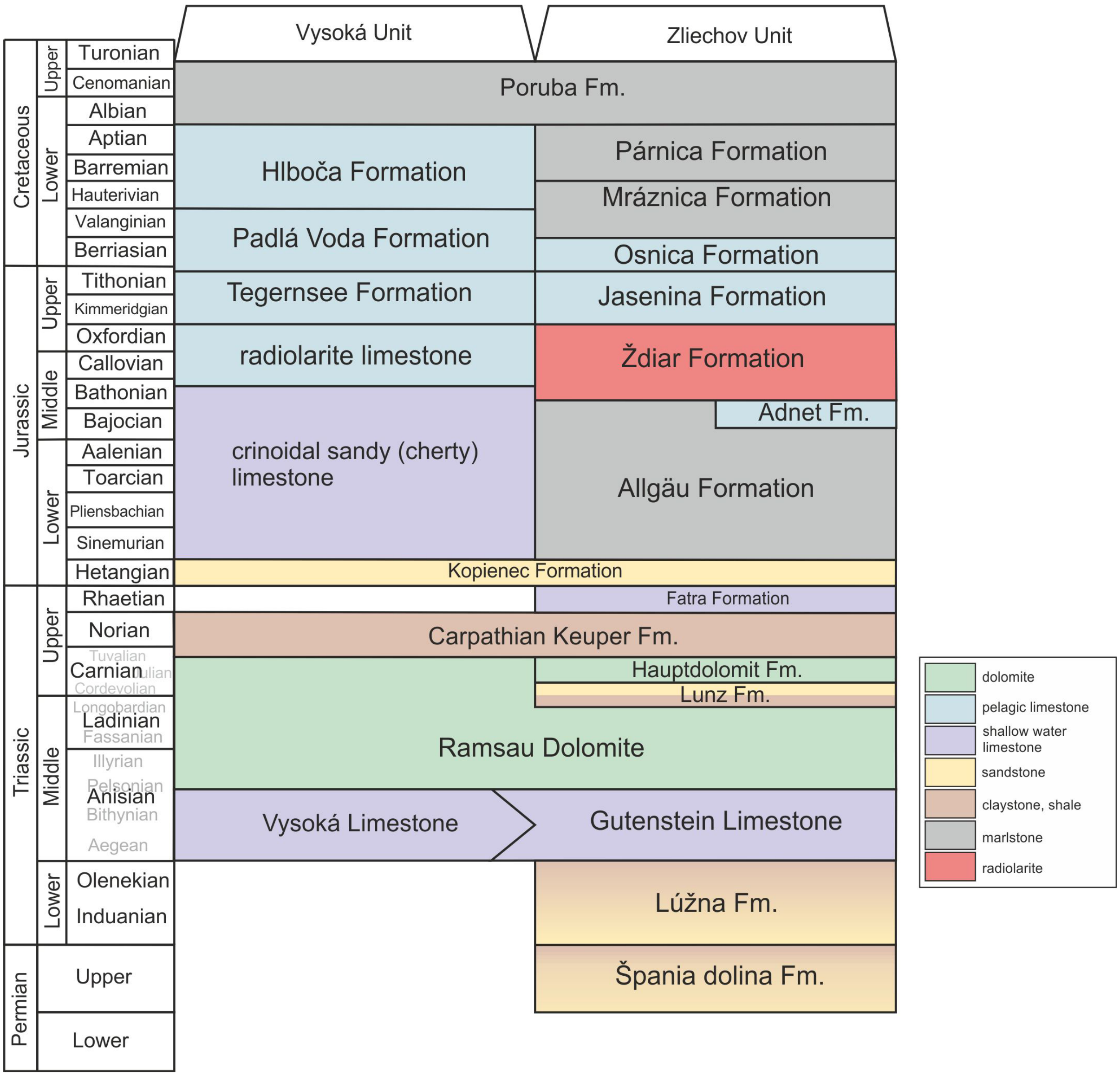


Fig. 11. Simplified lithostratigraphic column of the Fatricum (modified after Biely et al., 1996a).

Fatricum are known from the northern part of the Malé Karpaty Mts., the easternmost ones are known from the Humenské vrchy Mts. Hinterland (internal or southern) zones of the nappe are exposed in the Kráľovohoľské Tatry (eastern part of the Nízke Tatry Mts.), Starohorské vrchy and Tribeč Mts. In this context, often an obsolete term "Sub-Tatric" nappes for the Krížna and Choč Nappes is also still in use (e.g. Jurewicz, 2005; Wolska et al., 2016).

The former sedimentary basin of Fatricum was situated south (internally) of the Tatricum approximately in the area of present tectonically compressed boundary between the Veporicum and Tatricum. Recently, e.g. the Veľký bok Unit is situated in this area.

The rock complexes of Fatricum are composed almost exclusively of sedimentary rocks because the crystalline basement was separated during the nappe emplacement, except the Veľký bok Unit in the Nízke Tatry Mts., Veľké pole Unit in the Tribeč Mts. and tectonic slices of the Fatricum in the Starohorské vrchy Mts.

Stratigraphic range of Fatricum is from the Lower Triassic to earliest Upper Cretaceous (Albian–Cenomanian). The older Permian rocks are known only from few locations close to the root zone of the nappe. Lithostratigraphy of the Fatricum is entirely similar to that of the Tatricum cover (Figs. 8 and 11). Therefore, characteristic phenomenon with repeating sedimentary successions arises in the Core mountains Belt. The Fatricum is however characterized by the presence of thicker sequences of the Jurassic and Cretaceous age, which are not so well developed in the Tatricum and Hronicum. Another typical sign represents the locally up to 500 m thick formation of Albian–Cenomanian flysch known as the Poruba Formation, which forms the uppermost and at the same time the youngest member of the Fatricum sedimentary sequence. It is usually overlied by the Hronicum.

The Fatricum is usually tectonically divided into two units, distinguished mainly by the lithofacial character of the Jurassic part of the sedimentary sequence.

The **Zliechov Unit**, sometimes referred to as the Krížna Unit s.s. represents deep-water sequence. It is characterized by the presence of the Jurassic spotted limestones and marlstones (Allgäu Formation) and radiolarites (Ždiar Fm.). It represents the spatially dominant part of the Fatricum, usually located above the Vysoká Unit.

The **Vysoká Unit** and its equivalents (Beckov, Belá, Ďurčiná and Iľanovo units) represent shallow-water sequence characterized by the presence of Jurassic crinoidal and sandy-crinoidal limestones (Hierlatz Formation).

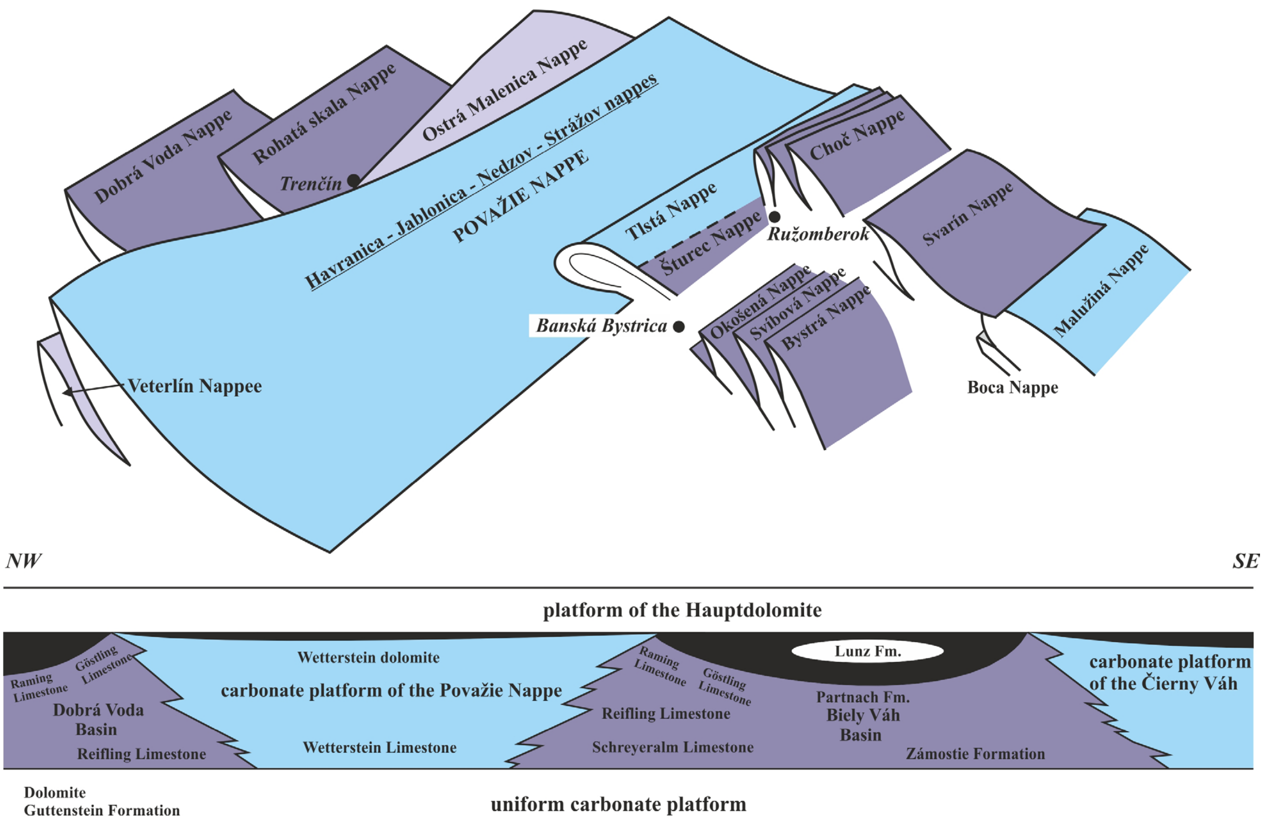


Fig. 12. Schematic cross-section showing position of the Triassic sediments arranged in partial nappes system across the sedimentary basin of the Hronicum (according to Havrila, 2011, simplified).

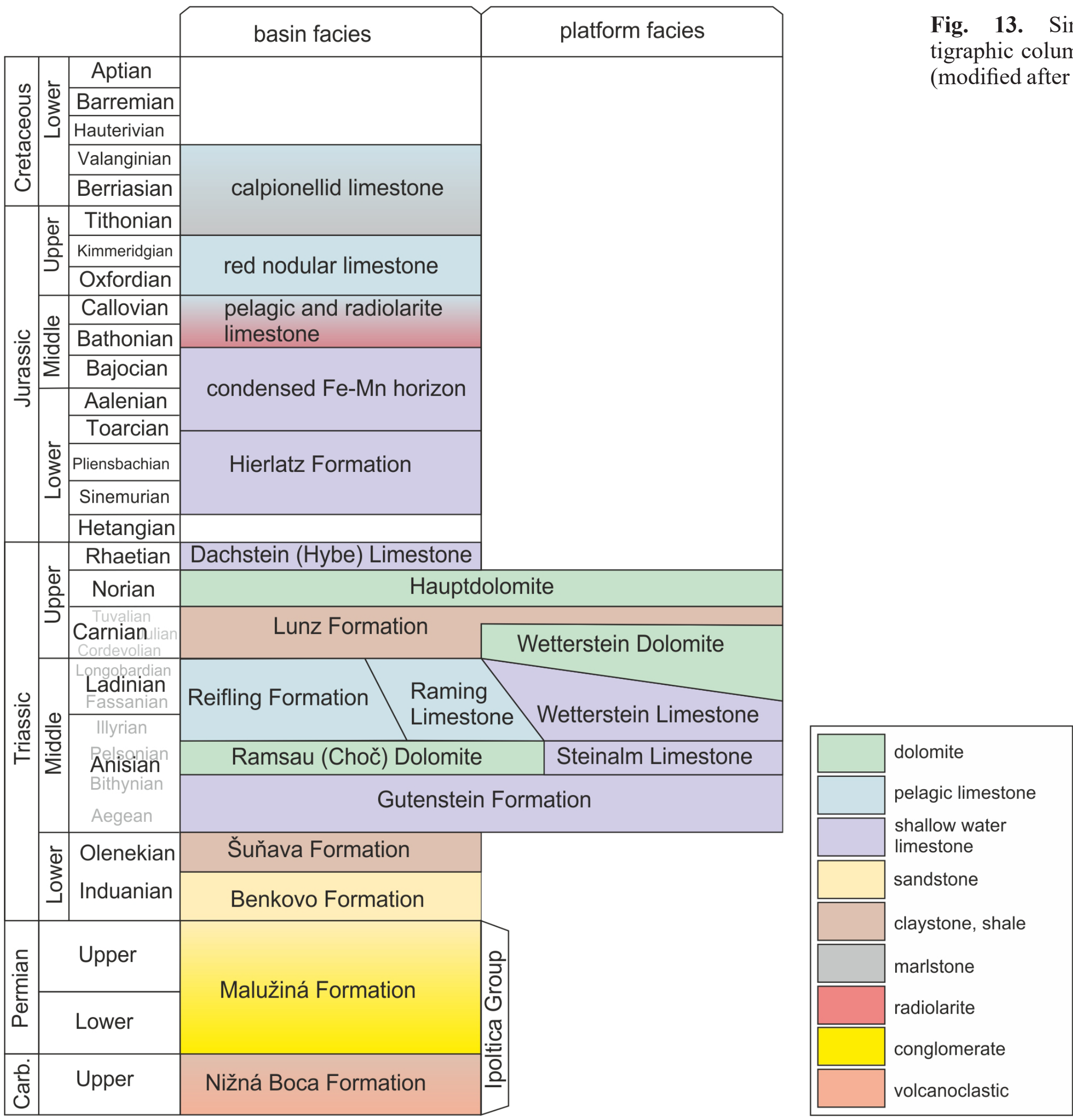


Fig. 13. Simplified lithostratigraphic column of the Hronicum (modified after Biely et al., 1996a).

Fatricum shallow-water units are spatially less significant than in the Zliechov Unit and are usually located in its footwall.

Hronicum

The Hronicum (syn. Choč nappe, formerly Upper Sub-Tatric nappe) represents structurally the highest nappe in the Middle Group of Nappes located above the Fatricum and Veporicum. Occurrences of the Hronicum are limited to the Core mountains and Vepor belts. It crops out in the Malé Karpaty Mts., Považský Inovec Mts., Tribeč Mts., Strážovské vrchy Mts., Žiar Mts., Malá Fatra Mts., Chočské vrchy Mts., Veľká Fatra Mts., Vysoké Tatry Mts., Nízke Tatry Mts., Branisko Mts. and Čierna hora Mts. Presence of the Hronicum was proven in deep boreholes of the northeastern part of the Slovak sector of the Vienna Basin under the sediments of the Neogene age. In several areas of the internal Western Carpathians, the Hronicum is tectonically imbricated into the system of partial nappes (Fig. 12).

Hronicum rock complexes stratigraphically range from Late Carboniferous to Early Cretaceous. Jurassic and Cretaceous sediments are, however, eroded and occur only in the Brezovské Karpaty and Čachtické Karpaty Mts., Strážovské vrchy Mts. and on the northern slopes of the Nízke Tatry Mts.

Characteristic feature of the Hronicum is the presence of Late Carboniferous and Permian volcano-sedimentary formations included in the **Ipoltica Group**, formerly known also as the Melaphyre Series (Vozárová & Vozár, 1979). It forms basal part of the nappe that is present predominantly across the more internal (southern) zones of the Hronicum occurrence. In the north, the Hronicum sequence usually starts with the Triassic carbonates.

Another characteristic feature is the alteration of shallow water and deep water lithofacies during the Middle

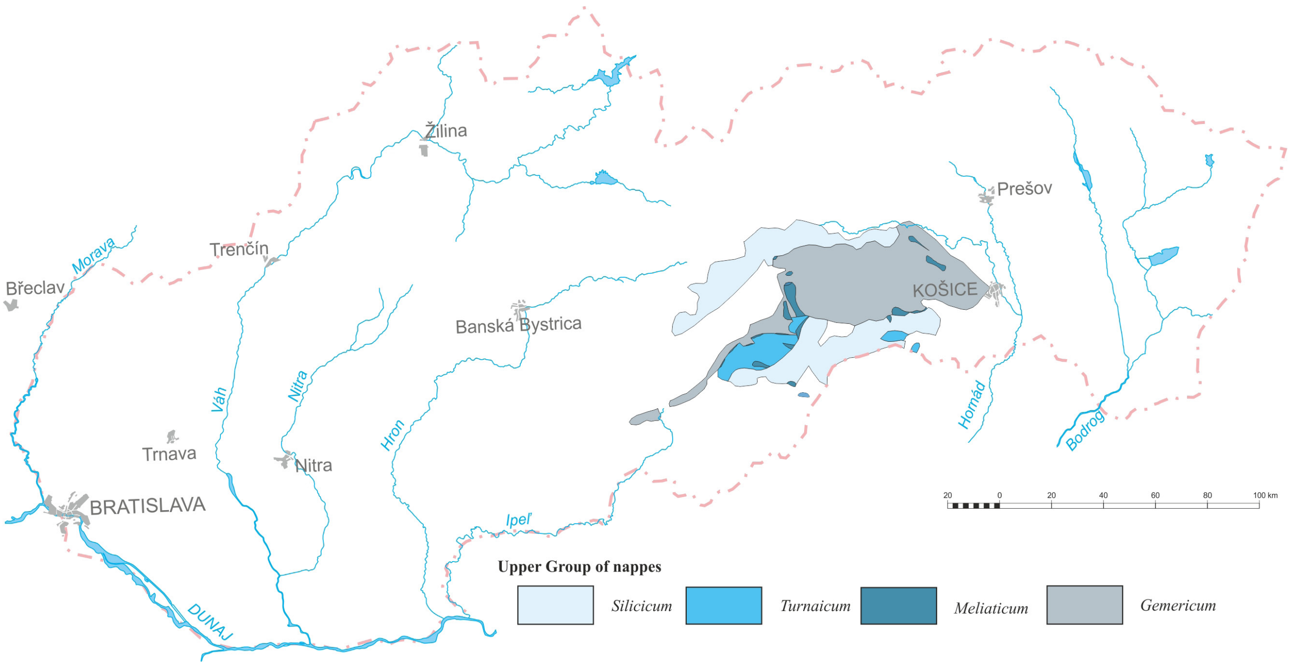


Fig. 14. Position of the Upper Group of Nappes (based on Hók et al., 2014).

Triassic (Fig. 12). The shallow water, reefal and lagoonal facies are represented by Wetterstein limestones and dolomites, which build Mojtín-Harmanec and Čierny Váh carbonate platforms. The deep-water facies are represented by Zámostie, Reifling and Schreyeralm limestones, forming Dobrá Voda and Biely Váh intra-platform basins. The Upper Triassic of Hronicum is characterized by levelling of basins and carbonate platforms and deposition of the Lunz Formation (Fig. 13), which thickness is much greater above the regions with basinal facies (Dobrá Voda and Biely Váh) than above the former platform areas. The Lunz Beds are overlain by thick Main Dolomite (Norian) - another characteristic and widespread lithostratigraphic member of the Hronicum.

Structuralization of the Hronicum occurred during the early Cretaceous and continued during the late Cretaceous and Paleocene, as it is confirmed by the boreholes in the Vienna Basin (boreholes of the Lakšárska Nová Ves series). The Triassic lithostratigraphy of the Hronic nappes system is in most of members similar to the Tirolic and Bajuvaric nappe system in the Northern Calcareous Alps (Janoschek & Matura, 1980; Piller et al., 2004).

Upper Group of Nappes

The Upper Group of Nappes is represented by the tectonic units of Gemericum (low grade metamorphic rocks and cover sequences), Meliaticum and Turnaicum nappes, that are occurring in the Gemer Belt and Silicicum nappe which is found in Vepor and Gemer belts (Figs. 1 and 14). The tectonic units of the Upper Group of Nappes occur in regions of Volovské vrchy Mts., Slovenský kras Plateau, Spišsko-gemerský kras Plateau (Muránska planina Plateau and Slovenský raj Mts.) and eastern part of the Revúcka vrchovina Mts. The Upper Group of Nappes is tectonically superimposed above the Middle Group of Nappes, in particularly over the Veporicum unit. It represents the highest structural element of the Alpine structure of the Internal Western Carpathians, being structuralized already during the Jurassic–Early Cretaceous transition (Fig. 2).

Gemericum

The Gemericum forms an extensive anticlinorium (Fig. 1) of the Volovské vrchy Mts. It differs from the rest of the W. Carpathian main tectonic units due to its rock composition, age and metamorphism (Grecula, 1982; Vozárová & Vozár, 1988; Vozárová, 1993). In contrast to the Tatricum and Veporicum the Gemeric Hercynian (Variscan) basement is on the surface composed by the low-grade metamorphic rocks mostly of Early Paleozoic age, with locally present Permian granitic rocks (Radvanec et al., 2009), volumetrically representing an important part of the tectonic unit according to the geophysical investigation (Šefara et al., 2017). Granitic rocks were during Alpine tectogenesis thrust northward as rigid blocks together with their surrounding lithology. The granites reach surface in Betliar, Hnilec, Poproč and Zlatá Idka localities. The Gemeric basement consists of three principal groups differing in lithology and metamorphic grade. The amphibolite facies metamorphic conditions are reported from the **Klátov Group** (Faryad, 1990), representing Variscan dismembered metaophiolite suite (Radvanec et al., 2017) and recently occurring in tectonic slices and fragments along the eastern and northern boundary of the low-grade Early Paleozoic complexes of Gemericum. The

Rakovec Group (formerly also "Phyllite-diabase Series") is in contrast composed of mafic rocks and their derivatives, mostly metabasalts, tuffs and tuffites, present mainly in the northern Gemericum (Fig. 15). Other sedimentary rocks are less common (Ivan, 1994). The age of the Rakovec Group is probably Devonian to Early Carboniferous, as the overlying Late Carboniferous sediments contain clasts of Rakovec Group rocks. Basalts are related to sub-marine volcanism and the occurrence of pillow-lavas was interpreted by Hovorka et al. (1988). According to other interpretation (Radvanec & Németh, 2018) some of them represent exhumed metagabbros, present along the axis of Variscan suture zone, which is evidenced also by structural and petrological findings, as well as occurrences of exhumed blocks of Variscan ultra-high pressure metamorphic rocks. The suture character of Rakovec Group is a product of collisional closure of the basin in Westphalian (Pennsylvanian: Kasimovian; Late Carboniferous; Németh, 2002; Radvanec & Németh, 2018). **The Gelnica Group** builds a substantial part of the Gemericum (Fig. 15) and morphologically occupies vast part of the Volovské vrchy Mts. The lower part of this unit consists of a thick turbiditic sequence of Ordovician-Early Devonian age with interbeds of bimodal volcanic rocks, gradually passing into volcanosedimentary sequence accompanied by products of massive rhyolite-dacite volcanism of the Late Devonian age (Grecula, 1982; Ivanička et al., 1989; Grecula & Kobulský, eds., 2011). On the basis of lithofacial and lithostratigraphic analysis, three formations were defined within the Gelnica Group from the bottom upwards: the Vlachovo Fm., Bystrý potok Fm., and Drnava Fm. (Ivanička et al., 1989). According to lithostratigraphy by Grecula (1982 and following works), reflecting the revealed Early Paleozoic riftogenesis within the pre--Hercynian (pre-Variscan) continental crust, the Betliar Fm., Smolník Fm. and Hnilec Fm. were distinguished.

More recent concept divides the Gemericum according to character of the sedimentary cover sequences into Northern Gemericum and Southern Gemericum (Vozárová & Vozár, 1988).

The Northern Gemericum is composed of **Rakovec** and **Klátov groups**. Their sedimentary cover is composed of numerous formations with their specific evolution, position and age. The Early Carboniferous sequences are represented by the **Ochtiná Group** of Gemericum with **Črmeľ Formation** in its eastern side (Vozárová, 1996).

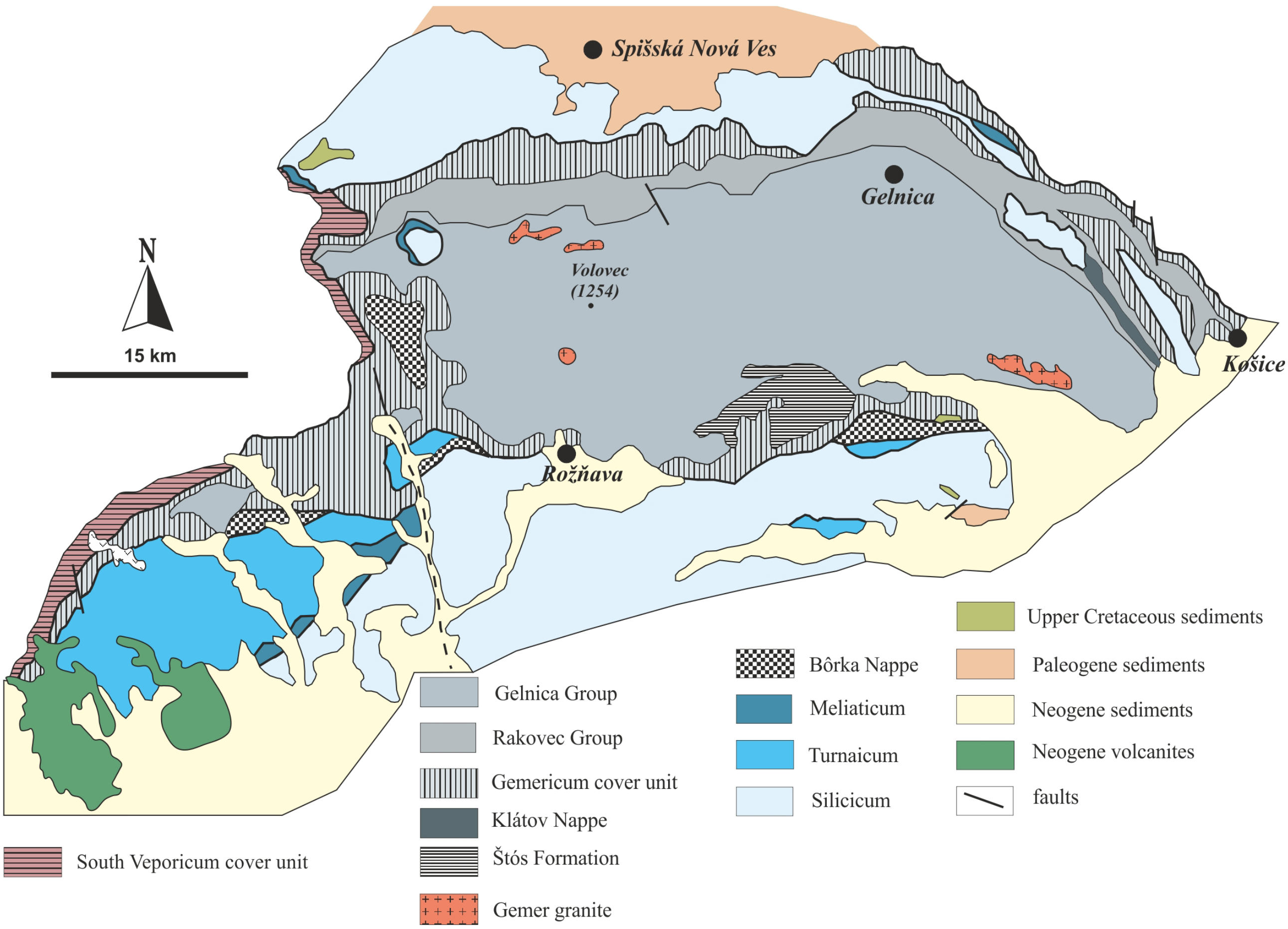


Fig. 15. Simplified tectonic scheme of the Gemericum and surroundings (modified after Hók et al., 2001).

They both represent volcano-sedimentary units with important deposits of magnesite (so called "*Magnesite-bearing Carboniferous"*). The cover Permian rocks of the **Krompachy Group** are typical by the presence of coarse-grained conglomerate material, sandstones and variegated shales (Knola and Petrova hora fms.). Conglomerate composition suggests that the source area was in the former Gemericum. The late Permian–early Triassic overlying sequences were deposited in lagoonal environment – evaporites and shales of the Novoveská Huta Fm. **The Southern Gemericum** is composed of Gelnica Group rocks and Štós Fm. The **Štós Formation** (Fig. 15) is mostly represented by the metamorphosed sandstones, phyllites (formerly probably shales), rarely also bodies of metabasalts. The pre-Permian age of the Štós Fm. is proved by geological data and the occurrences of the Štós Fm. rock fragments in Early Permian conglomerates (Vozárová et al., 2014). The cover of the Southern Gemericum is represented by the **Gočaltovo Group**.

Besides two generations of thrust systems (Variscan and Alpine), double unroofings (Permian and Late Cretacesous; Németh et al., 2016), the spectacular tectonic structure, overprinting the pre-Mesozoic metamorphic fabric of the Gelnica Group as well as in its NE margin also Rakovec Group, is the Gemericum Cleavage Fan. The cleavage forms an asymmetric positive fan structure developed transversally across the entire length of the Gemeric unit (Lexa et al., 2003). As recent investigations manifest, this cleavage fan trending NE-SW is a product of sinistral transpressional shearing (Transgemeric shear zone), and representing a conjugate system to dextral shear zones trending NW-SE (Grecula et al., 1990; Németh et al., 2012, Fig. 3 ibid).

Bôrka Nappe

The Bôrka Nappe was formerly considered as a part of Meliaticum. At present it is distinguished as a separate tectonic unit (however, not without doubts). It includes rock sequences of Permian to Jurassic age characterized mainly by the subduction-type higher metamorphic overprint (HP-LT) in comparison to other surrounding tectonic units. The Bôrka Nappe rock complexes are typical with the crystalline limestones (marbles) with volcanogenic admixture (Dúbrava Fm.) with evidences of blueschists facies metamorphism (Mello et al., 1998).

Meliaticum

The Meliaticum is a tectonic unit (mélange) of nappe character, known also from the territory of Austria (Kozur & Mostler, 1992). It occurs in relics emerging from below the Turnaicum and Silicicum nappes in the present-day surface (Fig. 15). Occurrences of Meliaticum are represented by the tectonic mélange of the Triassic carbonates, radiolarites and volcanic rocks, found within the grey shales and radiolarite beds of Jurassic age (Mock et al., 1998). Oceanic domain of former Meliaticum was closed during late Jurassic and early Cretaceous. Subduction of the oceanic crust and gradual closure of the sedimentary basin resulted in the north-vergent tectonic transport of rock complexes, originally deposited at the southern margin of this oceanic realm. According to present knowledge, north-vergently displaced rock complexes were later transformed into the Turnaicum and Silicicum nappes. Simultanously, the rock sequences of the future Bôrka Nappe, probably located between the Gemericum and Meliaticum, were pulled into the subduction zone. The detachment of Meliaticum, Turnaicum and Silicicum started the shortening of Internal Western Carpathians while preserving the polarity of the tectonic transport from the south (from the inside) to the north during the Early Cretaceous (the Upper Group of Nappes) to the Late Cretaceous (the Lower Group of Nappes).

Turnaicum

The Turnaicum is tectonic unit of nappe character exposed from below the Silicicum (Lačný et al., 2016). It occurs in the southern part of the Gemer Belt, mainly in the Slovenský kras Mts. The Late Carboniferous-Late Triassic sedimentary sequence of Turnaicum is characterized by metamorphic overprint and deep-water Triassic carbonate facies, distinguishing it from the Silicicum. The most characteristic member are the Upper Triassic (Carnian–Norian) grey nodular limestones (Pötschen Limestone) and grey shales with intercalations of volcanic rocks and sandstones of Middle Triassic age (Dvorníky Formation).

Silicicum

The Silicicum is structurally the highest tectonic unit of the Alpine nappe structure of the Internal Western Carpathians (Mello, 1979). It is exposed as relatively flat-lying nappe body in the Slovenský kras Mts., Slovenský raj Mts., Galmus and Muránska planina Mts. Similarly, as the Hronicum unit, also Silicicum was formerly divided into several partial nappes (the Silica, Muráň and Besník nappes). Now they are considered as erosional relics of one larger nappe – Silicicum (often called as the Silica Nappe *sensu lato*). Sedimentary sequence of Silicicum starts in uppermost Permian or lowermost Triassic and continues up to Upper Jurassic (Callovian–Oxfordian). The Lower Triassic has similar development as in the Turnaicum and is represented by the sandstones and shales (Fig. 16). Major part of the Silicicum is formed by the Middle–Upper Triassic shallow-water carbonates (mainly Wetterstein Limestones). The sparsely preserved Jurassic deposits form the youngest part of sedimentary sequence and characterize the deeper water environment. The vergence or sense of nappe displacement of Silicicum is still a matter of debate. Former concept presumed that Silicicum was transported together with the Hronicum from the present-day Margecany-Lubeník zone, whereby the Hronicum was transported to the north and Silicicum to the south (Mišík et al., 1985). Present model prefers an

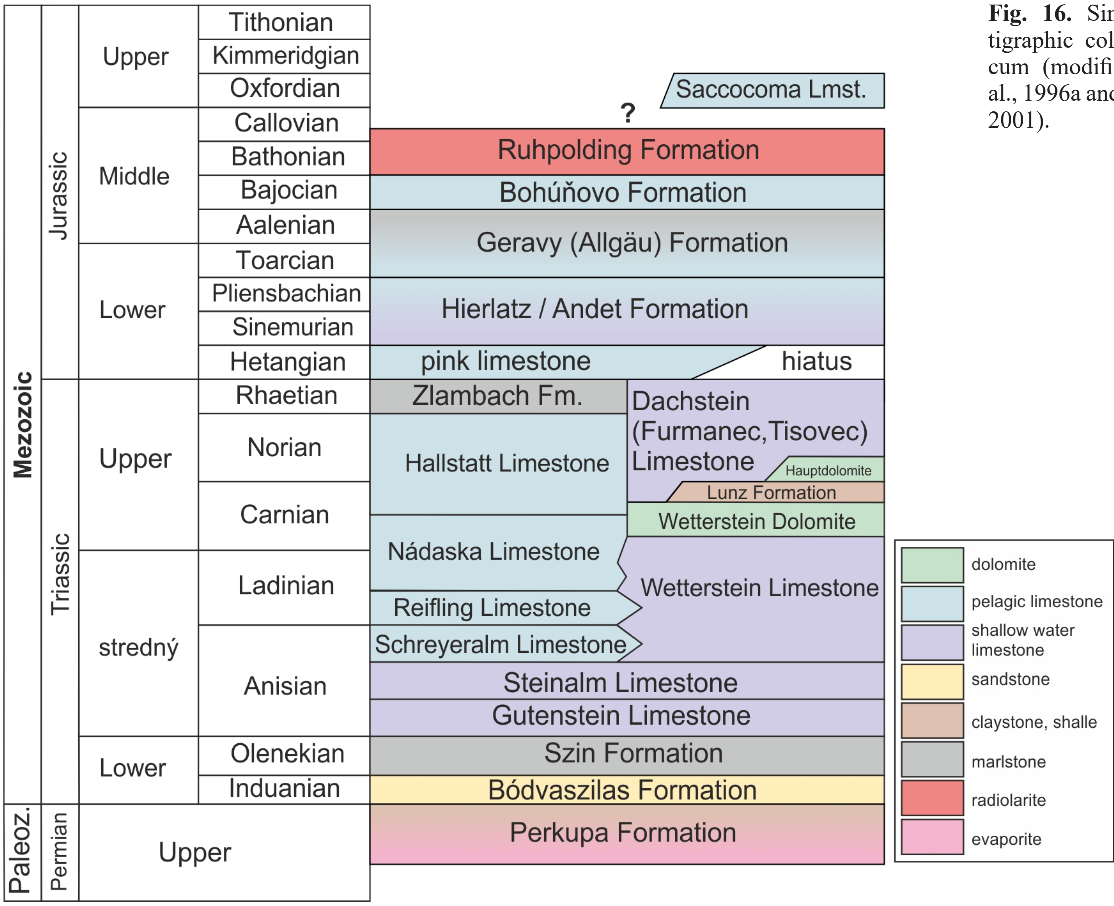


Fig. 16. Simplified lithostratigraphic colum of the Silicicum (modified after Biely et al., 1996a and Rakús & Sýkora, 2001).

interpretation that the tectonic transport of the Silicicum was northward from the South Gemeric zone (Plašienka, 2018). Silicicum is overlain by the locally preserved Upper Cretaceous ("Senonian") Gosau type sediments. Principal Triassic lithostratigraphic members of the Silicicum are resembling Juvavic nappe system.

Zemplinicum

Zemplinicum represents a tectonic unit occurring in the Zemplínske vrchy Mts. in the southeastern Slovakia (Slávik, 1976; Fig. 1). Its tectonic assignment is not satisfactorily resolved (Vozárová & Vozár, 1988; Grecula & Együd, 1977; Plašienka et al., 1997). The Zemplinicum is composed of high-grade Hercynian basement overlain by continental sediments of Carboniferous with coal seams and by Permian continental clastic red beds with acid volcanics. Overlying formations are represented by Lower Triassic quartzites and Middle Triassic carbonates. Correlation of the Zemplinicum with surrounding units is intricate, due to thick Neogene sedimentary cover as well as the nature of the East Slovak Basin pre-Neogene basement. Deep boreholes reaching the pre-Neogene basement suggest the presence of metamorphosed Jurassic to Paleogene succession (so called Iňačovce-Kričevo Unit). The Iňačovce-Kričevo Unit was correlated with the Belice Unit of the Považský Inovec Mts. (i.e. Vahicum, Plašienka et al., 1995) and both were together considered as equivalent of the Penninicum. Later (Plašienka & Soták, 2015), there was inferred that the Iňačovce-Kričevo and related units continue from the subsurface of the East Slovak Basin to the Pannonian Basin basement along the Mid-Hungarian fault zone (Sava-Szolnok Belt) to the Dinaridic Sava Zone (see also Schmid et al., 2008). Due to the presence of the Iňačovce-Kričevo Unit, the tectonic affiliation of the Zemplinicum becomes even the more obscure and complicated.

Post-nappe stacking formations of the Western Carpathians

All rock formations of the Late Cretaceous (Coniacian–Maastrichtian) and Cenozoic age are in the Internal Western Carpathians traditionally considered as the "post-nappe stacking" formations. They are unconformably and transgressively overlying the nappe structures. Later research, however, points to fact that mainly in the external parts of the Internal Western Carpathians the sediments of Late Cretaceous and Paleogene age are folded together with their substratum (Hók et al., 2016; Pelech et al., 2017; Plašienka, 2018). This means that the rock complexes of the Middle Group of Nappes in this part of the Western

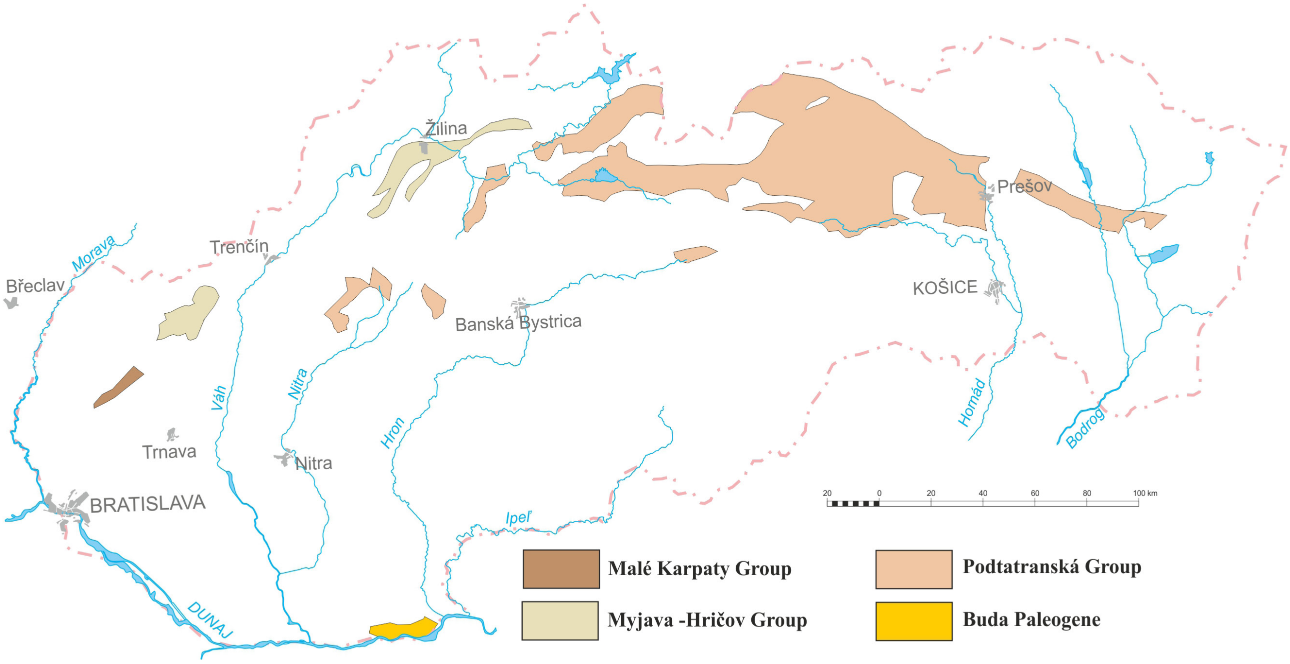


Fig. 17. Position of the Paleogene sediments in the Internal Western Carpathians (based on Hók et al., 2014).

Carpathians were displaced in the late Cretaceous–Eocene period, in contrast to the Upper Group of Nappes, where the Late Cretaceous sediments cover discordantly and transgressively their basement, represented by the Silicic nappes. The outer edge of the Internal Western Carpathian block was during the early Miocene affected by the back-thrusting (south-vergent), which is related to the Neo-Alpine phase of mountain building (e.g. Pelech & Olšavský, 2018).

Upper Cretaceous ("Senonian") sediments (Coniacian-Maastrichtian)

The Upper Cretaceous sediments were preserved only sporadically on few localities (the Miglinc Valley west of Moldava nad Bodvou; Dobšinská ľadová jaskyňa Cave; Šumiac; Myjavská pahorkatina Upland; Brezovské Karpaty and Čachtické Karpaty Mts.). Deep drillings confirmed the presence of Upper Cretaceous rocks also in the area of Krupina and Rimavská Sobota (Čierna Lúka Fm., Vass et al., 2001) in Central Slovakia and from the pre-Neogene basement of the Vienna Basin. Oldest (lowermost) parts of these sedimentary sequences, correlated with Gosau Group, were deposited mostly in freshwater environment. The higher parts are represented by marine, often deep-water sediments.

The Upper Cretaceous rock occurrences could be divided into two groups. The first one is covering solely the Silicic nappes, representing the highest structural element of the Upper Group of Nappes (Miglinc Valley; Dobšinská ľadová jaskyňa Cave; Šumiac and Čierna Lúka Fm. occurrences). Among them, the most widespread and lithologically most complete are the occurrences in the wider area of the Dobšinská ľadová jaskyňa Cave, which are represented by two lithologically different formations. The "lower formation" of ?early Santonian to early Campanian age contains freshwater limestones and brown-grey to grey shales with coal interbeds. It was formed in the freshwater to the brackish environment, with its highest parts being formed in the marine environment. The "upper formation" of probably Maastrichtian to Paleocene age is represented by variegated conglomerates with interbeds of red and green shales with planktonic foraminifers pointing to marine environment (Mello et al., 2000; Pipík et al., 2009; Hók & Littva, 2018).

The second group of the Upper Cretaceous rock occurrences is located atop of Hronicum, which represents highest structural element of the Upper Group of Nappes (Myjavská pahorkatina Upland, Brezovské Karpaty and Čachtické Karpaty Mts. and pre-Neogene basement of the Vienna Basin). The most widespread occurrences are located in the Myjavská pahorkatina Upland and are represented by the Brezová Group (Coniacian – Maastrichtian, Salaj et al., 1987). Lower part of the Brezová Group is due to its lithological and facial content similar to the Upper Cretaceous rocks of the Eastern Alps (Wagreich & Marschalko, 1995). The basal part is composed of conglomerates and sandstones. The upper part, which is clearly of marine origin is composed of "flysch-like" sediments, red marlstones and limestones. The occurrences of the Brezová Group rocks continue also into the basement of the Vienna Basin Neogene sedimentary infill.

Paleogene sediments

The Paleogene sediments (Fig. 17) are divided into several lithostratigraphic (lithofacial) groups which are at the same time localized in the particular areas: Central Carpathian Paleogene Basin (or Podtatranská Group sensu Gross et al., 1984; Gross, 2008), Myjava-Hričov Group, Malé Karpaty Group and so-called Buda Paleogene (North Hungarian Paleogene Basin). Paleogene sediments are deposited transgressively and discordantly above pre-Cenozoic rocks. During the early Paleogene (Paleocene) most of the Internal Western Carpathians territory was probably sub-aerially exposed land. The Paleocene sediments are mostly located only along the Pieniny Klippen Belt (Myjava-Hričov Group).

Podtatranská Group

The Podtatranská Group (sensu Gross et al., 1984; also termed as the Inner Carpathain Paleogene or fill of Central Carpathian Paleogene Basin) represents prevailing part of the Paleogene rocks in the Internal Western Carpathians (Fig. 17). Sediments of Podtatranská Group morphologically form the mountainous regions of Skorušinské vrchy, Spišská Magura, Levočské vrchy, Bachureň and Šarišská vrchovina, but mainly the Tertiary intramountain basins of Žilinská kotlina, Turčianska kotlina, Hornonitrianska kotlina, Podtatranská kotlina, Hornádska kotlina and Horehronské podolie. Stratigraphic range of the Podtatranská Group sediments is from Eocene to Oligocene (in the Hornonitrianska kotlina Basin up to early Miocene). The rock sequence starts with transgressive basal breccias and conglomerates (Borové Fm.). The transgression has progressed generally from W to E and was diachronous in time. The basal formation is overlain by the packet of claystones (Huty Fm.) and typical mass transport deposits ("flysch" sandstones and claystones, Zuberec Fm.). The sedimentary sequence was terminated by the deposition of predominantly sandy gravity flow deposits (Biely Potok Fm.).

Malé Karpaty Group

The Malé Karpaty Group represents the westernmost occurrence of the Paleogene sediments within the Western Carpathians (Fig. 17). The rock sequence represents only a relic of a larger basin transgressively and discordantly overlying various litostratigraphic units of the Hronicum (Buček in Polák et al., 2012). Age of the Malé Karpaty Group sediments – conglomerates, breccia, sandstones and claystones – is early to middle Eocene, though the sedimentation continued after hiatus in the early Oligocene. Sediments differ from those in the Podtatranská Group.

Myjava-Hričov Group

The Myjava-Hričov Group contains a lithologically diverse "flysch"-type rock sequence, mainly sandstones, claystones, limestones and conglomerates (Súľov Conglomerates). It is located along the inner edge of the western part of the Pieniny Klippen Belt (Fig. 17). The sediments are predominantly transgressively overlying its footwall, manifesting hiatus during the early Paleocene. However, the Paleocene sediments of the Polianka Fm. were exceptionally deposited continuously since Late Cretaceous. The stratigraphic record of the Myjava-Hričov Group ends in the late Eocene (Buček in Mello et al., 2011; Plašienka & Soták, 2015).

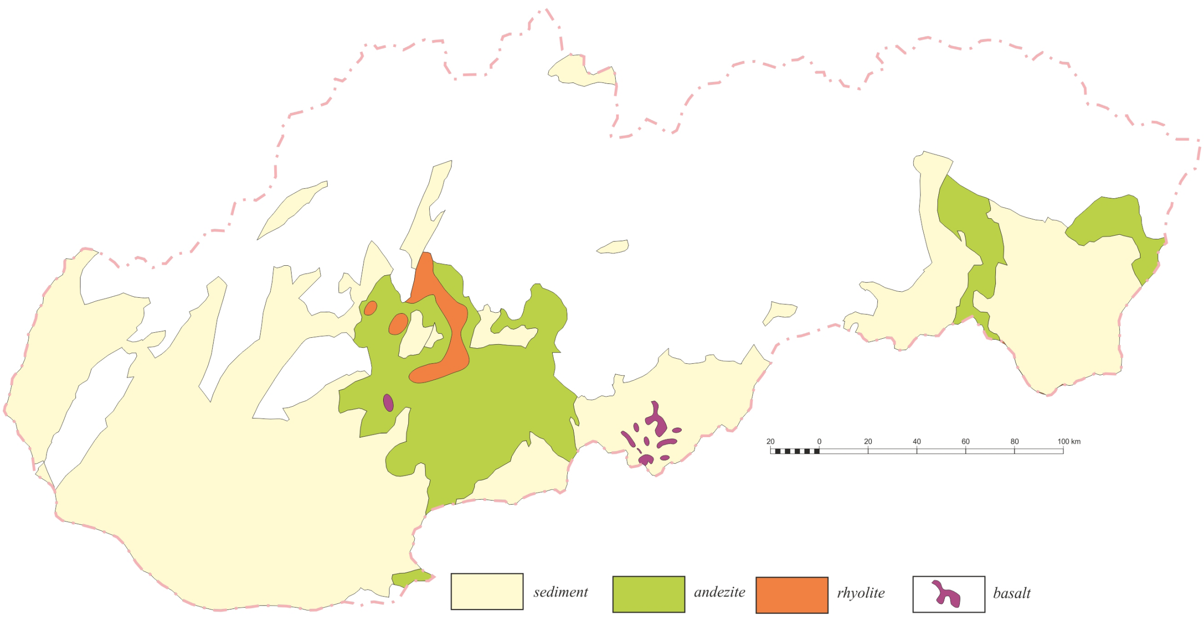


Fig. 18. Occurrence of Neogene sediments and volcanites (based on Hók et al., 2014).

Buda Paleogene

The Buda Paleogene sequence (late Eocene–early Oligocene) occurs only in southern Slovakia (mainly in the area of the Štúrovo town and the South Slovak Basin). In the region of Štúrovo the Buda Paleogene sediments are not exposed on the surface but were revealed by boreholes. The Buda Paleogene sequence is not an integral part of the W. Carpathians. Overlying the tectonic units of Hungarian Transdanubian range, they are lithofacially closer to units of Southern Alps. The sediments of the Buda Paleogene are characterized by the alternation of the brackish (mixed marine and freshwater environments) and the marine sedimentation, and in particular the occurrence of the coal seams (Vass, 2002).

Neogene sediments

The Neogene sedimentary basins and intermontane depressions (in Slovak usually termed *kotlina;* Fig. 18), together with the Core mountains represent the most characteristic morpho-tectonic features of the W. Carpathians. Regarding the common origin and evolution, the Neogene sedimentary basins cannot be separated from Carpathian Neogene volcanic province (Konečný et al., 2002) occurring in Central and Eastern Slovakia, and at the same time, they must be understood in the context of the whole Pannonian Basin System and wider Paratethys region (Royden & Horváth, 1988; Kováč, 2000; Haas et al., 2013).

The Neogene basins in the Slovak territory are represented by complex and extensive Vienna, Danube, South Slovak and East Slovak (Transcarpathian) basins. The intramontane depressions have usually thinner and structurally less complicated Neogene infill and are often situated between the (Core) mountains. The northern embayments of the Danube Basin – the Blatné, Rišňovce and Komjatice depressions (formerly known as the Piešťany, Topoľčany and Zlaté Moravce embayments) are included among the intermontane depressions since their evolution is closely related to surrounding mountains. The smaller Neogene intermontane basins include Trenčín, Ilava, Orava, Bánovce, Horná Nitra, Turiec, Žiar, Zvolen and Rožňava basins. The intermontane depressions are bounded by normal faults, delimiting them from the surrounding areas. The sediment thickness often reaches several kilometers and Neogene rocks unconformably and transgressively overlie dismembered basement of various ages and tectonic affiliation. The Neogene rocks are characterized by great diversity and many local names (e.g. Vass, 2002, Fig. 19).

The evolution of the Neogene basins and intermontane depressions was coeval with subduction-accretion processes in the Outer Western Carpathians. Since the Oligocene, the subduction and collision of the Flysch Belt with Bohemian Massif and North European platform took place. The subduction was diachronous and proceeded continually from the west (Eggenburgian) to the east (end of Neogene). Gradual consumption of the Flysch Belt basement resulted in contraction of the area between fixed and consolidated European Platform and the Internal Western Carpathian (ALCAPA) block. The Internal Western Carpathian block was due to the subduction roll-back effect generally moving to the north and rotated counter clockwise at the same time. The rotation was controlled by actually active segments of subduction (Jiříček, 1979; Márton et al., 2016). The aforementioned processes in the Internal W. Carpathian regions resulted in stress regime that enabled strike-slips and normal faulting. The Neogene evolution of W. Carpathian sedimentary basins can be divided into several stages (Kováč et al., 2018, Fig. 19):

Pre-rift stage of Early Miocene (Eggenburgian–early Badenian) can be characterized by transtensional regime. Early Miocene marine sediments (e.g. Čausa, Bánovce, Lakšárska Nová Ves and Rakša fms.) were deposited in the northern part of the Danube Basin (Blatné, Bánovce, Horná Nitra and Turiec depressions), as well as in the Vienna, East Slovak and South Slovak basins.

Syn-rift stage of the middle Miocene (Badenian–Sarmatian) is characterized by the marine sedimentation and regional extension that reached maximum during this time in the whole Internal W. Carpathians. The onset of the main rift phase is marked by regional unconformity, where the middle Miocene sediments often overlap the pre-Cenozoic basement. Considerable amount of sediments has accumulated in relatively short time (nearly 3000 m of sediments during Badenian in the Blatné Depression). Extension to transtension was diachronously moving to the SE (Hók et al., 2016). Typical horst and graben structure of the Core mountains belt was formed during this stage and accompanied by considerable tilting of several hanging wall blocks. Clays, marls and sandstone at the beginning of marine environment (e.g. Špačince and Báhoň fms.) were later replaced by deltaic to brackish sedimentation (Vráble Fm.). This stage was terminated by regional unconformity at the end of Sarmatian.

Post-rift stage represented the thermal collapse of the Pannonian Basin lithosphere. It was accompanied by wide rift normal faulting, which dominated in the evolution of the sedimentary basins during the late Miocene (Pannonian) to Quaternary. Main depocenters were located in Rišňovce, Komjatice and Gabčíkovo depressions. The sedimentary sequences were changing from brackish to freshwater (Ivanka Fm.), deltaic (Beladice Fm.) to alluvial sedimentation (Volkovce Fm. and Kolárovo Fm.). Important unconformity and hiatus occurred during the Pontian–Dacian due to basin inversion.

Neogene–Quaternary volcanic rocks

The Neogene volcanic activity was geotectonically tightly bound to the processes of subduction in the External Western Carpathians (Konečný et al., 2002). The petrographic and geochemical character of volcanic rocks

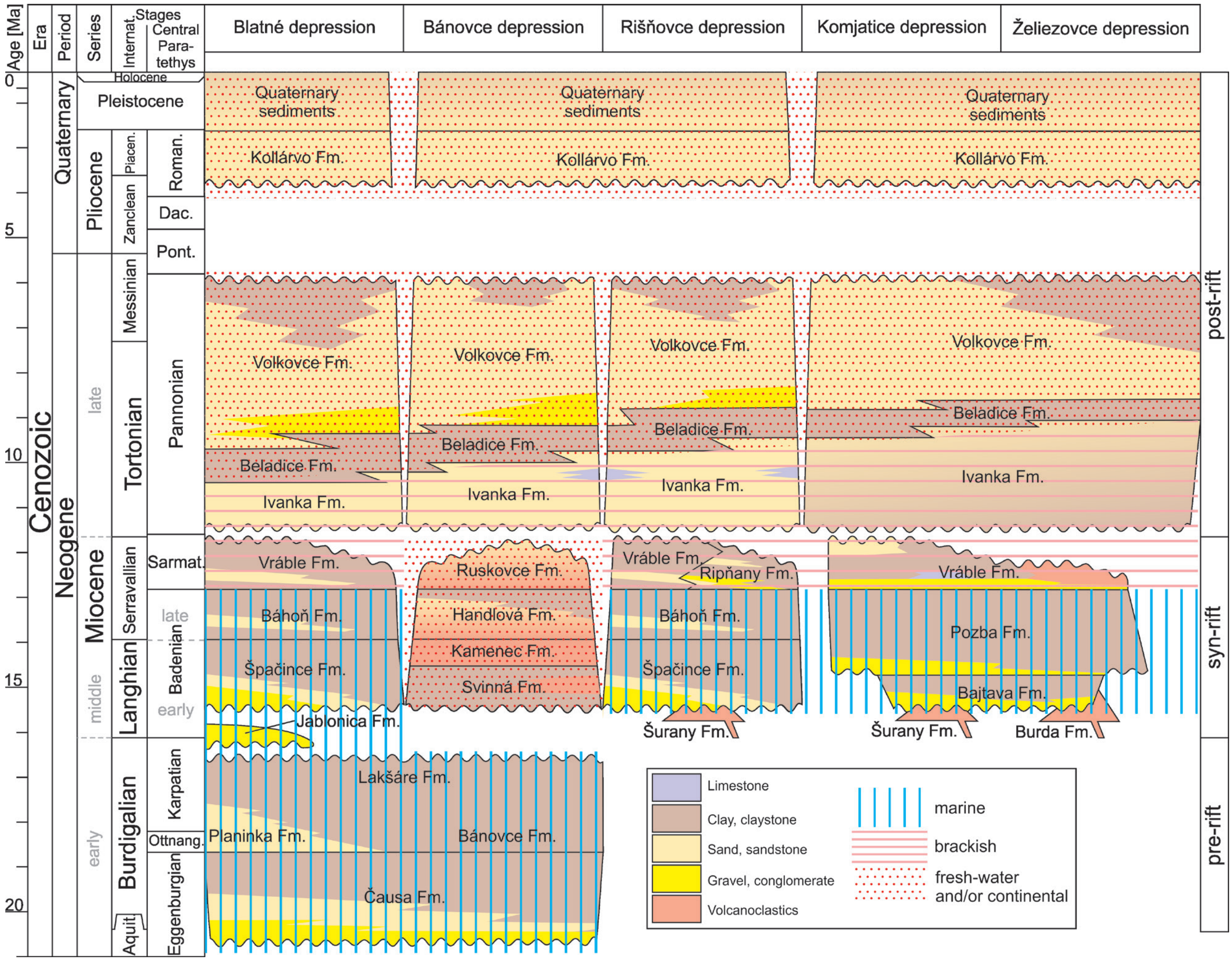


Fig. 19. Lithostratigraphy of the Slovak part of the Danube Basin (based on Vass, 2002, and Kováč et al., 2018).

is directly limited by the nature of the subduced plate as well as the upper mantle (Biely et al., 1996b). Regarding the geotectonic evolution, succession of volcanotectonic events, different petrological and volcanological types and forms, it is not possible to separate Neogene and Quaternary volcanic activity, having following individual stages (Lexa et al., 1993):

Acid calc-alkaline areal volcanism is represented mainly by rhyolites, rhyodacites and their products of two periods: (1) The **early Miocene** (Eggenburgian–early Badenian) restricted only to marginal facies – tuffs, recorded in the South Slovak basin and the East Slovak basin. Geodynamically, they can be parallelized with the pre-rift stage of the Neogene extension. (2) The **late Miocene** (Sarmatian–Panonian) volcanism can be parallelized with processes of the post-rift stage. Volcanic products are more widespread and occur together with andesite volcanoes, especially in the Central Slovakia region.

Intermediate calc-alkaline areal volcanism represented mainly by the middle Miocene (Badenian–Sarmatian) granodiorites, andesites, dacites and their volcaniclastic products. It represents the lowest part of the large Štiavnica, Javorie and Poľana stratovolcanoes. Geodynamically, they can be parallelized to the syn-rift stage (maximum back-arc extension).

Intermediate calc-alkaline arc volcanism mainly of basaltic andesites, rare dacites and their products is documented in particular during the middle Miocene (Sarmatian). The occurrence is mainly connected to the region of Eastern Slovakia (the volcanoes of Slánske vrchy Hills and Vihorlatské vrchy Mts.). Petrological character of rocks reflects the processes of active subduction.

Alkali basalt volcanism (besides basalts also nepheline basanite) is found only in the central Slovak region – predominantly in the Cerová vrchovina Upland and represents the final stage of late Miocene–Quaternary volcanic activity. The youngest products (nepheline basanites) with documented age of 100 000–140 000 years BP, were found near Nová Baňa (Putikov vŕšok; Šimon & Maglay, 2005).

Summary

The territory of Slovakia is formed by the north convex-bent arch of the Western Carpathian mountain range and the northern margin of the Pannonian Basin. The geological/tectonic structure of the W. Carpathians was formed by the north-vergent Alpine orogenic processes. The deformation advanced generally from internal (southern) to the external (northern) parts of the present-day arc. The Internal W. Carpathians (IWECA) were tectonically transformed to the present structure during the Cretaceous period and the External W. Carpathians (EWECA) during the Neogene period. The main tectonic units are from north to south and from bottom to top as follows: The Flysch Belt composed of Krosno and Magura nappe systems. The border between the EWECA and IWECA is the Klippen Belt containing the Oravic tectonic units. IWECA is built by the Lower, Middle and the Upper Group of Nappes. The Vahicum and Tatricum tectonic units form the Lower Group of Nappes. The Veporicum, Fatricum and Hronicum are present in the Middle Group of Nappes and finally the Gemericum, Meliaticum, Turnaicum and Silicicum represent the Upper Group of Nappes. The Tatricum, Veporicum and Gemericum can be considered as the thick-skinned units involving the Paleozoic crystalline basement. Other tectonic units represent cover nappes containing mostly Mesozoic carbonate sediments. Rock formations of the Late Cretaceous (Coniacian–Maastrichtian) and Cenozoic age are in the IWECA traditionally considered as the "post-nappe stacking", however, in the external parts of the IWECA the sediments of late Cretaceous and Paleogene age are tectonized together with their basement. The most characteristic Cenozoic elements in the IWECA include: (1) the Paleogene sediments of the Podtatranská Group transgressively overlapping IWECA nappes and reaching thickness of several thousand m in the central and eastern Slovakia; (2) horst and graben system of the Core mountains, representing the transitional zone between the IWECA and northern part of the Miocene Danube/Pannonian Basin; (3) Miocene to Pliocene rhyolitic, andesitic and later basaltic volcanism (Neovolcanism) particularly extensive in central and eastern Slovakia.

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Prehľad geologickej stavby Slovenska

Územie Slovenska tvorí pásmové pohorie Západných Karpát vyklenuté na sever a severný okraj Panónskej nížiny (obr. 1). Geologická stavba Západných Karpát je výsledkom alpínskej orogenézy, pričom deformácia postupovala od vnútorných častí dnešného oblúka smerom na sever. Vnútorné (interné) Západné Karpaty (IZK) vznikali hlavne v období kriedy a Vonkajšie (externé) Západné Karpaty (EZK) v období neogénu (obr. 2). Za hlavné tektonické jednotky EZK môžeme zo severu na juh a zdola nahor považovať flyšové pásmo tvorené krosnianskym a magurským systémom príkrovov a štruktúru bradlového pásma, ktorá je zároveň deliacim elementom medzi EZK a IZK (obr. 1). V rámci IZK sú prítomné tektonické jednotky spodnej skupiny príkrovov (váhikum a tatrikum), strednej skupiny príkrovov (veporikum, fatrikum a hronikum) a vrchnej skupiny príkrovov (gemerikum, meliatikum, turnaikum a silicikum). Tatrikum, veporikum a gemerikum vzhľadom na prítomnosť paleozoického kryštalinického podložia sa považujú za celokôrové tektonické jednotky. Ostatné tektonické jednotky tvoria pripovrchové príkrovy (obr. 2). Horninové súbory vrchnej kriedy (koňak – mástricht) a kenozoika sa v rámci IZK tradične považujú za popríkrovové útvary, no pri vonkajšom okraji IZK sú často zvrásnené spoločne so svojím podložím (obr. 2). Medzi charakteristické popríkrovové štruktúry IZK patria: 1. paleogénne sedimenty podtatranskej skupiny, transgresívne prekrývajúce príkrovy IZK a dosahujúce vo východnej časti územie hrúbku niekoľko tisíc metrov (obr. 17); 2. štruktúry horských chrbtov a depresií jadrových pohorí predstavujúce prechodnú zónu medzi IZK a severnou časťou Podunajskej, resp. Panónskej panvy (obr. 7 a 18); 3. miocénny až kvartérny vulkanizmus, obzvlášť rozsiahly na strednom a východnom Slovensku (obr. 18).

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