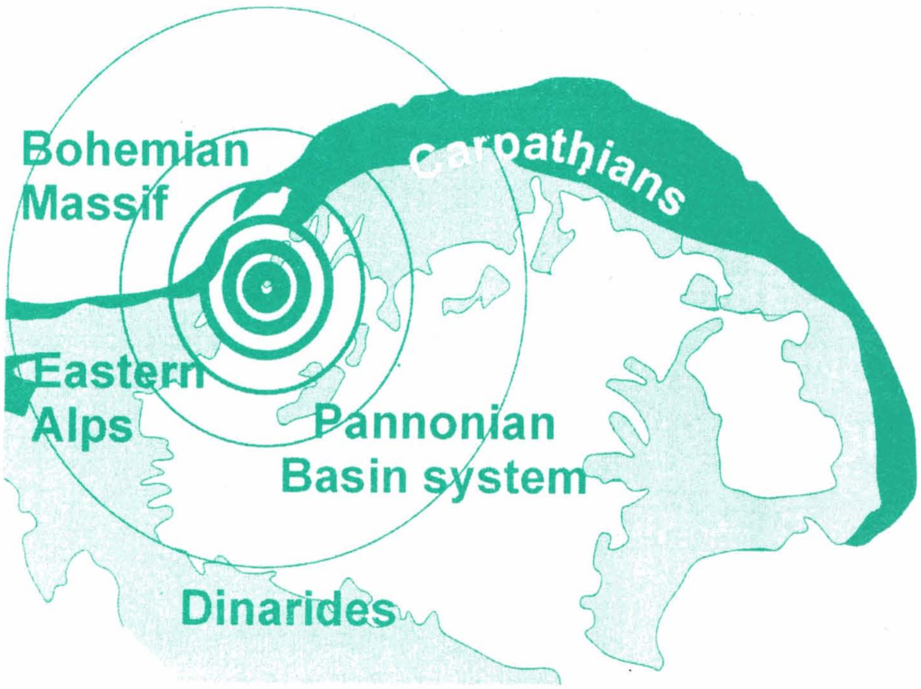
Geological structure of the Alpine-Carpathian-Pannonian junction and neighbouring slopes of the Bohemian Massif



Edited by

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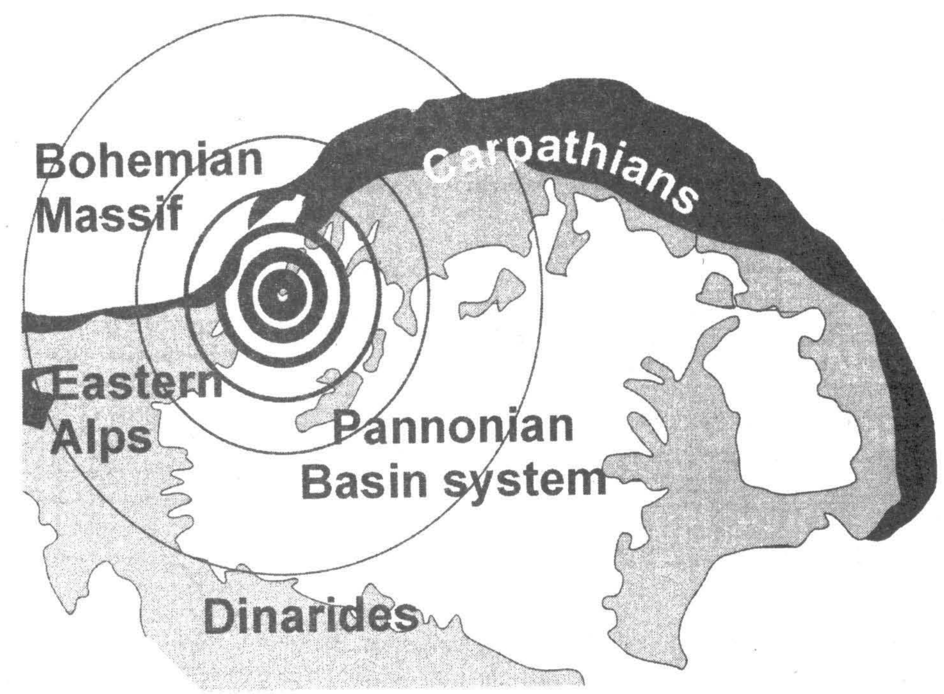

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1.

INTRODUCTION

This textbook describes the structure of a geologically unique part of Europe located at the junction of three principal regional geological domains – the Bohemian Massif, the Alpine-Carpathian Orogenic Belt and the Pannonian Basin System. This area is not strictly defined; it covers the areas of western Slovakia, southern Moravia, northeastern Austria and northwestern Hungary. Some units, which do not occur in these areas, but are important for understanding the structure of the entire orogen are characterized here too. From the point of view of plate tectonics, all the important phenomena and tectonic elements accompanying the origin of collisional mountain belts are present: (1) platform foreland, including the inner and frontal parts of the Variscan orogen in the Moravian part of the Bohemian Massif (even with its own Variscan foreland); (2) flexural basin of the Alpine-Carpathian Foredeep situated above the submerged slopes of the platform; (3) Meso-Alpine accretionary complex of the Flysch Belt, comprising sedimentary, and partially also volcanic complexes detached from the submerged part of the platform and probably also from the subducted zones originally underlain by oceanic crust; (4) complex and long time deformed zones at the boundary between external and central zones of the Alpine-Carpathian orogen, with various units of enigmatic origin; (5) central orogenic zones with Paleo-Alpine nappe structure, involving superficial detachment nappes of sedimentary cover, as well as huge nappes of the pre-Alpine basement. Metamorphic core complexes are exhumed from beneath these nappes, exposing the deep structures of the orogen and partially also subducted oceanic complexes of more external zones; (6) internal zones of the Alpine-Carpathian orogen, reflecting the earliest Alpine compression events; (7) remnants of superimposed, partly still compressional synorogenic Meso-Alpine sedimentary basins in several zones; (8) Neo-Alpine basin structures of several genetic types with complex tectonic and sedimentary evolution, reflecting the processes of back-arc rifting and lithospheric extension; (9) chains of neovolcanic mountains related to the processes of back-arc extension and (10) miscellaneous Pliocene to Quaternary deposits that recorded the terminating, but still active orogenic and basin-forming processes in the area.

The area is complex, not only geologically but also geomorphologically. The Bohemian Massif is an old peneplain, with locally rejuvenized relief, whereas the Alpine-Carpathian orogen gradually rises from a flat foredeep, through highlands of the Flysch Belt as high as the extremely high mountain relief of the Eastern Alps. This is a reflection of Tertiary collision in the Alpine area that, to a large extent, modified the pre-Tertiary structure of the inner Alpine zones. On the other hand, the Western Carpathians underwent a different Tertiary history, as a consequence of slight frontal collision and strong extension in the orogenic hinterland. This resulted in a different erosional niveau and denudation of various structural levels in the Alps and Carpathians. This fact also led to diverse views on the correlations of pre-Tertiary units. The transitional zone between the Alps and Carpathians is therefore a key area for interpretation of both mountain systems. Moreover, this zone is a place of ongoing neotectonic activity (e.g. seismic activity). At the same time, this zone is an area of intensive neotectonic activity expressed by increased seismicity. Numerous engineering activities are present in the area, particularly the building of power plants, as well as numerous settlement agglomerations with high density of population. Deciphering of the geological structure, including the recent motion tendencies in this area has therefore important and practical application, mainly from the point of view of environmental hazards, despite the relative scarcity of raw material deposits. In this textbook, knowledge of scientists from four universities: Bratislava, Brno, Budapest and Vienna, is joined to describe present day opinions on the geological structure and evolution of this interesting area. It is a "natural laboratory" with numerous geological phenomena and processes, which are investigated by practically all geological methods. However, the knowledge of individual geological branches is at various levels of evolution and, moreover, concepts and opinions of several geological schools overlap here. Therefore, this textbook does not provide a complete model of evolution and structure of the Alpine-Carpathian-Pannonian system at its junction with the Bohemian Massif but, instead, an overview of the actual state of knowledge with references to the most important literature. Emphasis has been laid upon correlation of the main units of the Alpine-Carpathian orogen. As such, this text should serve mainly for MSc. and PhD. students of the geological disciplines, as well as workers handling problems of geological practice in this area and to all who are interested in such problems. At the same time, it should serve as an introduction and basis for an intended guide to the important geological localities in this area, which would be a helpful tool in arranging of geological excursions for students of all participating or other universities, as well as for excursions connected with occasional scientific meetings.

Individual parts of the text were compiled by different authors with their own experience and opinions. This is reflected by their approach to the topics and by the way of their presentation. Consequently, the text is not and cannot be, fully compatible. The most striking inconsistencies can be detected in the approach to determine the regional geological units and in the ratios between the description and interpretation sections of certain chapters. After accepting the reviewers' comments, only a few portions of the manuscript were slightly modified during the final editing, in order to adjust at least the basic regional terminology.

In the aim of a better intelligibility and for didactic reasons, the names of important regional geological structures and units have been highlighted in those parts of the text, where they are defined or mentioned for the first time:

- in bold – the regional morphotectonic units (e.g. the **Moravo-Silesian Region, Vepor Belt, Internal Western Carpathians, Vienna Basin**), important structures (e.g. the **Dyje Dome, Peri-Pieniny Lineament, Muráň Fault**), and/or characteristic evolutionary time levels;
- the tectonic units of various orders are emphasized in bold italics (e.g. the ***Slovakocarpathian System, Tatricum, Muráň Nappe***);
- in italics – the material-based regional terms (e.g. the *Letovice Crystalline, Vepor Pluton*), especially the formal lithostratigraphic units (e.g. the *Ipoltica Group, Zuberec Formation*) and sediments of a certain time interval where the regional lithostratigraphic units are not listed (e.g. *Jurassic sediments*).

2.

BOHEMIAN MASSIF – PLATFORM FORELAND OF THE ALPS AND CARPATHIANS

The Bohemian Massif, as a part of the North European Platform, is the easternmost element of the Variscan branch of the European Hercynides not involved in the Alpine orogen. Within the scope of the present work, parts of the Bohemian Massif that crop out west of the Carpathian Foredeep and those forming the substratum of the External Western Carpathians, i.e. the Carpathian Foredeep and the Flysch Belt as far as the Pieniny Klippen Belt (Tomek, 1993), are described. However, some opinions have been published suggesting underthrusting of the Bohemian Massif much more to the east, beneath the Central Western Carpathians (e.g. Roth, 1980; Bezák et al., 1997a).

Compared to the West Carpathians, the Bohemian Massif represents a geological unit consolidated much earlier, during the Hercynian orogeny when the Brunovistulicum (the Brno Unit) collided with the Lugodanubicum. That is why the Bohemian Massif behaved as a platform during the Mesozoic and the Tertiary. The Alpine orogeny, having progressed in its southern and eastern surroundings, influenced the Bohemian Massif especially by a rejuvenation of pre-existing faults during that time. For instance, in the southeastern part of the Bohemian Massif, one can find several NNE-SSW trending sinistral strike slip fault zones accompanied by mylonites and cataclasites. According to isotopic dating, the shear zones are interpreted as a late Variscan conjugate system with partial Alpine reactivation. The brittle deformation within the shear zones likely represents foreland deformation during the Alpine orogeny (Wallbrecher et al., 1991). In our studied territory, the Diendorf fault (shear zone) is the most important example of such a sinistral strike slip fault. It is linked to the eastern fault of the Boskovice Furrow and the horizontal displacement on the fault is estimated at several tens of km.

2.1 GEOLOGICAL STRUCTURE OF THE EASTERN PART OF THE BOHEMIAN MASSIF

The eastern part of the Bohemian Massif is represented predominantly by the **Moravo-Silesian Region** and marginally by the **Moldanubian, Kutná Hora-Svratka** and **Central Bohemian (Bohemic) Regions** (Fig. 1).

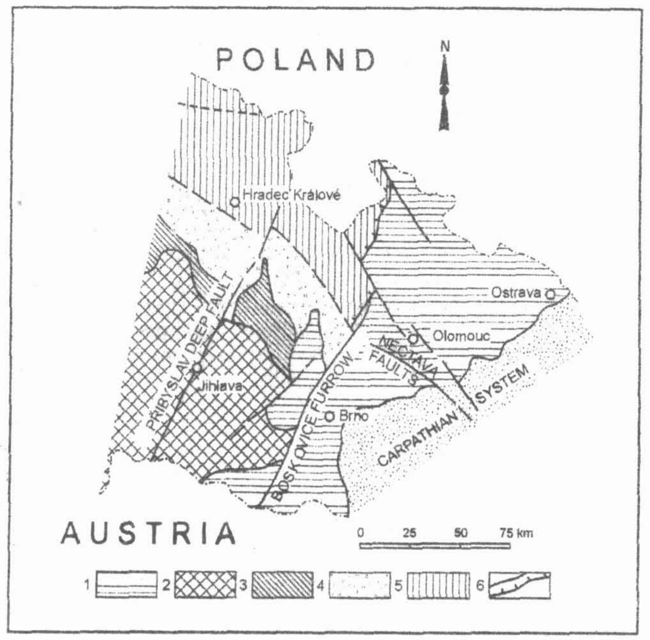


Figure 1. Regional geological division of the eastern margin of the Bohemian Massif (after Misař et al., 1983).

Explanations: 1 – Moravo-Silesian Region, 2 – Moldanubian Region, 3 – Kutná Hora-Svratka Region, 4 – Central Bohemian Region, 5 – Lugic Region, 6 – faults and thrusts important for the defined regions.

2.1.1. The Moravo-Silesian Region

The Moravo-Silesian Region consists of pre-Variscan metamorphic and magmatic rocks with overlying transgressive sequences of Paleozoic (Devonian, Carboniferous and Permian) age. The basement of Variscan units in the Region is formed by pre-Devonian (Precambrian) crystalline rocks designated as the ***Brunovistulicum*** or ***Brno Unit***. During the Hercynian orogeny, the western part of the Brunovistulicum was incorporated in the geological structures of ***Moravicum*** and ***Silesicum***. Brunovistulic rocks crop out separately in the Brno Massif in the crystalline inliers in the Hornomoravský úval Valley (Fig.2). The Moravo-Silesian Region is in perpendicular contact with all the above mentioned parts of the Bohemian Massif, with a boundary formed by the heterogeneous Moravo-Silesian Fault Zone (dislocations, overthrusts, strike-slips and mylonite zones).

Brno Massif

The *Brno Massif* is about 600 km^2 in area and is formed predominantly by Cadomian granitoids, with remains of a crystalline envelope and a bimodal volcanic association in the *metabasic zone*. This N-S trending zone runs approximately in the middle of the massif and splits it into eastern and western granitoid parts.

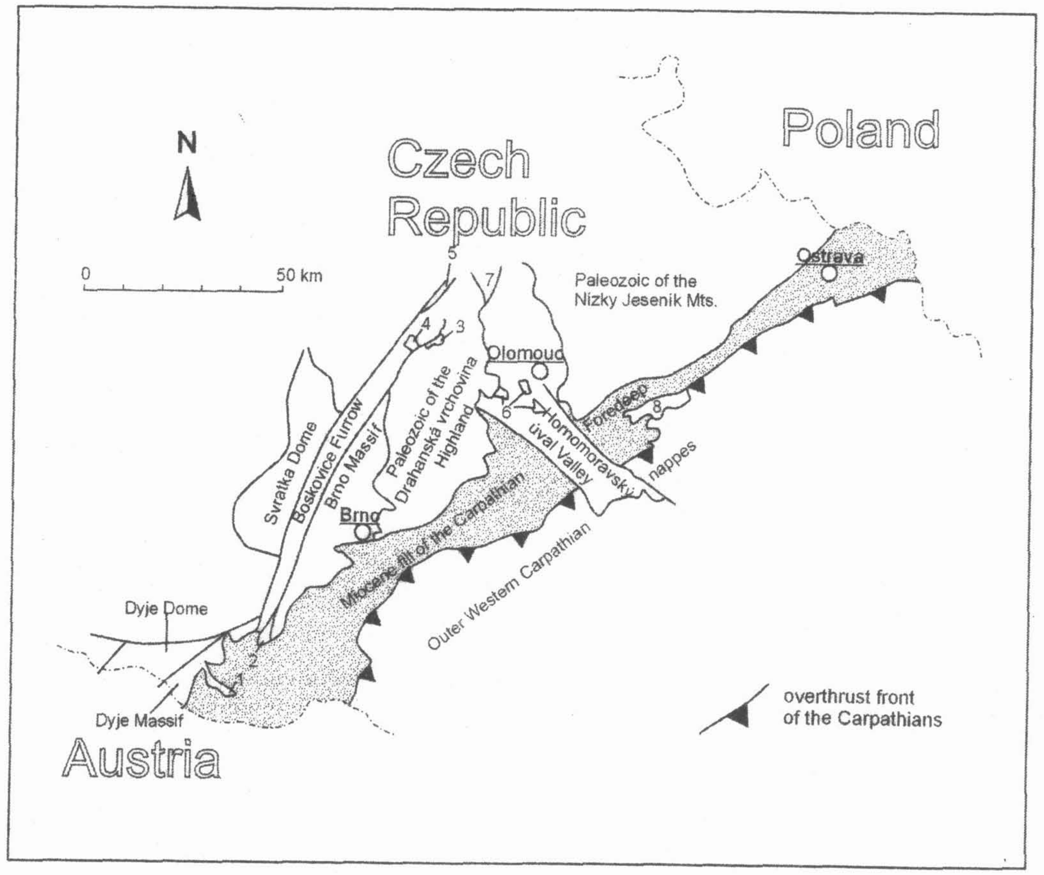


Figure 2. Division of the Moravo-Silesian Region into partial geological units (after Mísař et al., 1983)

Explanations: 1 – Krhovice Crystalline Complex, 2 – Miroslav Horst Crystalline Complex, 3 – Klady Crystalline Complex, 4 – Nectava Crystalline Complex, 5 – Svinov-Vranov Crystalline Complex, 6 – outcrops of brunovistulic crystalline rocks in the Hornomoravský úval Valley, 7 – southern promontory of the Vrbno Group, 8 – Moravo-Silesian Paleozoic.

Brunovistulicum in the basement of the Carpathian Foredeep

The Brunovistulicum (Dudek, 1980) is the term for the pre-Variscan crystalline basement and its Paleozoic cover in the eastern part of the Bohemian Massif. The Brunovistulian block forms the lower plate and foreland of the eastern branch of Variscides in Moravia and Silesia. It is composed of Precambrian (Cadomian) metamorphic and plutonic rocks (e.g. the Brno Massif) overstepped by predominantly Devonian and Carboniferous sediments. During the Tertiary Alpine orogeny, the Brunovistulicum again formed the lower plate and foreland for the overthrust nappes of the External

Western Carpathians. The Brunovistulicum is segmented by transversal NW-SE trending fault zones into blocks with somewhat different evolution and structure.

The pre-Miocene basement of the Carpathian Foredeep is well-known from boreholes. Metamorphosed pelitic-psammitic rocks (muscovite-biotite paragneisses with garnet, weakly migmatitized in NE part) prevail north of the Haná Fault Zone; mid-Moravian and south-Moravian blocks are composed of plutonic rocks of Brno Massif, with the envelope consisting of metamorphosed volcano-sedimentary complexes (phyllites, paragneisses, greenschists, hornblendites). This crystalline complex is overlain by a sedimentary cover starting with Lower Cambrian deposits, but dominated by Devonian sediments. The extent of the Lower Paleozoic sedimentary complexes is governed by the Nesvačilka Furrow fault zone. North of it, Devonian and Carboniferous sediments were preserved, whereas in the south, the Paleozoic strata are not present (Fig. 3). Instead, there are Jurassic, Upper Cretaceous and mainly Paleogene sediments more than 1600 m thickn (Stráník et al., 1993).

Svratka and Dyje Domes of the Moravicum

Both Moravic domes are, since the era of Suess (1912), considered as tectonic half-windows cropping out from below the overriding Moldanubian and Kutná Hora-Svratka Units. The best known, **Svratka Dome** (Fig. 2), is formed by a lower autochthonous unit and the overthrust ***Moravic Nappe*** (Jaroš & Mísař, 1976). The autochthonous part of the **Dyje (Thaya) Dome** is formed by the Cadomian *Dyje Massif* and the pre-Devonian *Deblín Group* (gneisses, mica-schists, cataclastic granites), considered to be the original part of Brunovistulicum, overlain by transgressive Devonian sediments (basal clastics, limestones). The Moravic Nappe consists of the lower, *Bílý potok Group* (phyllites, quartzites, limestones), then the *Bíteš Group* (several types of biotite, two-mica and muscovitic gneisses with hornblendite and limestone intercalations) and the upper, *Olešnice Group* (mica-schists with paragneiss bodies, metabasalts, graphitic phyllites and limestones). The Deblín Group was metamorphosed in the biotite to garnet zone with subsequent retrogressive chlorite-zone metamorphosis, mylonitization and cataclasis. The Moravic Nappe is characterized by an increasing degree of metamorphism.

Silesicum

The Silesicum resembles the Moravicum in many aspects. However, due to the more intensive Hercynian tectogenesis, a whole series of nappes and slices of pre-Devonian crystalline complexes was formed here, together with metamorphosed Devonian volcanics and sediments. This group is formed by phyllites and greenschists with occurrences of Lahn-Dill-type iron ores.

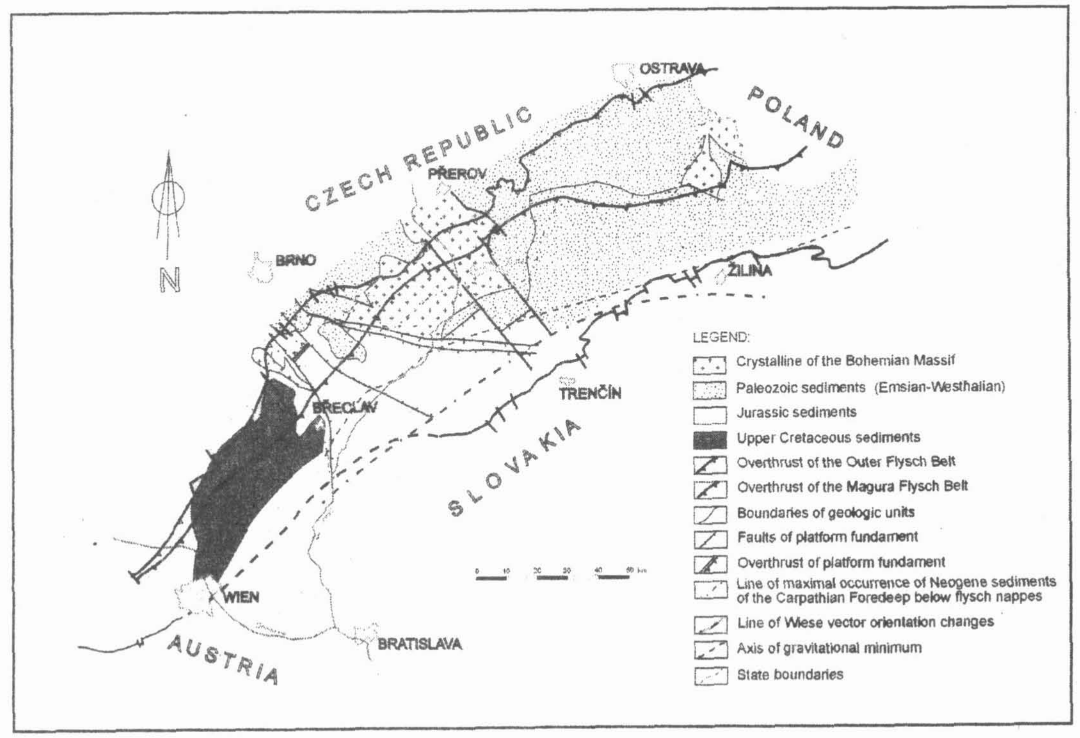


Figure 3. Geological map of the pre-Tertiary basement of the Flysch Belt in the Eastern Alps and Western Carpathians, after Krejčí et al. (1996).

2.1.2. The Moldanubian Region (Moldanubicum)

The ***Moldanubicum*** forms the southern and central part of the Bohemian Massif (Fig.1), built up of highly metamorphosed complexes, for the most part presumably of Precambrian age, which are penetrated by large Hercynian granitoid plutons. Recently, the classical lithostratigraphic division into "monotonous" and "variegated" groups has been completed by the tectonostragraphic division into lithotectonic units – nappes, terranes (Fiala et al., 1995). From this point of view, the ***Gföhl Unit*** dominates in its eastern part. This unit partly corresponds to the *Variegated Group* with high-pressure granulites of 340–350 Ma age (according to U-Pb dating). The granulites are accompanied by garnet and spinel peridotites, pyroxenites, dunites and some eclogites. High-grade metamorphosed anatectic orthogneisses and paragneisses with hornblendites and metamorphosed gabbros are also present. More to the west, there is the ***Drosendorf Unit*** that is a part of the Variegated Group. Metamorphism of this unit is of medium to high grade, free of high-pressure granulites, with dominant sillimanite-biotite paragneisses (original greywackes and pelites) interlayered by marbles, calc-silicate hornfels, graphitic rocks, quartzites, leptinites, hornblendites, metadolerites and metagabbros (Fiala et al. 1995). The central part of the Moldanubicum is penetrated by the large Variscan *Moldanubian Pluton*; in the eastern part, the *Třebíč Intrusive Massif* occurs, formed by variegated granitoids ("durbachites", i.e. syenites to granites) and vein rocks.

2.1.3. The Kutná Hora-Svratka Region

Despite the still existing opinion that this unit is only a part of the Moldanubian Region (recently for example Zoubek, 1988), the prevailing general opinion is that the Kutná Hora-Svratka Region should be treated separately due to the lower grades of metamorphism (Mísař et al., 1983). The muscovite isograde, though it is locally an up to 10 km wide transitional zone, is considered as a boundary between Moldanubicum and Kutná Hora-Svratka Crystalline Complex. The *Svratka Crystalline Complex* in the western part consists lithologically of alternating two-mica mica-schists (usually with garnet), two-mica migmatites and orthogneisses. In addition, isometric serpentinite bodies and tiny amphibolitic, micaceous quartzite and calc-silicate interlayers are found in the mica schists.

2.1.4. The Central Bohemian Region (Bohemicum)

The eastern part of the Central Bohemian Region consists of the *Letovice Crystalline Unit*. It is a mesozonally metamorphosed complex of Proterozoic or Paleozoic sediments and volcanics outcropping between the Svratka Dome of the Moravicum and the Boskovice Furrow (Fig.1). It consists of mica-schists, gneisses, metaquartzites (metalydites), amphibolites, metagabbros and metamorphosed ultrabasic rocks. The metasediments represent about 30%, amphibolites and metagabbros 60% of the complex. The lower complex of ultrabasic rocks, cumulate rocks, basic volcanics and local basic dykes is believed to be a dismembered ophiolite suite metamorphosed under conditions of amphibolite and greenschist facies (Mísař et al., 1984).

2.2. PHANEROZOIC SEDIMENTARY COVER

2.2.1. Moravo-Silesian Paleozoic complexes

Lower Cambrian rocks are known from boreholes only (Měnín-1, Němčičky-3 a 6; Jachowicz & Přichystal, 1997), Silurian rocks form a small occurrence near Stínava on the Drahanská vrchovina Upland. Devonian rocks form two fundamental developments in the Moravo-Silesian area: platform and basinal. The platform development overlaps on the Brunovistulic basement by basal clastics, and then continuously passes up to the Lower Carboniferous carbonate formations.

The classic basin development is preserved only in relics in the newly defined **Moravo-Silesian Klippen Belt** (Přichystal, 1996), in which basic volcanics of spilite-quartz keratophyre association dominate together with slates, radiolarites and resedimented slope carbonates. Lower Carboniferous sediments, forming the Drahanská vrchovina Upland and Nízký Jeseník Mts. (Fig. 2), are in the Kulm development represented by conglomerates, greywackes, siltstones and claystones. Thick coarse-grained Upper Viséan conglomerates in the southern part of the Drahanská vrchovina Upland are considered to be the products of a deltaic system. Upper Carboniferous (Stephanian) and Permian (Autunian) rocks are present in the **Boskovice Furrow**, a N-S oriented Late Variscan graben. The western part of the furrow is lithologically variegated, with coal seams, the eastern one is composed of proluvial cones of conglomerates.

2.2.2. Mesozoic sediments

Jurassic sediments outcrop in several small erosional relics only on the SE margin of Brno and in the middle part of the Moravian Karst in the **Blansko Furrow**. The base of the sequence consists of calcareous sandstones and conglomerates, passing upwards into shallow marine, locally cherty limestones. Their stratigraphical range is Callovian – Oxfordian.

Lower Cretaceous sediments are represented by terrestrial clays, sands and gravels. Their erosional remnants are preserved again along the fault system of the Blansko Furrow (Fig. 4). Jurassic limestones, which were of much wider extent at that time, and were the main original source of the clastic material.

During the late Lower Cretaceous, the marine transgression coming from the Western Carpathian region reached the Kuřim area through the Nesvačilka Trough and **Kuřim-Řečkovice ramp valley** (Krystek & Samuel, 1978). Evidence of its presence can be found only in tectonic breccia composed of the micritic limestone clasts of Aptian-Albian age and dioritic rocks of the Brno Massif. These limestone fragments were preserved within a reverse fault zone, which thrusts the western granitoid part of the Brno Massif over the metabasaltic zone.

The studied area is reached by the SE projections of the **Bohemian Cretaceous Basin**. Sedimentation started with Cenomanian terrestrial sediments; marine Cenomanian strata are represented by clayey glauconitic sandstones. The base of the Lower Turonian sequence has a transgressive character; its upper part is formed by calcareous siltstones and sandy spongolitic marlstones with chalcedonic cherts.

2.2.3. Tertiary sediments and volcanics

Autochthonous Paleogene sediments do not occur in outcrops in the eastern part of the Bohemian Massif. They are known, however, from the filling of the **Nesvačilka and Vranovice Furrows**, below the Flysch Belt overthrust. With regard to the *Miocene sediments*, relics occur also outside the Carpathian Foredeep. They are usually related to long-term sinking areas (Boskovice Furrow, prolongation of the Nesvačilka and Vranovice troughs, Nectava Fault System, Fig. 4). The maximum geographical extension of marine Miocene sediments towards the Bohemian Massif is documented as far as the line connecting Jaroměřice n. Rokytnou and Třebíč. Pliocene terrestrial deposits are preserved within the Hornomoravský úval Valley. *Lower Miocene volcanics* of basaltic composition occur near Jaklovec (Ostrava region) and Otíc (Opava region). Lava flows of nepheline-bearing basanites overlie Lower Badenian basal clastics near Opava (Kobeřice Volcano).

2.2.4. Quaternary cover

Pleistocene sediments are represented mainly by Würm loess, as well as gravels and sands of river terraces. Air-borne sands, known from the area south of Židlochovice, originated at the Pleistocene/Holocene boundary. Alkaline basalts, probably of Early Pleistocene age, occur within the examined area at Červená hora near Domašov in Nízký Jeseník Mts. These volcanics geotectonically represent, together with other localities, the signs of embryonal continental rifting. Small occurrences of *travertines* in the SE vicinity of Přerov are noteworthy. They are probably related to the Haná Fault System. According to the paleontological investigations, the travertine production was active during over a long period, probably since the Cromerian interglacial up to its end during the Würm period (Musil, 1993).

2.3. JUNCTION ZONE OF THE BOHEMIAN MASSIF AND CARPATHIANS

Based on the results of deep geophysical research, the extent of the Bohemian Massif underneath the Western Carpathian nappes as far as the line running along a gravity minimum axis, crossing Vienna, Hodonín, Valašské Klobouky, Kysucké Nové Mesto and Námestovo, is presumed (Stráník et al., 1993). This line, located deep below the Magura Flysch Zone, coincides well with a boundary indicating a change in the orientation of Wiese vectors of electric conductivity (Pícha, 1980, Jankowski et al., 1985; Fig. 3).

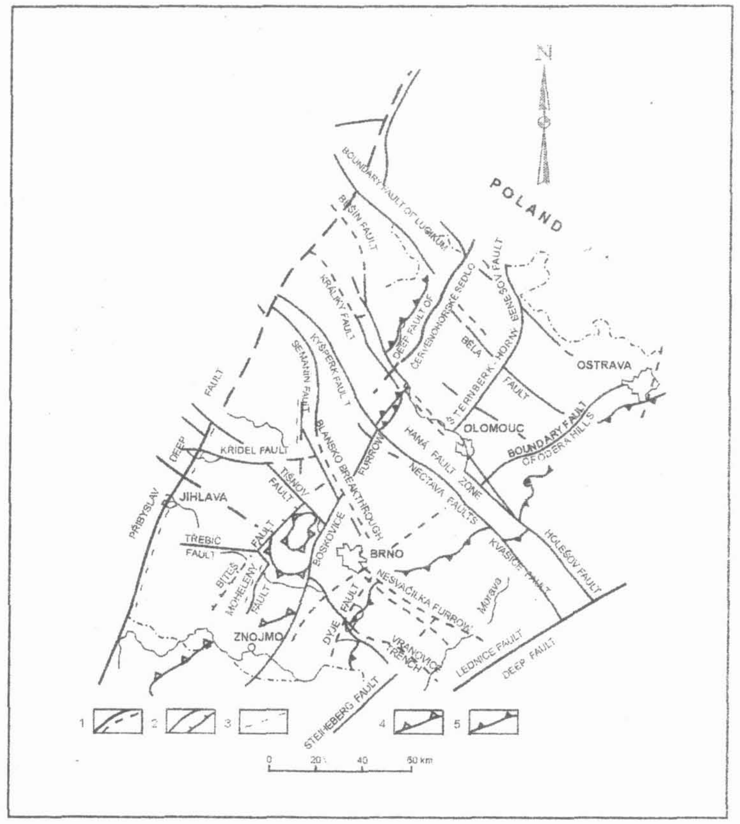


Figure 4. The main fault systems at the eastern margin of the Bohemian Massif (after Misař et al., 1983, modified).

Explanations: 1 – geophysically indicated deep seated faults (full line – verified fault, dashed line – presumed fault), 2 – other important faults, 3 – mylonite zones, 4 – thrusts and nappe overthrusts, 5 – boundary of the Flysch nappes overthrust.

Similarly, on the basis of re-evaluation of geomagnetic and geoelectric data (Gnojek & Heinz, 1993) from the junction area of the North European Platform, Alps and Carpathians, it is presumed that the platform of the Bohemian Massif ends at the line of orientation change of the Wiese vectors (Fig. 3). New geochemical results from magmatite pebbles of the Rača Unit conglomerates indicate their affinity to granitoids of the Central Western Carpathians (Hanžl & Krejčí, 1996; Hanžl et al., 1997). According to current day geotectonic ideas (Plašienka, 1995, Tomek, 1993) their source might could have been represented by a crystalline basement in the Middle Penninic (Briançonnais) zone. The Silesian source area (cordillera), situated more northward, would have involved remnants of the Brunovistulian cover succession (e.g. Devonian carbonates, coal-bearing Carboniferous strata), but clasts of these have not been found in the Magura flysch sediments. On the contrary, clasts from more "southern" paleogeographic areas, e.g. pebbles of deep-water Triassic sediments, were found in the Rača Unit conglomerates (Soták, 1990).

The platform basement below the flysch nappes overthrust is composed of Brunovistulic crystalline complexes and sedimentary cover from Paleozoic and Mesozoic (Jurassic, Lower and Upper Cretaceous) age. The Nesvačilka and Vranovice Troughs (Fig. 4) are filled with sediments of the Upper Cretaceous – Paleogene age. According to Dudek (1980), the basement can be divided into the South Moravian, Central Moravian and North Moravian blocks. The boundary between the first two blocks is in the Nesvačilka Trough. The western margin of these blocks is the eastern marginal fault of the Boskovice Furrow; the SE margin is represented by a hypothetical basement margin of the SE slopes of the Bohemian Massif below the Carpathian allochthonous units. The Central Moravian Block is limited to the NE by the Kvasice fault, which forms the southern boundary of the Hornomoravský úval Valley.

The South Moravian Block can be divided, according to Špička (1976), into four principal morphotectonic units, which are expressed clearly in the pre-Tertiary platform relief: (a) the **Nesvačilka Trough**, (b) the **Nikolčice-Kurdějov Swell**, (c) the **Vranovice Trough**, (d) the **Pavlov Unit**. Mutual restriction of the aforementioned units, with different extent of Paleozoic, Mesozoic and Tertiary complexes, is defined by both the NW-SE fault systems and erosional slopes and edges. The sedimentary fill of both furrows (Upper Cretaceous – Oligocene) locally transgressively overlaps the particular branches of the fault systems.

The Central Moravian Block contains only rudimentary remnants of Paleozoic sediments. This block is in a higher structural position with respect to the surrounding blocks in SW and SE. This higher position persisted from the Paleozoic until the Paleogene age. Unlike in the South Moravian block to the SW, where thick carbonate and clastic sediments of the Paleozoic, Jurassic and Paleogene age were drilled by deep boreholes (e.g. Němčičky, Dambořice), the aforementioned sediments of the Central Moravian Block occur at much shallower depths. The same applies to the relation to the North Moravian Block with a huge development of Paleozoic sediments (Jablůnka-1 borehole). The more continuous Paleozoic to Paleogene sediments occur much farther toward the SE in the Central Moravian Block, below the Magura Nappe. An inversion of this elevated block took place during the deposition of Lower Miocene sediments, hence the Carpathian Foredeep sediments extend far below the Magura Flysch.

The North Moravian Block is divided by the Rožnov-Súlov step of the platform basement into a shallow and a deep block. The deep block is characterized by a great thickness of Paleozoic sediments and the absence of Mesozoic and Paleogene rocks.

2.3.1. Brunovistulic crystalline complexes

The shallowest crystalline complexes below the Flysch nappes occur in the areas of the Ždánice and Rusava elevations, at a structural depth less than 500 m. At the western margin of the Vienna Basin, the depth of the crystalline basement surface reaches 7000–9000 m. Magmatic rocks in the South Moravian Block belong to the *Brno Pluton*. The crystalline basement of the Central Moravian Block consists of Cadomian tonalites, leucogranites, and gabbros. In the area of the North Moravian Block, mostly rocks of the metamorphic envelope of the Brno Pluton occur and consist chiefly of migmatitized gneisses.

2.3.2. Sedimentary platform cover

The oldest part of the platform cover, underthrust below Flysch nappes, is consist of *Paleozoic sediments* (Late Devonian to Late Carboniferous). The Paleozoic sequence begins with Devonian basal clastics, partly in the continental *Old-Red* facies, reaching over 600 m thickness in the South Moravian Block. Later, carbonate sediments of the *Macocha Formation* (1300 m) and *Líšeň Formation* (1200 m) were deposited over the previous formation. The sedimentation persisted until the Viséan, when the deposition of the flysch *Myslejovice Formation* (Kulm facies) started. A large alluvial cone of conglomerates, reaching a maximum thickness of 1800 m occurs within the Myslejovice Formation in the South Moravian Block. The *Ostrava Formation* (Namurian A) of the Variscan foredeep molasse development is known only from the South Moravian and North Moravian blocks. In the northern part of the South Moravian Block (Němčičky-1 and 2 boreholes) the formation is up to 1300 m thick. Near the Czech/Austrian border, Austrian authors presume the occurrence of Paleozoic rocks just west of the Flysch nappes front (e.g. Brix et al., 1977, Ladwein, 1988). They are, however, Carboniferous-Permian rocks of the Boskovice Furrow. An important fact about the restricted extent of Paleozoic sediments was revealed by the Aderklaa ÜT-1 borehole, situated NE of Vienna, above the front of the Northern Calcareous Alps. The borehole directly penetrated the crystalline basement below nappe units and autochthonous Mesozoic sediments.

Jurassic sediments (Toarcian – Upper Tithonian) are divided in a basal clastic formation and an overlying carbonate and pelitic-carbonate development (Eliáš, 1981, Brix et al., 1977). The overall thickness of the basal development is 300 m and is divided into the *Gresten* and *Mikolčice Formations*. The basal clastic formation is followed by the Oxfordian *Vranovice limestones and dolomites*, then by the *Mikulov marlstones* (Oxfordian – Middle Tithonian), *Kurdějov limestones and dolomites* (Middle Tithonian) and *Ernstbrunn Limestones* (Upper Tithonian), in a cumulative thickness of 2000 m. Unlike in the Moravian part, a much thicker Middle Jurassic deltaic system of the Gresten Formation developed in Austria. These deposits fill troughs of rift origin. Cessation of the tectonic activity in the Late Jurassic resulted in formation of platform and basin domains in the Jurassic sedimentary area in Austria and Moravia (Wessely, 1988, Eliáš & Wessely, 1990).

Lower Cretaceous sediments (Upper Albian) are represented by oncoid beds (Řehánek et al., 1984). They consist of compact organodetrital to muddy limestones, with dominant nodular Girvanella limestones followed by oyster limestones.

Upper Cretaceous sediments (Turonian – Maastrichtian) are frequently called sandy-glauconitic series (Adámek, 1986). These sediments were found in only three boreholes – Nové Mlýny-2, Sedlec-1 and Strachotín-2; their redeposited clasts and microfauna are known from Eggenburgian and Ottnangian sediments of the Carpathian Foredeep. In Austria they are called the "Glaukonitische Serie" of the Klement Formation; generally placed in the Cenomanian-Campanian interval. Their greatest thickness was penetrated by the Ameis-1 borehole (517 m).

The fill of the Nesvačilka and Vranovice Troughs is represented by *Campanian – Oligocene sediments*, which were deposited in previously formed erosional canyons. The filling took place in several sedimentary cycles separated by erosional phases. The most intense is the erosional phase between the Early and Middle Eocene. The sediments have transgressive character at the base, whilst the content of coarse terrigenous admixture diminishes upwards. The coarse detrital sedimentation ended in the late Early Paleocene, and a sandstone to siltstone deposition took place from the Late Paleocene until the Early Eocene. From the Middle Eocene until the Early Oligocene, deposition of a uniform siltstone and claystone complex predominated. The thickness of the sediments in the axial parts of the troughs exceeds 2000 m.

Neogene sediments of the Carpathian Foredeep, below the Flysch nappes overthrust, are represented by Eggenburgian to Karpatian deposits. In Moravia, the extent of the autochthonous Eggenburgian sediments below the Flysch nappes is restricted mostly to the South Moravian area. The maximum thickness (500 m) was registered close to the Flysch nappes front at the Austrian border. As a rule, the autochthonous Eggenburgian sediments underlying the Waschberg Zone do not exceed 100 m in thickness. These sediments are overlain by the Ottnangian *Rzehakia (Oncophora)* and Karpatian *Laa Formations*. A part of the Carpathian Foredeep sediments in Austria at the Flysch nappes front, belongs to the allochthonous complex of folded molasse.

Data on the Ottnangian sediments (Rzehakia beds), close to the front of the Flysch nappes are scarce. The extent of the Karpatian sediments in the southern part of the area is almost identical with that of the Eggenburgian sediments. Toward NE, the Karpatian sediments dominate under the Flysch nappes and are up to 700 m in thickness. In the North Moravian Block, the Lower Badenian sediments are distributed below the front of the Flysch nappes (Čtyroký & Adámek, 1988).

2.4. POST-HERCYNIAN TECTONIC EVOLUTION OF THE EASTERN MARGIN OF THE BOHEMIAN MASSIF

At the eastern margin of the Bohemian Massif, a fault rejuvenation occurred due to the Alpine orogeny. Two main fault-systems were rejuvenated: the Sudetian (NW-SE) and Rhenian (NNE-SSW) faults. Tectonic movements, which predated the final overthrust of the Flysch nappes after the Early Badenian are documented only in the Hornomoravský úval Valley, Vienna and Opava basins.

The most important representative of the Sudetian (NW-SE) directed faults are the **Haná Fault System** (Fig. 4), which is linked to the Labe Lineament. It is accompanied by mineral water springs and travertine deposits. Its continuation is reflected also towards the SE in the morphology of the Flysch Belt and by deposits of Badenian-Sarmatian trachytic andesites and basalts in the surroundings of Bojkovice. In the Hornomoravský úval Valley, the NW-SE oriented faults were rejuvenated during the Pliocene. The tectonic movements continued in the Pleistocene as well, during the neotectonic Drahany phase (Late Günz – Early Mindel). In the last centuries, earthquakes generated in the Alpine-Carpathian region have been registered in the towns and villages located near the NW-SE faults (Olomouc, Hněvotín, Přerov).

Faults in the Sudetian direction are also represented by faults limiting the Blansko Fault Zone and those limiting the Nesvačilka Trough. On the other hand, in the Nízký Jeseník Mts. there are neovolcanic deposits concentrated along these faults. In the **Blansko Fault Zone**, an upthrust of the Brno Massif rocks onto the Upper Cretaceous sediments has been documented. This fault zone also clearly affects the extent of Jurassic sediments and Lower Cretaceous, Rudice Beds, in the Moravian Karst.

The fault system in Rhenian direction, is represented by the **Boskovice Furrow**, the indistinct **Jihlava Furrow** and the **Červenohorské sedlo Fault Zone**. For example, the town of Jihlava was frequently mentioned in the early Middle Ages, as the site of an earthquake.

Faults in Carpathian direction (NE-SW) were active mainly in the Vienna Basin. At its northern margin in the Hradiště Graben, some fault lines which influenced sedimentation in the Morava alluvial plain, even in Holocene, can be observed. They represent a rejuvenation of vertical movements within the older Middle and Late Miocene strike-slip system.

Recent movements in the Bohemian Massif – Western Carpathian junction zone have been published by Vyskočil & Zeman (1980). Vertical movement activity reaches up to 5 mm/y. Horizontal movements are active in a direction normal for the Carpathian Flysch arc, with the West Carpathians tending to drift away from the Bohemian Massif.

3.

ALPINE-CARPATHIAN SYSTEM

The Alpine-Carpathian system is part of the European Alpine orogenic belt originating in the Mediterranean part of the Tethys. It was born during the Middle Cretaceous to Miocene, from the continental collision of Africa and Europe. The studied area belongs to the Eastern Apine-West Carpathian-Pannonian junction zone. The external zones of the Eastern Alps and Western Carpathians are formed by the Tertiary Flysch Belt, which is their unifying element enclosing the internal zones of the pre-Tertiary units, with their complex mutual relationships. The Austroalpine units dominate in the central zones of the Eastern Alps and are related to the Slovakocarpathian units of the Central Western Carpathians. On the other hand, the units of the Internal Western Carpathians (Hungarocarpathian units), mostly submerged below the Neogene fill of the Danube Basin, are closely related to the Southern Alps and Dinarides.

3.1. WESTERN CARPATHIANS

The Western Carpathians cover the territories of Slovakia, NE Austria, Moravia, southern Poland and northern Hungary. The western geographical boundary of the Carpathians and the Eastern Alps is situated in the Devín Gate along the Danube river valley. The geological location of this boundary is, however, more complicated. Eastern Alpine units, forming the basement of the Vienna Basin, reach almost the Malé Karpaty area on the west. On the other hand, the Hainburg Hills, south of the Devín Gate, still belong to the Western Carpathians.

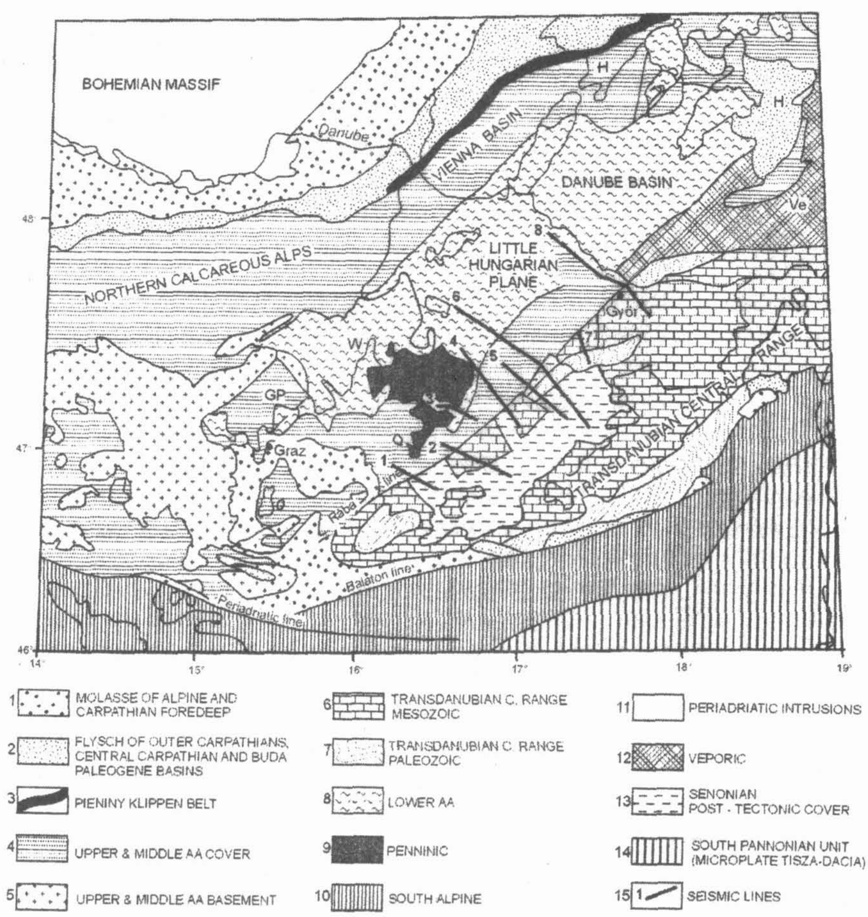


Figure 5. Geological map of the pre-Tertiary surface of the Alpine-Carpathian-Pannonian junction zone (Horváth, 1993; Tari, 1996, modified after Fusán et al., 1987; Fülöp et al., 1987; Fuchs, 1984, 1985). The units exposed on the surface are drawn in a thicker pattern than the units buried under the Tertiary sediments. The numbered thick lines represent the seismic profiles.

Explanations: H – Hronicum, F – Fatricum, Ve – Veporicum, GP – Graz Paleozoic Unit, W – Wechsel crystalline complexes, PN – Penninic of the Rechnitz window.

The Eastern Alps and Western Carpathians originated together in neighbouring areas. Due to their common development, their units often possess similar, mutually correlatable features. The most important distinguishing feature is the fact that the inner zones of the Eastern Alps, after the Middle to Upper Cretaceous orogeny, were largely affected by the Tertiary collision. During this tectogenesis, the Austrolpine units were thrust over the Penninic units and then, altogether, over the Bohemian Massif, whereas in the Western Carpathians the Tertiary nappe movements affected only the external zones. Unlike the Eastern Alps, extensional basin structures are typical for the Western Carpathians. They accompanied the Tertiary orogenic collapse in transtensional to extensional conditions (e.g. Kováč et al., 1997a).

The correlation of subsurface units of the Pannonian Basin s.l. and units of the surrounding mountain systems is very difficult, because of their thick Late Tertiary and Quaternary sedimentary cover. This area was considered as an intermontane block ("Zwischengebirge") in the classical geosynclinal theory. It was thought to be the reason for the formation of the Carpathian arc due to its rigidity. Recently, it has become evident, however, that the basement of this basin consists of several tectonic units that are relatively correlatable with the neighbouring regions (Fig. 5).

The structurally deepest basement unit of the westernmost part of the Danube – Little Hungarian Plain basin is formed by the Penninic units, outcropping in the Rechnitz-Köszeg tectonic window, which are covered by the Lower to Upper Austroalpine units of the Eastern Alps. The Transdanubian Central Range, which belongs to a different tectonic superunit called Transdanubicum, is in upper nappe position with respect to the Austroalpine units (Fig. 6).

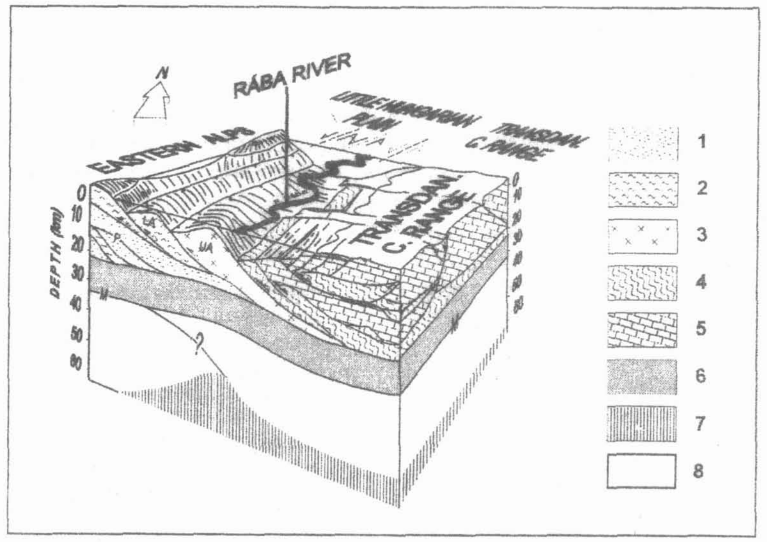


Figure 6. Block-diagram illustrating the mechanism of lithospheric extension of the southern and central part of the Danube Basin (Little Hungarian Plain); Horváth, 1993; Tari, 1996.

Explanations: 1 – units of Alpine Penninic (P), 2 – Lower Austroalpine rocks represented by Wechsel Unit in this area (LA), 3 – Upper Austroalpine complexes represented by the Graz Paleozoic Unit (UA), 4 – Late Paleozoic rocks of the Transdanubian Range, 5 – Jurassic and Triassic sequences of the Transdanubian Range, 6 – ductile lower crust over the MOHO discontinuity, 7 – lower lithosphere and astenosphere, 8 – inverse and strike-slip fault movements.

The Western Carpathians, as well as the neighbouring areas of the Eastern Alps and the northern part of the Pannonian Basin, underwent a very complicated evolution with multiple structural reworking of crustal segments in this region. Reconstruction of the processes is extremely difficult for several reasons: numerous reactivations of the tectonic zones and lineaments, metamorphism of older rock complexes, extensive erosion and, together with, deposition of new sedimentary sequences filling the post-Senonian basins and widespread Tertiary volcanism.

Formerly, according to the geosynclinal theory, the Western Carpathians were divided into two basic zones: externides represented by the Outer Western Carpathians and internides represented by the Inner Western Carpathians. Recently, from the plate tectonic point of view, a division into three principal zones becomes more convenient. They are as follows: Outer, Central and Inner Western Carpathians (Mišík et al., 1985, Mahel', 1986), or External, Central and Internal West Carpathians (EWC, CWC and IWC, respectively – Plašienka, 1999a, b, Fig. 7). These three zones are separated by two diachronic oceanic sutures (Fig. 8 and 9). The Early Alpine (Late Jurassic or Late Cimmerian) Meliata Suture separates the Internal and Central Western Carpathians. Its exact position is, however, hidden below the later Cretaceous nappes of the Silicicum and by a thick Tertiary cover. The Central and External Western Carpathians are separated by the suture in the area of the Pieniny Klippen Belt, which is considered as one of its superficial expressions. South of the Pieniny Klippen Belt, a closure of the South Penninic (Ligurian-Piemont or Vahic) oceanic basin is presumed during the latest Cretaceous and Earlyt Paleogene. North of it, the supposed oceanic basins of the Magura and later also of the Silesian-Krosno zones were closed during the Tertiary. However, in the recent erosional surface, no units proving an oceanic character of these zones have, as yet, appeared.

Superimposed Tertiary basins and volcanic edifices are considered as overstep complexes that originated after the main phase of deformation of the units in their basement or at their peripheries.

This means that their primary boundaries are transgressive, or intrusive and extrusive contacts. These overstep sequences were formed mainly in the IWC and CWC and, only to a lesser extent, in EWC zones. The main superimposed structures are: the Central Carpathian Paleogene Basin, the North Hungarian (Buda, South Slovakian, Novohrad) Paleogene – Lower Miocene Basin, the Vienna Neogene-Quaternary Basin, the Danube (Little Hungarian Plain) Neogene-Quaternary Basin, the Central Slovakian Neogene volcanics, the East Slovakian Neogene-Quaternary Basin and the intra-mountain Neogene-Quaternary basins.

Units morphotect.		TECTONIC SYSTEMS		SUPERUNITS	PRINCIPAL UNITS (examples)
IWC	Zemplín Belt	TISIA?		Zemplinic	
IWC	Bakony Belt	HUNGARO-CARPATHIAN		Transdanubic	
IWC	Bükk Belt	HUNGARO-CARPATHIAN		Bükkic	*Fensík paraautochthon Mónosbél -Szarvaskő Nappes, Igal Zone*
IWC	Meliata Belt	MELIATA	Silicic	Turnaic	*Rudabánya, Szendrő, Torna Nappe, Slov. Skala Nappe*
IWC	Meliata Belt	MELIATA	Silicic	Meliatic	*Meliata Unit s.s., Jaklovce Unit, Bôrka Nappe*
CWC	Gemer Belt	SLOVAKO-CARPATHIAN	Silicic	Gemeric	*Štós Unit, Volovec Unit, Ochtiná-Črmeľ Unit*
CWC	Vepor Belt	SLOVAKO-CARPATHIAN		Veporic	*Markuška, Foederata, Kraklová, Ľubietová, Veľký Bok, Čierna Hora Units*
CWC	Tatra - Fatra Belt	SLOVAKO-CARPATHIAN	Hronic	Fatric	*Staré Hory, Rázdiel, Križna (Zliechov), Vysoká, Manín, Klape, Drietoma*
CWC	Tatra - Fatra Belt	SLOVAKO-CARPATHIAN		Tatric	*Infratatric: Borinka, Orešany, Kozol Units, Inovec Nappe* *Bratislava Nappe, Panská Javorina Nappe,*
CWC	Iňačovce - Krichevo Belt; Považie - Pieniny Belt	PENNINE		Vahic	*Belice Unit* *Iňačovce - Krichevo Unit* *Surovin Unit ?*
CWC	Považie - Pieniny Belt	PENNINE		Oravic	*Kysuca, Czorsztyn Units*
EWC	Magura Belt	PENNINE		Magura Nappe group	*Biele Karpaty, Krynica, Bystrica, Rača Units*
EWC	Silesian - Krosno Belt	MOLDAVIAN		Krosno Nappe group	*Dukla, Silesian, Subsilesian, Ždánice, Skole Units*
EWC	Foredeep				
FORELAND		Systems Moldanubian, Moravian, Brunovistulian...			

Figure 7. Overview of the principal morpho-tectonic and tectonic units of the Western Carpathians (Plašienka, 1999b).

3.1.1. External Western Carpathians

The Outer (External) Western Carpathians (Polonides sensu Mahel', 1986) can be divided into the **Carpathian Foredeep** (Palavicum), situated on the slopes of the Bohemian Massif, and the **Flysch Belt** (Beskydicum). The superficial boundary between the External and Central Western Carpathians is represented by the **Pieniny Klippen Belt**, which is still treated as part of the Outer Western Carpathians. Although neither the Pieniny Klippen Belt, nor the Silesian-Krosno Zone of the Flysch Belt have any equivalents in the Alps, the Magura Zone of the West Carpathian Flysch Belt can be compared with the Rhenodanubian Flysch Zone of the Eastern Alps. The Carpathian Foredeep continue in the Alpine Molasse Zone, thus the outer zones of the externides represent a unifying element of both orogenic systems.

Western Carpathian Foredeep

The frontal foredeep is a constituent of each prograding orogen and its creation is partly controlled by the flexural downbending of the elastic foreland continental plate under the load of the prograding accretionary prism. The foredeep contains autochthonous to paraautochthonous sedimentary complexes deposited on the foreland continental crust, the thickness of which increases towards the orogenic front. The foredeep is associated with those adjoining parts of a relatively consolidated foreland, which were then influenced by tectonic events transmitted from the orogen itself (e.g. the peripheral bulge of the elastic platform plate and related faults originated due to loading by the orogenic front). The Western Carpathian Foredeep is laterally connected with the Eastern Alpine Molasse Zone. Its evolution shows the gradual frontal and lateral cessation of orogenic movements. The foredeep sedimentary complexes may either accreted on the tip of the accretionary wedge (e.g. the Pouzdřany Unit, Waschberg Zone) or, in some instances, their mass may be underthrust below the orogen front.

The *Miocene sediments* of the Carpathian Foredeep in the Morava territory, fill the Dyje-Svratka Valley, Vyškov Gateway, the periphery of the southern half of Hornomoravský úval Valley and the Moravian Gateway. Thickness of the fill of the Carpathian Foredeep is tectonically influenced by fault-line systems of NE-SW and NW-SE directions.

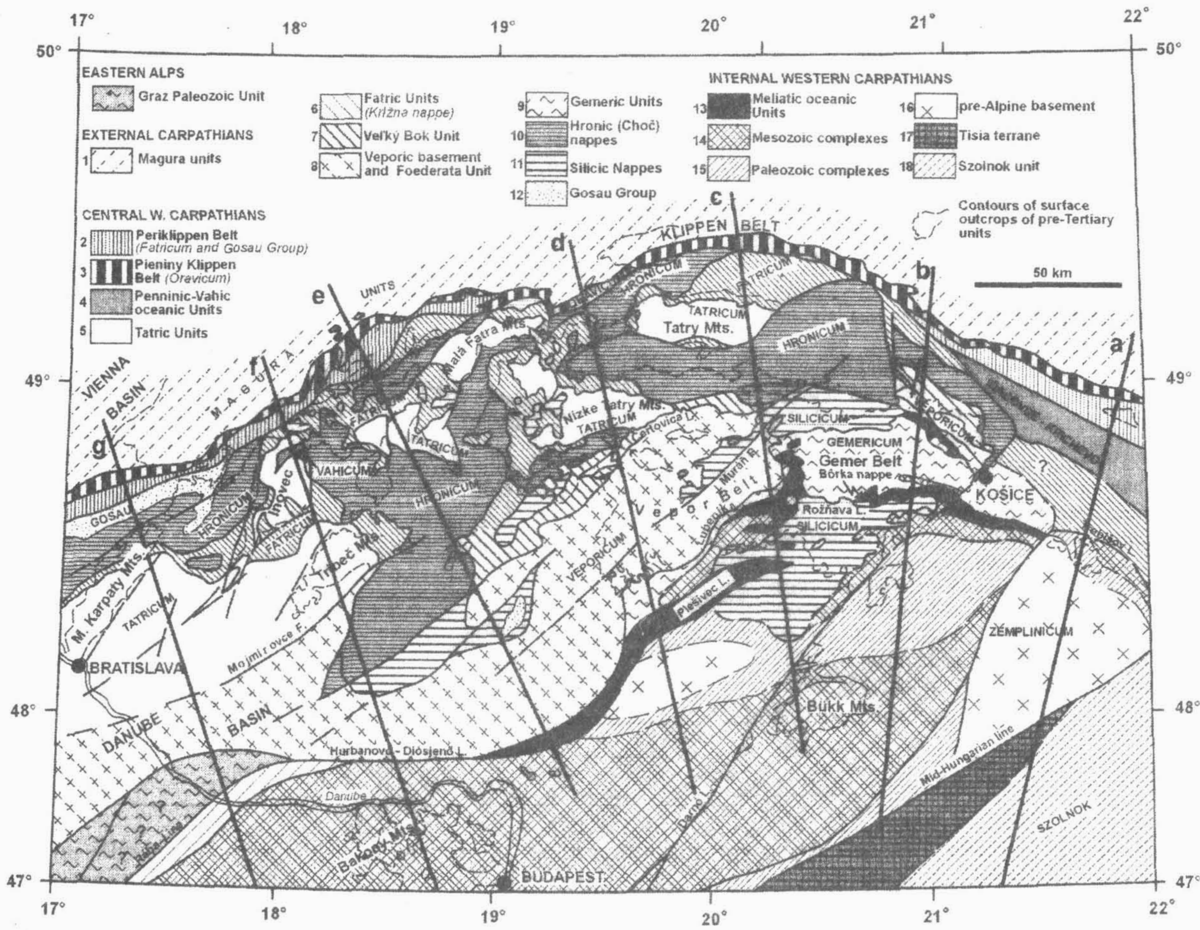


Figure 8. Distribution of the pre-Tertiary units of the Central and Inner Western Carpathians (Plašienka, 1999b). Profiles a-g correspond with the schematic cross-sections through the Western Carpathians in Fig. 9

The oldest known deposits are represented by the terrestrial *Žerotice Formation* (Egerian – Eggenburgian), and consist of proluvial sediments originating in the by reworking of the weathered underlying crystalline complexes and Paleozoic rocks. The *Eggenburgian transgression* led in the SW part of the basin (Znojmo area) to the formation of variable deposits (gravels, sands, clays). Fauna documents an alternation of brackish and marine deposits. The uppermost Eggenburgian member is formed by a rhyolite tuffite horizon. The variability of the sediments decreases eastward. The base is then formed by glauconitic sands, greywackes and sandstones passing upwards to pelites. The thickness of Eggenburgian sediments reaches up to 500 m at the Flysch nappes front.

During the *Ottnangian*, the whole foredeep area was uplifted, as a consequence of the Styrian orogenic phase. After partial erosion of the Eggenburgian deposits, sedimentation of brackish, lagoonal and/or freshwater sands and clays took place. North of the Miroslav Horst, the *Rzehakia Formation* was deposited.

In the *Karpatian*, a new sedimentary cycle began, connected with tectonic progradation of the flysch units. Basal clastics of Karpatian age are only locally developed. Topwards, clay, siltstone, sandstone and schlier sedimentation took place. The final overthrusting of flysch nappes onto the older Karpatian sediments reduced the foredeep width and the sedimentation terminated in a relatively

narrow depression at the nappe front (Brzobohatý & Cicha, 1993). The maximum thickness of Karpatian sediments varies between 700–1200 m.

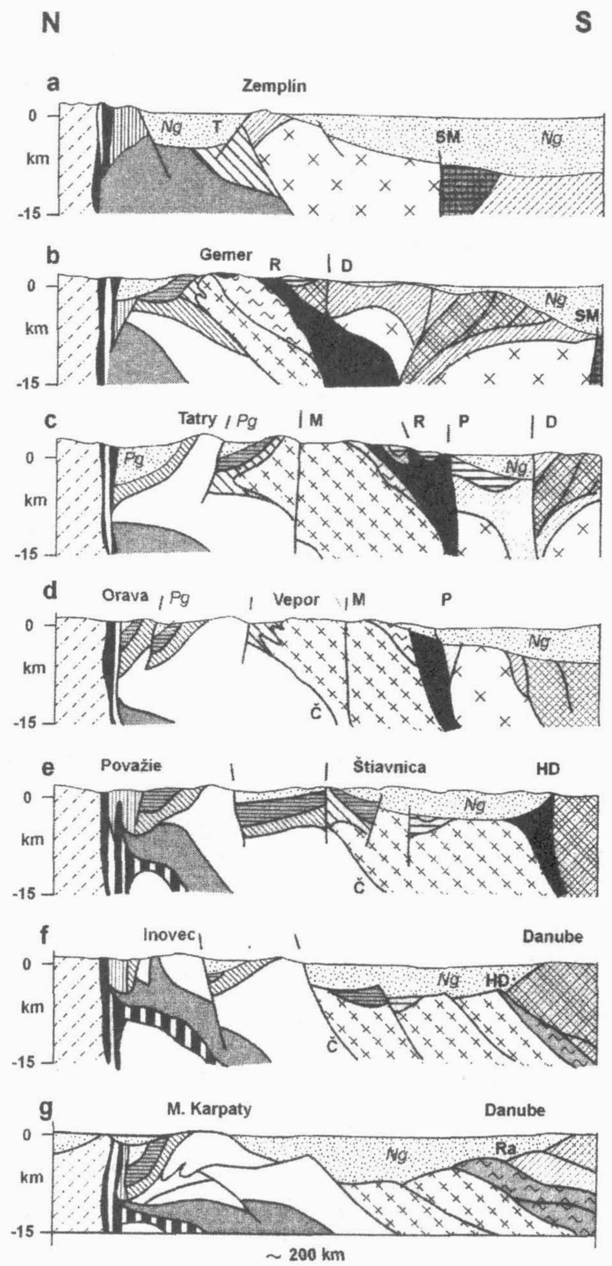


Figure 9. Schematic cross-sections through Western Carpathians along the lines in Fig. 8. The cross-sections are vertically exaggerated (Plašienka, 1999b).

Explanations: Pg – Paleogene and Ng – Neogene sedimentary and volcanic cover units. Principal faults: T – Trebišov, SM – Mid-Hungarian, R – Rožňava, D – Darnó, M – Muráň, P – Pleši-vec, Č – Čertovica, HD – Hurbanovo-Diósjenő and Ra – Rába faults.

The last marine transgression occurred in the *Early Badenian*. Sedimentation in the entire foredeep was relatively uniform. Deposition of terrestrial debris was followed by basal clastics and carbonatic clays sedimented in the axial part of the foredeep. Marine transgression extended far into the Bohemian Massif, mostly in the tectonically controlled zones. At this time, the unstratified calcareous clays sedimented far from the coastline, sometimes in depressions several hundred metres in depth. At the end of the Early Badenian, the lenses of sands, as well as algal and bryozoan limestones accumulated in shallower conditions. Thickness of Lower Badenian sediments reaches 500–800 m.

After the termination of the Late Styrian orogeny in Early Badenian, the depocenters of the foredeep were shifted toward the N and NE onto Polish territory, at the front of the progressing Flysch nappe thrust. The Middle to Late Badenian foredeep in the North Moravian territory (Opava area) had a rudimentary character with typical evaporitic sedimentation during the *Middle Badenian* (Cicha et al., 1985).

In the latest Miocene and mostly in the *Pliocene*, lacustrine, fluvial and proluvial clastics (gravels and clays) were deposited in the recent areas of Hornomoravský úval Valley and Mohelnice Gateway. Their composition was influenced by sources from the Bohemian Massif in the north, and from the Western Carpathian flysch units in the south.

Flysch Belt

The Carpathian Flysch Belt is composed of nappe units, in the inner zone consisting of Upper Jurassic to Lower Miocene siliciclastic flysch complexes, reaching a thickness of several thousand meters. In the external units, Late Jurassic and Early Cretaceous carbonates and volcanics are also common. The nappes are completely detached from their subducted basement complex and stacked in a fold-and-thrust accretionary wedge. The wedge is about 70–80 km wide on the surface, and, vertically reaches down to mid-crustal levels (15–20 km) in its southern, deepest part near the Pieniny Klippen Belt (Tomek, 1993, Tomek & Hall, 1993).

Since the whole wedge consists only of sediments, the original sedimentary area had to be many hundreds of kilometers wide and the crustal basement had to be consumed by subduction. Hence a model is now preferred which assumess an oceanic crust in the original Flysch Belt substratum and its Neogene southward subduction, inducing also calc-alkaline volcanism (Csontos et al., 1992; Lexa et al., 1993, Lexa & Konečný, 1998; Tomek & Hall, 1993). However, according to other opinions, the flysch sediments were detached from the North European platform margin, now underthrust beneath the Central Western Carpathians (e.g. Grecula & Roth, 1978; Bezák et al., 1997). Sedimentation and deformation processes in the Outer Western Carpathians show a distinct polarity towards the NE and N.

The Carpathian Flysch Belt consists of an outer, Silesian-Krosno group of nappes and an inner, Magura group of nappes (Fig. 10).

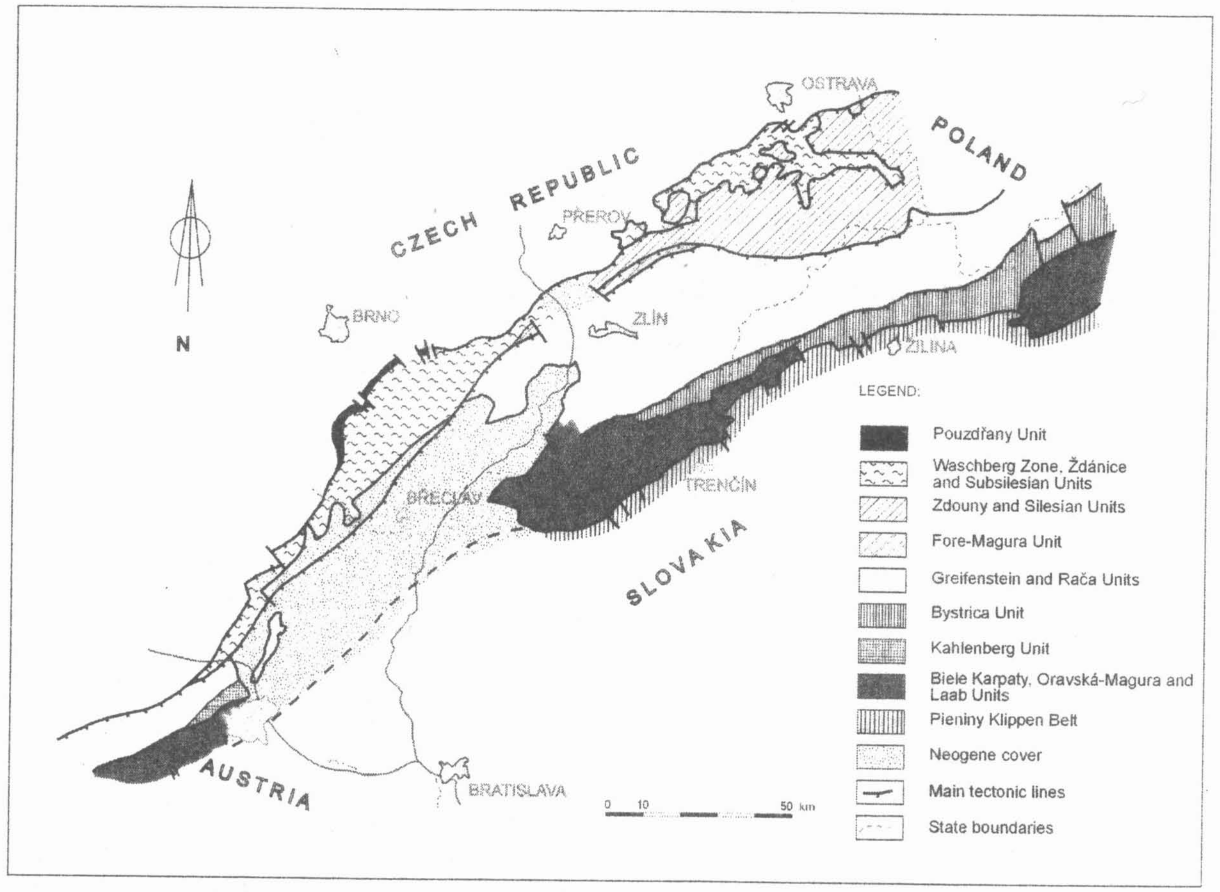


Figure 10. Geological map of the Flysch Belt units of the Western Carpathians and Eastern Alps (Krejčí et al., 1996).

The **Silesian-Krosno Belt** is the most external West Carpathian zone completely involved in the compressional orogenic wedge. This belt, accreted at the Oligocene/Miocene boundary, contains sedimentary and some volcanic complexes from the Late Jurassic to Egerian, that were completely detached from their subducted, in part oceanic substratum. Vertically, the lower surface of the ***Silesian-Krosno units*** is defined by the thrust plane of the accretionary prism (and the entire orogen) over the foreland continental plate, with low-angle to moderate dips under the West Carpathian orogen, i.e. in SE direction (on the west) and SSW (on the east). The upper surface is the basal thrust plane of the Magura nappe units (Fig. 11). The units of Silesian-Krosno Belt are common all over Carpathians, starting with the Waschberg Zone at the Alpine/Carpathian boundary and continuing as far as the Eastern Carpathians, where they are closely related to units of the ***Moldavides***. The Silesian-Krosno group of nappes in the Moravian and southern Poland territories consists of the following units: Pouzdřany, Ždánice (including the Čejč-Zaječí Zone), Subsilesian, Zdounky, Silesian and Fore-Magura units. The Ždánice and Subsilesian units formed originally in one common sedimentary area.

The **Magura Belt** is an obvious continuation of the Rheno-Danubian Flysch Belt of the Eastern Alps. However, in the Ukrainian Carpathians it is forced out by a gradual merging with the Pieniny Klippen Belt. It contains Cretaceous – Paleogene, predominantly flysch sedimentary complexes detached from their entirely subducted, probably mainly oceanic crustal substratum. The ***Magura units*** markedly differ from those of the Silesian-Krosno- Moldavian Zone by their contents and evolution. The lower surface of the Magura units is a relatively flat dipping thrust fault plane (documented by tectonic windows of the underlying Silesian-Krosno units); the upper surface is represented by a more or less subvertical tectonic boundary with the Pieniny Klippen Belt (Fig. 9, 11). The Magura Zone has thus a wedge-like shape, typical for accretionary complexes. The Magura group of nappes consists of the Rača, Bystrica, Biele Karpaty and Krynica (Oravská Magura) units.

The Flysch Belt nappe units are transgressively overlain by Miocene sediments, preserved mainly in the Šakvice syncline (Eggenburgian-Badenian), Kobylí Lake (Eggenburgian) and Vienna Basin (Eggenburgian – Romanian).

Units of the Silesian-Krosno Belt

The ***Pouzdřany Unit*** extends in front of the Ždánice Nappe, from Pavlovské vrchy Mts. as far as Slavkov, in a belt about 3 km in width (Fig. 10). It consists mainly of claystones and siltstones of Oligocene age, with an overall thickness of 500–800 m. The folded sediments of Pouzdřany Nappe are transgressively overlain by erosional relics of Lower Badenian deposits.

The ***Ždánice Unit*** is linked with the Subsilesian Unit in the NE (Fig. 10), both being often united under one name. The Ždánice Unit is tectonically divided into the Ždánice Nappe s.s. and to the structurally higher partial nappe of the Čejč-Zaječí zone. The oldest strata are represented by the *Ernstbrunn limestone Formation* (Jurassic – Lower Cretaceous, about 250–300 m). The *Pálava* (Coniacian – Campanian) and *"Submenilite" Formations* (Campanian – Lower Oligocene) are composed mainly of claystones with local bodies of sandstones and conglomerates about 300 m thick. The *"Menilite" Formation* (Middle Oligocene) consists of claystones with chert layers (several metres thick). The thickness of the entire formation is 50 m. The youngest *Ždánice-Hustopeče Formation* (Upper Oligocene – Lower Miocene) is formed by alternating sandstones and claystones, reaching 1250 m of thickness. Folded deposits of the Ždánice Unit and Čejč-Zaječí Zone are transgressively overlain by Lower Miocene sediments of Eggenburgian to Karpatian age, filling the Šakvice syncline.

The Ždánice Unit continues towards the SW to Austria where it is named the ***Waschberg Zone***. Besides Jurassic and Cretaceous members, it contains the *Brudendorf Formation* of Paleocene – Eocene age, then the *Waschberg, Haidhof* and *Reingrub Formations* (Sauer et al., 1992). The *"Menilite" Formation* is overlain by Egerian, Eggenburgian and Karpatian formations.

The ***Subsilesian Unit*** (Fig. 10) consists of claystones and sandstones of the *Frýdek Formation* (Turonian – Lower Paleocene), reaching 600 m in thickness. The *"Submenilite" Formation* (Paleocene – Eocene), about 600 m thick, is mostly composed of claystones. The *"Menilite" Formation*, including pebble-mudstone layers, is only 70 m thick. The *Ženklava Formation*, as an equivalent of the Ždánice-Hustopeče Formation, is about 300 m thick.

The ***Zdounky Unit*** in its lower part consists of marlstones, limestones and claystones of Aptian to Santonian age. Moreover, the greenish-grey and reddish-brown clays and claystones with scarce sandstone layers (Campanian – Eocene), occur also in the lower part. The overall thickness of the lower part is about 150 m. The upper part contains flysch sandstones and dominant claystones. The age of the upper part ranges from Upper Eocene to Lower Oligocene; its presumed thickness is 500–600 m.

The ***Silesian Unit*** is unique among other Outer Flysch units, mostly on account of its huge Upper Jurassic – Lower Cretaceous deposits. Its sedimentary complexes are divided into the northern Kelč slope, Baška swell and Godula basinal developments (Eliáš et al., 1990).

A complete sequence of the *Godula development* is presumably as thick as 6000 m. The oldest, Oxfordian – Albian *Těšín-Hradiště and Veřovice Formations* consist of pelagic marlstones, limestones and claystones, with lavas and vein volcanic bodies of alkaline basalts – *teschenites*. Thick flysch deposits are represented by the *Godula Formation* (Cenomanian – Santonian) which is up to 3000 m thick and *Istebná Formation* (Campanian – Maastrichtian) up to 1200 m thick. Paleocene and Eocene sediments in the Godula development are mainly represented by the *"Submenilite" Formation* (up to 800 m thick). The age of the overlying flysch *Krosno Formation* is Oligocene. This formation is up to 500–600 m thick.

The *Baška development* is represented by Late Jurassic to Early Cretaceous platform limestones (*Štramberk, Olivetská hora Formation)* and Early Cretaceous dark claystones. Higher up, the flysch *Baška Formation* (Albian – Turonian) occurs, are up to 500 m thick. The *Palkovice Formation* is represented by coarse-grained sandy flysch (Coniacian – Early Paleocene) up to 500 m thick.

The ***Fore-Magura Unit*** outcrops in a zone between the Silesian Unit and the Rača Unit in northern Moravia (Fig. 10). The oldest sediments here are clays and claystones of Campanian – Maastrichtian age (up to 300 thick). The *"Submenilite" Formation* (Campanian – Eocene), resembling of thin-rhythmical flysch, is dominated by pelites. At the top, sandstones together with conglomerates are concentrated in independent lithofacies. The whole formation is 300–500 m thick. The formation is overlain by the *"Menilite"* and *Krosno Formations* (Oligocene), and are about 500 m thick.

Magura group of nappes

The ***Rača Unit*** (Fig. 10) and related Greifenstein Unit of the Eastern Alps are the largest units in the entire Magura Flysch Zone. The oldest known sediments – Upper Jurassic to Lower Cretaceous carbonate turbidites (*Kurovice limestone, Tlumačov marlstone*) form tectonically amputed slices in frontal parts of the unit. Terrigenous turbiditic deposition started in the Albian and terminated in the Early Oligocene. The mid-Cretaceous *Gault flysch* is composed of dark, calcite-free claystones and represents an element unifiing the Rača Unit with its Eastern Alpine equivalents. The *Kaumberg Formation* (Cenomanian – Maastrichtian) is dominated by variegated non-calcareous shales up to 500 m thick. The *Soláň Formation* (Campanian – Paleocene) is up to 2000 m thick. The *Beloveža Formation* (Upper Paleocene – Eocene) represents a thin-rhythmical flysch with predominance of variegated claystones and is about 300 m thick. The mainly eocene *Zlín Formation* is lithologically quite variable. Several hundreds to thousand m thick Eocene to Oligocene formations contain flysch sandstones and shales, along with conglomerates in proximal parts.

The ***Bystrica Unit*** (Fig. 10) forms a narrow strip between the Nezdenice Fault and the Slovak/Polish boundary; W of the Nezdenice Fault it occurs rarely. The *Beloveža Formation* (Eocene, 300 m thick) resembles thin-rhythmical flysch, with bodies of coarse-grained sandstones. The *Bystrica Member* (Eocene) represents turbidites dominated by calcareous claystones, and are up to 1600 m thick.

The ***Biele Karpaty (Bílé Karpaty) Unit*** (Fig. 10) is divided into the Hluk and Vlára facies developments, consisting of Lower Cretaceous to Lower Eocene sediments.

The *Hluk development* extends mostly in the SW part of the Biele Karpaty Mts.; in the east, and is cut by the Nezdenice Fault System. The *Hluk Formation* (Hauterivian – Albian) is characterized by dark-grey to black claystones, calcareous claystones and marlstones with turbiditic limestone layers which become more frequent in the upper part. The overall thickness of the formation is 120 m. The *Kaumberg Formation* (Cenomanian – Maastrichtian), characterized by variegated non-calcareous claystones, is about 300 m thick. Higher up, the variegated *Púchov Marls* (Campanian – Maastrichtian, 100 m thick) occur. The *Antonínek Formation* (Campanian – Maastrichtian, 30 m thick) is characterized by turbidite rhythms, up to 30 m thick. The *Svodnice Formation* (Maastrichtian – Paleocene), being as thick as 1000 m, contains flysch rhythms formed by an alternation of calcareous claystones and calcareous subgreywackes. The *Nivnice Formation* (Paleocene – Lower Eocene), consisting of thin- to medium-rhythmical claystone-dominated flysch, is up to 600 m thick. The *Kuželov Formation* (Upper Paleocene – Lower Eocene, 250 m thick) is characterized by a variety of calcareous claystones.

The *Vlára development* is more detritic; it consists of two nappes, the southern one is named the ***Javorina Nappe***. Besides the *Kaumberg Formation* it includes the *Javorina Formation* (Campanian – Lower Paleocene, 750 m thick) with prevalence of sandstones over claystones. The *Svodnice Formation* (Maastrichtian – Lower Eocene, 1500 m thick) corresponds to the Svodnice Formation of the Hluk development. Another distinctive unit is formed by the *Rajkovec Beds* (Paleocene – Lower Eocene) in the vicinity of the Vlára valley, which have some affinity to the Paleocene flysch units of the Pieniny Klippen Belt (the Proč Formation, common carbonate detritus).

The **Oravská Magura (Krynica) Unit** is composed of the *Magura Formation* (Upper Paleocene – Middle Eocene), which is up to 1100 m thick; the *Racibor Formation* with the pelitic *Račová Member* (Lower to Middle Oligocene, 600 m thick), the *Zábava Formation* (Lower to Middle Eocene) and the *Maľcov Formation* (Upper Eocene – Lower Oligocene, 650 m thick).

Tertiary volcanics

Igneous rocks of the Tertiary age have been identified in all partial units of the Magura Group of nappes together with some rare occurrences in the Pieniny Klippen Belt (Horné Sŕnie). The largest body, 1500 m long and 200 m wide, outcrops S of Nezdenice. It represents subsurface sills with a

maximum verified (drilled) vertical false thickness of 60 m. As the volcanic bodies crosscut the overthrust and fault planes related to the flysch nappes, their age is clearly post-tectonic (Karpatian and younger). From the petrographical point of view, (usually propylitized) leucocratic trachyandesites and olivine basalts have been identified (Adamová et al., 1995).

Tectonic structure and evolution of the External Western Carpathians

The origin of the accretionary prism is related to the Tertiary subduction of the Mesozoic oceanic crust underlying the Magura and partially the Silesian-Krosno Belt. Gradual folding of the internal flysch units started in the Paleogene, during active sedimentation. In the inner part of the Magura Zone, the Biele Karpaty Unit originated during the Pyrenean orogeny (Late Eocene). During the Helvetian orogeny (after Early Oligocene), the whole accretionary wedge of the Magura Zone was detached and folded. The nappe front became a source area for the Subsilesian-Ždánice domain, where substantial paleogeographic changes took place, after deposition of the Oligocene "Menilite" Formation. The Ždánice- Hustopeče Formation (molasse-like) was deposited in the Ždánice Unit, while flysch deposition of the Krosno Formation occurred in the Silesian Unit. In the early Lower Miocene (Savian orogeny), an initial folding took place in the Subsilesian-Ždánice domain and the Carpathian foredeep originated at that time. The flysch sedimentation was still active in the Pouzdřany sedimentary area.

During the Early Miocene, the sediments of the Pouzdřany domain were folded and, together with the Ždánice Nappe, thrust over the Eggenburgian – Ottnangian sediments of the Carpathian foredeep (early Styrian phase). Tectonic movements, related to the nappe overthrusting in the Flysch Belt, terminated in southern Moravia during late Styrian phase (17 Ma). At that time, the Lower Miocene sediments became part of the nappe structure. Overthrust of the flysch nappes in north Moravia territory terminated as late as Middle Miocene (after Early Badenian). At this time, a relic Middle to Upper Badenian foredeep (area of Opava) persisted, dominated by evaporitic sedimentation (Cicha et al., 1985).

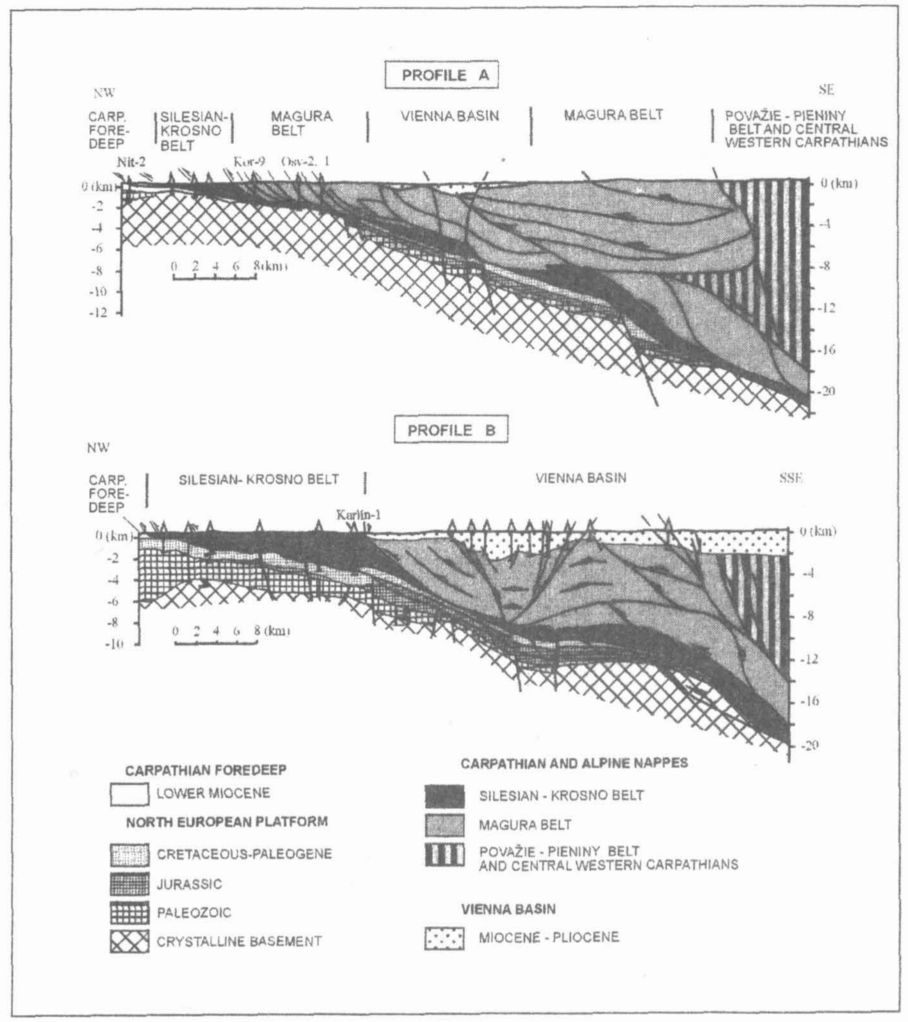


Figure 11. Geological cross-sections through the Flysch Belt (Krejčí et al., 1996).

Geological cross-section B (Fig. 11), in the south-Moravian block area (Krejčí et al., 1996), was based on interpretation of the 8AHR/86 seismic profile. The profile was made for the purpose of verification of the deep structure above the Bohemian Massif/Western Carpathians junction zone (Stráník et al., 1993). In the profile, the Flysch Belt is represented mainly by the Rača Unit, and, to a lesser extent, by the Bystrica and Biele Karpaty units in the rear parts, close to the Pieniny Klippen Belt. The Magura Group of nappes consists of several nappe lamellae, up to 10 km thick. The lowest nappe portion (in the profile drawn only schematically) and a basal duplex lamella are composed of the so-called lower complex of the Magura Group, presumably of Lower Cretaceous to Triassic age. The lowest duplex structure of the Flysch Belt consists of outer units of the Silesian-Krosno group of nappes, represented mainly by the Ždánice Unit. The basement of the flysch units is formed by platform deposits of the Bohemian Massif, represented mainly by the the Jurassic Mikulov marlstones and Paleogene clastics, but is a lesser extent by Paleozoic carbonates and/or clastics as well. The distance of the Styrian overthrust of the Ždánice Nappe in southern Moravia, which was determined by drilling, is more than 20 km (Krejčí & Stráník, 1993). Taking into consideration the position of the Pouzdřany Unit at the front of this nappe, the overall estimated displacement is more than 100 km. The maximum distance of the nappe thrust over the foredeep sediments, determined by the Berndorf-1 drillhole (Austria), is 40 km (Wachtel & Wessely, 1980).

The geological structure of the Flysch Belt and its basement in the central Moravian block is shown in the geological cross-section A (Fig. 11). This cross-section represents a similar geological structure as in cross-section B. Sediments of the outer Flysch Belt (the Ždánice and Zdounky Nappes) have a relatively simple fan-shaped structure near the surface, consisting of monoclinal slices. Both nappes form a duplex system below the Magura group, together with the folded Lower Miocene sediments of the Carpathian foredeep. In both cross-sections, the Pieniny Klippen Belt and Central Western Carpathians are separated from the Flysch Belt nappe structure by a sinistral strike-slip.

3.1.2. Central Western Carpathians

The **Central Western Carpathians** (CWC) are divided here, into the following principal morphotectonic belts:

The **Považie-Pieniny Belt**, which is a narrow and long, complexly deformed zone following the boundary between the External and Central Western Carpathians, which incorporates various Mesozoic tectonic units united by the Senonian – Paleogene cover;

The **Tatra-Fatra Belt** of "core mountains" with classic Cretaceous superficial nappe structure;

The **Vepor and Gemer Belts** representing the deeply denuded core of the Western Carpathian orogen with a prevalence of basement units.

Považie-Pieniny Belt

The **Považie-Pieniny Belt** embraces the classically defined Pieniny Klippen Belt (PKB; e.g. Andrusov et al., 1973), including the so-called peri-Klippen Zone (Maheľ, 1980, 1986) and marginal, deformed parts of the Central Slovakian Paleogene Basin. Further out, this belt embraces the Mesozoic Fatric complexes of the Humenské vrchy Mts. in eastern Slovakia, as well as the Biele vrchy, Brezovské and Čachtické Karpaty Mts. and the Myjava Upland in western Slovakia. This zone extends westward below the Vienna Basin fill, and continues in the Northern Calcareous Alps. The Považie-Pieniny Belt involves units of the Penninic system (***Oravicum*** and a part of the ***Magura Units***), as well as the Austroalpine-Slovakocarpathian tectonic system (***Bajuvaricum, Tirolicum, Juvavicum, Fatricum, Hronicum***; cf. Fig. 7). and their sedimentary cover (*Gosau Group*). However, Early Miocene (mainly Eggenburgian) sediments are to some extent also involved in the deformed structure in the wider vicinity of the Pieniny Klippen Belt in western Slovakia.

The northern edge of the Považie-Pieniny Belt is mostly subvertical or a steeply S- to SE-ward dipping boundary (it is also a deep geophysical boundary designated as the "Peri-Pieniny Lineament"). The boundary flattens towards the Alps in the west and changes into a thrust fault. Eastward, this boundary follows the northern and then NE margin of the Šariš and Ukrainian sector of the PKB, where it is a subvertical or steeply north-dipping fault. The southern boundary of the belt dips northward in the Alps and connects with the northern boundary below the Northern Calcareous Alps, so forming a fan-wise megasyncline (Fig. 14). In the Middle Váh Valley (Považie) sector, this boundary is steeply south-inclined (i.e. below the Tatra-Fatra Belt). In the Orava, Pieniny and Šariš sectors, it is most probably dip steeply northward. At the near-surface levels, this belt comprises a mixture of Mesozoic sedimentary successions, which belong to numerous tectonic units of various paleogeographic affiliations. The thick synorogenic, Senonian – Paleogene sedimentary complexes, which developed in an accretionary zone in front of basement units of the CWC, are their unifying and the most characteristic elements. At the same time, this zone was active as an important transpressional and transtensional zone during the whole Tertiary. This caused an extensive disintegration and intermixture of sedimentary sequences of different provenances.

To some extent, the Považie-Pieniny Belt is a transitional element between the EWC and CWC; its affiliation depends on the criteria accepted. The CWC, defined as a purely paleo-Alpine (pre-Gosau) nappe system, excludes units formed during Late Cretaceous and Early Tertiary. Nevertheless, if the EWC is defined as a Tertiary (Late Paleogene – Early Miocene) accretionary complex, it is better to rank the described zone to the CWC, on account of the evident presence of paleo-Alpine units in this zone.

The **Pieniny Klippen Belt** (PKB), considered as a part of the more broadly defined Považie-Pieniny Belt, is only several km wide. On the surface, it extends from the NE margin of the Vienna Basin (Podbranč), northern Orava and continues through southern Poland, eastern Slovakia and Ukrainian Carpathians to northern Romania, ending near Poiana Botizii. Its outcrops are composed exclusively of sedimentary rocks, mainly limestones (rare Triassic, frequent Jurassic – Lower Cretaceous), marlstones (Middle – Upper Cretaceous) and flysch sediments (Upper Cretaceous – Paleogene). The PKB is characterized by the so-called klippen structural style, where the competent limestones represent "klippen" (tectonically disconnected blocks of several m^3 to a few km^3), and the incompetent marlstones and flysch complexes form their softer envelope. This structure resulted from complex, intensive tectonic processes, including detachment of sedimentary successions from their original basement, folding, overthrusting, formation of slices and finally lateral strike-slip deformation. However, all deformation processes must have taken place near the surface, since the PKB rocks are not metamorphosed.

In western Slovakia, the PKB is morphostructurally divided into four sectors: Podbranč-Trenčín, Púchov, Varín and Orava, which differ in their inner structure and in representation of individual units recognized. The geological and tectonic division of the PKB is, however, more complex. Numerous successions, developments, lithostratigraphic and tectonic units have been distinguished during long-term investigations (e.g. Mišík et al., 1996; Mišík, 1997). Maheľ (1980) favoured the along-strike division of the PKB into the Klippen Belt s.s., involving only the Oravic units (Pieninic resp., i.e. units representing an independent paleogeographic zone, chiefly the Czorsztyn and Kysuca units), and the **Peri-Klippen Zone**, situated between the PKB s.s. and the Tatra-Fatra Belt of the CWC. The latter zone is presumed to comprise mainly the pre-Sennonian Central Carpathian units and their Gosau cover. Maheľ (1980) supposed the Peri-Klippen Zone to be linked with the Northern Calcareous Alps and with the Kichevo Belt in Ukraine. However, this concept has little following, since there is no general agreement about the provenance of some important units (e.g. the Klape Unit).

According to the presumed palinspastic arrangement of the PKB isopic zones, the northernmost unit is the ***Czorsztyn Unit***. The existence of a more northerly Grajcarek Unit, distinguished in Polish territory as a transitional to the Magura units, is often considered unlikely in Slovakia. Czorsztyn klippen occur all along the PKB, the largest of which is the Vršatec Klippe at the Váh river Valley (Mišík, 1979). The main components of the unit are: very few Lower Jurassic syn-rift terrigenous formations (*Allgäu, Szlachtowa*), Middle to Upper Jurassic variegated shallow-water, partly pelagic and partly reefal, massive limestones with frequent stratigraphic gaps (the largest gap includes virtually the whole Early Cretaceous in the Czorsztyn Unit), condensed horizons, neptunian dykes, features of emergence and erosion (*Smolegowa, Krupianka, Czorsztyn, Vršatec Formations*), which all indicate deposition on a rising and locally emerging pelagic swell (Mišík & Sýkora, 1993; Mišík, 1994; Mišík et al., 1994; Aubrecht, 1997). Over the Jurassic limestones, usually separated by the Albian hardground, occur red pelagic "couches rouges" type marlstones (Upper Cretaceous *Púchov Formation*) and synorogenic flysch deposits of the uppermost Cretaceous (*Jarmuta Formation*).

The ***Kysuca (Kysuca-Pieniny) Unit***, as opposed to the Czorsztyn Unit, is composed of basinal pelagic and flysch formations of Lower Jurassic to Upper Cretaceous age. The Lower Jurassic syn-rift clastic and hemipelagic formations (*Gresten, Zázrivá, Allgäu, Szlachtowa*) were replaced by pelagic sediments deposited partly below the CCD during the Middle and Late Jurassic (radiolarite *Czajakowa Formation*) and by characteristic Lower Cretaceous pelagic, platty cherty limestones (*Pieniny Formation*). The mid-Cretaceous (Aptian – Cenomanian) formations (*Koňhora, Tissalo, Lalinok, Kysuce*) are mainly composed of dark spotted and variegated marlstones. Starting with the Turonian, beds of distal turbidites appear (*Snežnica Formation*), replaced by variegated marlstones during the Late Senonian (*Gbeľany Formation*). The Kysuca Unit occurs all along the PKB in numerous klippen; the largest one is Rochovica (Rudinka, Brodno) Klippe in the Kysuca Gateway (Michalík et al., 1990a, 1995). There are also some transitional developments with mixed deep- and shallow-water facies, e.g. Czertezik, Pruské (Niedzica), Podbiel, Orava and Nižná successions (Birkenmajer, 1977; Gross et al., 1993; Aubrecht & Ožvoldová, 1994; Ožvoldová et al., 2000).

The ***Klape Unit*** is considered either as a part of the Vahic accretionary complex (Maheľ, 1981; the Vahicum being be a zone with Jurassic oceanic crust, analogous to the South Penninic zones of the

the Eastern Alps), marginal wildflysch complex of a transform plate margin (Marschalko, 1986), or as a diverticulation Fatric nappe (Krížna Unit) of the CWC (Plašienka, 1995b). It consists of thick mid- and Upper Jurassic, mostly flysch complexes with exotic conglomerates (*Upohlava conglomerates*) and "klippen" (olistoliths in this case) of Jurassic and Triassic carbonates. The flysch complexes are separated by a sequence of shallow-water oyster-bearing sandstones of Cenomanian age (*Orlové Formation*). Conglomerates contain an extraordinary variety of sedimentary and magmatic pebbles derived from the inner (Carpathian) margin of the Klape flysch basin. Since a lot of „exotics" could not be derived from the central Carpathians (e.g. Mišík & Sýkora, 1981), their sources were often placed in the completely disappeared "Ultrapieninic Cordillera", later renamed as the exotic "**Andrusov Ridge**" (Birkenmajer, 1988). The Klippe Klape is built by shallow-water Jurassic limestones. The Klape Unit is exposed in the Púchov and Varín sectors of the PKB (Marschalko & Kysela, 1980; Salaj, 1994a, b, 1995; Rakús & Marschalko, 1997).

Pre-Turonian members of the Drietoma (Bošáca) and Manín Units, occurring in the Peri-Klippen Belt, represent probably original parts of Fatricum. The ***Drietoma Unit*** outcrops in the Podbranč-Trenčín sector of the PKB. It also contains also the Upper Triassic rocks – the *Carpathian Keuper* and *Kössen Formations* which is not typically for the Klippen Belt. Overlying strata are akin to the Zliechov succession of the Fatricum, as the thick Lower Jurassic *Kopienec* and *Allgäu Formations*, Upper Jurassic radiolarites and nodular limestones, as well as Lower Cretaceous cherty and biodetrital limestones. Terrigenous turbiditic sequence, resembling the Klape or Poruba flysch complexes, is the youngest, Albian – Cenomanian member of the Drietoma Unit (Began, 1969).

The ***Manín Unit*** includes two large antiformal "klippen" – the Manín and Butkov. It comprises the southernmost part of the Púchov sector of the PKB and is regarded, from the paleogeographical point of view, to be either the most external extremity of the Tatric area anr/or an independent paleogeographic zone between the Tatric area and the Klippen Belt (Andrusov, 1972; Rakús, 1977), or a constituent of the Fatric nappe system in the Vysoká development (Mahel', 1978; Borza et al., 1979; Michalík & Vašíček, 1987). Compared to the latter, its lithostratigraphic succession of comparatively shallow-water Jurassic – Lower Cretaceous, is quite similar: Lower – Middle Jurassic sandy crinoidal limestones, Upper Jurassic silicites and red nodular limestones, Lower Cretaceous grey bedded cherty and marly limestones (Michalík & Vašíček, 1987). However, thick Barremian – Aptian platform *Urgonian limestones* are the most typical members of the Manín Unit. These are terminated by a characteristic horizon of a lower Albian hardground, which is overlain by Albian pelagic marlstones of the *Butkov Formation* passing into the Cenomanian flysch of the *Praznov Formation*. In places, there is Upper Turonian hiatus (Marschalko & Kysela, 1980), followed by thick Senonian flysch and pelagic, Gosau-type formations (*Podmanín Group*).

The Late Cretaceous (Senonian) sediments are situated in two positions in the Považie-Pieniny Belt. In the Oravic units, they are part of continuous successions, whereas in the peri-Klippen units (considered to be Fatric) and in the Upper Austroalpine units of the Northern Calcareous Alps, they were deposited after at least a short (Late Turonian) hiatus in the time when these units were tectonically transported to form nappes. Accordingly, they may be placed in the *Gosau Group*. The Gosau sediments in the Alps include Senonian and Paleogene formations that extend in several synforms, which continue into the basement of the Vienna Basin (Glinzendorf and Gieshübel synclines, Lakšárska n. Ves Slice System). On the surface, they outcrop in the Brezovské Karpaty Mts. and Myjava Upland (here, the Senonian *Brezová Group* and Paleogene *Myjava Group* are distinguished – Samuel et al., 1980; Salaj & Priechodská, 1987). They represent several hundreds of meters of basal clastics, pelagic marlstones and carbonate flysch sediments (Wagreich & Marschalko, 1995). The imbricated structure of the southern rim of the Považie-Pieniny Belt locally includes sediments of the so called "peri-Klippen" Paleogene *Žilina-Hričov Group*, unconformably overlying Mesozoic formations. It is represented mainly by Paleocene – Eocene flysch with typical olistoliths of Paleocene reefal limestones (Köhler et al., 1993). The klippen envelope locally (mostly in eastern Slovakia) includes also the Latest Senonian (Maastrichtian) *Jarmuta Formation* to Eocene flysch sediments (*Proč Formation*). According to some authors, they sedimented after the first deformation phases of the underlying klippen successions.

Seismic sections display the PKB as an indistinct, probably subvertical suture zone, with roots reaching mid-crustal levels, located between large blocks of the External Western Carpathians (passive margin of the North European Platform – Bohemian Massif) and the Central Western Carpathians. The continental fragment representing the original basement of the Czorsztyn Ridge occurs near the mid- to lower-crustal levels of the CWC (Fig. 12; see Tomek, 1993). The entire PKB is followed by the so-called **Peri-Pieniny Lineament**, a deep crustal fault detected by various geophysical methods.

Paleotectonic evolution of the Pieniny Klippen Belt

Based on the structural and sedimentary rock record, the following paleotectonic evolution of the Oravic units of the PKB can be reconstructed: (1) Rifting in the Early Jurassic, formation of dissected submarine relief and the principal isopic zones, (2) Middle Jurassic – Early Cretaceous deposition of predominantly pelagic, shallow- or deep-water sediments, with deepening and levelling of the sedimentary environments during the Middle Cretaceous, (3) Late Cretaceous commencement of flysch trench sedimentation (from the south), subsequent tectonic shortening, detachment of Oravic units from the subducted basement, their stacking and incorporation (together with the CWC units) into a fold-and-thrust zone in front of the Vahic accretionary complex (this was amalgamated with the frontal CWC units in the Paleocene and partly emerged), (4) Late Paleocene to Eocene collapse with deep-water turbiditic sedimentation of the Proč Formation and northern marginal developments of the Central Carpathian Paleogene Basin (Myjava Group, Žilina-Hričov Group). (5) During the Paleocene to Early Miocene, the PKB was affected by dextral transpression, resulting in subsequent amalgamation with the Magura unit of the Flysch Belt. (6) The Miocene and Pliocene sinistral transtension caused faulting and opening of small pull-apart basins (Ilava, Orava Basins). One of a few important transversal structures of the PKB is the **Zázrivá (or Párnica) sigmoid** between the Varín and Orava sectors, which originated from a dextral strike-slip along the N-S trending **Zázrivá-Revúca (Central Slovakian) fault system** during the Late Miocene (Kováč & Hók, 1993, 1996; Nemčok & Nemčok, 1994, 1998).

Tatra-Fatra, Vepor and Gemer belts of the Western Carpathians

The Central Western Carpathians (Slovakides according to Mahel', 1986) underwent very complex evolution and contain a number of nappe units of various orders and ages. The principal ones are crustal superunits that comprise the pre-Alpine basement together with its Late Paleozoic – Mesozoic sedimentary cover: ***Tatricum, Veporicum and Gemericum***. Other important units are superficial detached cover nappe systems containing Late Paleozoic to Mesozoic sedimentary rocks with scarce volcanics: ***Fatricum, Hronicum and Silicicum*** (Fig. 12). Main crustal shortening and nappe generation took place during the Middle to Late Cretaceous. The deformation processes reflect an outward (northward) polarity. The central zones of the Western Carpathians on the inner side of the Považie-Pieniny Belt can be divided into the following regional zones:

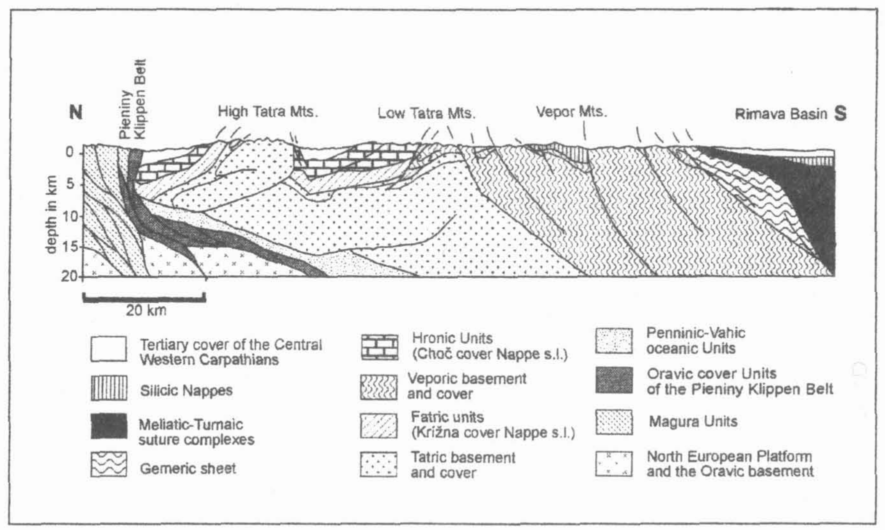


Figure 12. Geological cross-section through the Central Western Carpathians.

1. The subsurface **Iňačovce-Krichevo Zone** is represented by a Tertiary metamorphic core complex, exhumed in the basement of the Transcarpathian pull-apart basin (Soták et al., 1993a, 1994). Rocks in this zone do not occur on the surface; they are known only from boreholes. In the outer side, it is separated from the Považie-Pieniny Belt (Peri-Klippen Belt comprising the Chmeľov-Beňatiná part of the Central Carpathian Paleogene Basin and fartic complexes of the Humenské vrchy Mts.) by a moderately to steeply northward dipping boundary (Soták et al., 1997); from the units of central and inner zones of the Western Carpathians (Zemplinicum) it is separated by a low-angle SW-dipping extensional fault (Vozár et al., 1996, 1998; Fig. 9). The Iňačovce-Krichevo Unit, containing mostly deep-water, low-grade metamorphic Triassic to Eocene sediments and slices of ultrabasics ultrabazitov (Soták et al., 1993a, 1994), is considered to be a part of West Carpathian Penninicum.

2. The **Tatra-Fatra Belt** of the core mountains (Pezinské Malé Karpaty Mts., Považský Inovec Mts., Tribeč Mts., Žiar Mts., Strážovské vrchy Mts., Malá Fatra Mts., Ďumbierske Nízke Tatry Mts. and Hight Tatra Mts.) embraces mountains with a Tatric-type crystalline basement and classic "Sub-Tatra" nappes (Fig. 8, 9, 12). The belt takes in sporadic exposures of the ***Vahic units*** outcropping from beneath the thick ***Tatric superunit*** that involves the pre-Alpine basement and its Late-Paleozoic-Mesozoic sedimentary cover, superficial nappe systems of the ***Fatricum*** (Križna Nappe s.l.) and ***Hronicum*** (Choč Nappe s.l.), as well as their Paleogene (Central Carpathian Paleogene Basin), Neogene and Quaternary cover. In the CWC, the division into regional belts practically coincides with tectonic ranking of basement in these zones. The northern boundary of the Tatra-Fatra Belt is defined by the contact with the Považie-Pieniny Belt, which is a steeply to moderately southward dipping reverse and oblique fault system. The southern boundary is accurately defined in the Nízke Tatry Mts. by the so-called **Čertovica Line**. It is a moderately southward dipping fault, representing an overthrust plane of the North Veporic basement and its sedimentary cover superimposed on the Tatric Superunit. Its westward continuation is though to occur beneath the Mesozoic complexes of the so-called Hron Synclinorium; further towards the SW it continues beneath the Central Slovakian Neovolcanic Area and south of the Tribeč Mts., where it was reactivated as a Neogene extensional normal fault system (Mojmírovce faults – Hrušecký et al., 1993, 1996; Hók et al., 1999; Fig. 8). A further SW prolongation of this line below the Neogene fill of the Danube Basin has not been verified. The Čertovica Line understood as a Late Cretaceous thrust fault should have, however, its equivalent in a thrust plane between the Lower Austroalpine units (analogues of the Infratatricum) and the Middle Austroalpine units (analogues of the Veporicum) in the Rosaliengebirge Mts. of the easternmost Alps. Eastwards of the Nízke tatry Mts., the Čertovica Line is overlain by Hronic nappes and Paleogene sediments of the Central Carpathian Paleogene Basin; its course maz be taken to run below the northern margin of crystalline complexes of Kráľovohoľské Nízke Tatry Mts. After a sinistral shift on the Muráň Fault, it disappears in the basement of Levočské vrchy Mts. and, somewhere north of Branisko Mts., it presumably joins the Považie-Pieniny Belt (Fig. 8).

3. The **Vepor Belt** involves superficial outcrops of the pre-Tertiary basement islets of the Central Slovakian Neovolcanic Area, Kráľovohoľské Nízke Tatry Mts., western part of the Slovak Ore Mountains (Veporské and Stolické vrchy Mts.), Sľubica Massif of the Branisko Mts., Čierna Hora Mts., i.e. areas with a Veporic-type basement and cover complexes. Besides the dominant ***Veporic Superunit***, the Vepor Belt embraces also the southern limits of the ***Hronic*** nappes, overriding the Veľký Bok Unit, small leftovers of the overriding ***Gemeric*** complexes and large nappe outliers of the ***Silicic*** system (Drienok, Muráň, Vernár and Stratená Nappes), along with remnants of the Senonian Gosau cover, and superimposed Paleogene sedimentary and Neogene volcanic complexes. The southern boundary of the Veporic Zone is, on the surface, formed by the **Lubeník-Margecany Line** (Fig. 8 and 9), which is a complex fault zone that underwent a complicated kinematic evolution. Its precursor was a thrust plane, which along with the Gemeric superunit, was thrust over the Veporicum, probably during the Early Cretaceous. During the Late Cretaceous, its SW-NE Lubeník sector acted as a sinistral transpressional zone. Simultaneously, the recent NNW-SSE part followed by the younger Štítnik Fault (so-called Gemer ramp) was reactivated as a low-angle normal fault that enabled a top-to-east unroofing of Veporic metamorphic core complex (Plašienka et al., 1999). SW-wards the Lubeník Line probably merges with the important Hurbanovo-Diósjenő fault zone making a boundary between the Central and Internal Western Carpathians (so-called Pelso Megaunit). The SW-ward continuation of the Vepor Belt is documented by inliers of the pre-Tertiary substratum within the Central Slovakian neovolcanics (Pliešovce, Lieskovec, Sklené Teplice, Turovce-Levice horst), where Veporic rocks outcrop, overlain in the northernmost Sklené Teplice inlier by Hronic units and in more southerly zones by Silicic units (Levice). The belt continues in the substratum of the southeastern part of the Neogene Danube Basin between the Mojmírovce faults (reactivated Čertovica Line) and the **Rába-Hurbanovo Line**. According to borehole data, the belt is mainly composed of basement complexes here, and continues westward to the Central Eastern Alps (Fig. 5, 8).

4. The **Gemer Belt** embraces the eastern part of the Slovak Ore Mountains (Volovské vrchy Mts.), built mostly of the Gemeric basement. The ***Gemericum*** is formed by Paleozoic, mainly low-grade metamorphic volcano-sedimentary complexes with disputable Mesozoic cover. It is overlain by remnants of the Jaklovce and Bôrka Nappes that belong to the ***Meliatic*** Superunit and by the ***Silicic*** cover nappes (Stratená and Galmus along the northern margin, Radzim and Opátka outliers in the central part and the northern margin of the Silica Nappe s.s., on the boundary with the Slovak Karst Mts.). Tertiary cover rocks are present on the periphery of the exposed part of the belt. The southern boundary of the belt is poorly defined, interpreted here by the course of the **Meliatic Suture** separating the Central and Internal Western Carpathians. This suture is probably followed by reactivated fault zones, as the **Rožňava Line** continuing toward the west and southwest along the **Plešivec, Diósjenő, Hurbanovo** and **Rába Lines** (Fig. 8 and 9; cf. Plašienka, 1999).

Basement units

Vahicum

The term was introduced by Maheľ (1981, 1986) as a West Carpathian analogy of the Alpine South Penninic, i.e. the units derived from a supposed Jurassic and Cretaceous oceanic realm that was thought to have extended between the northern margin of the Tatricum and southern margin of the Oravicum (Czorsztyn and Kysuca units of the Pieniny Klippen Belt). The ***Vahic Superunit*** would then have been laterally connected with the oceanic ***South Penninic*** complexes occurring in the Late Tertiary tectonic windows in the eastern sector of the Eastern Alps (Rechnitz-Kőszeg, Bernstein, Möltern, Eisenberg inliers). The Vahic complexes represent a suture of an oceanic zone, which, during Jurassic and Cretaceous, linked the Ligurian-Piemont Ocean in the west and the Iňačovce-Krichevo Ocean in the east. In recent time they crop-out from below the Austroalpine and Slovakocarpathian continental units. As a result of the differing Tertiary evolution of the Eastern Alps and Western Carpathians, the Penninic-Vahic oceanic complexes are only rarely seen on the surface in Slovakia. Maheľ (l.c.) originally included mainly the Klape Unit of the Pieniny Klippen Belt in his view of the Vahicum. Nowadays, the ***Belice Unit*** in the Považský Inovec Mts. and the subsurface ***Iňačovce-Krichevo Unit*** beneath the Transcarpathian Basin Neogene fill in eastern Slovakia are considered to be parts of the Vahicum (Plašienka et al., 1995).

The Belice Unit consists of low-grade metamorphic sedimentary formations occurring near Hlohovec and in a strip between Selec and Trenčianske Jastrabie villages in the northern part of the Považský Inovec Mts. The oldest known members are Late Jurassic radiolarites overlain by Early Cretaceous siliceous shales (*Lazy Formation*) and Senonian coarsening-upward wildflysch of the *Horné Belice Formation* with olistoliths and slices of metabasalts (Soták et al., 1993b; Plašienka et al., 1994). Rocks of the Horné Belice Unit underwent complex, polyphase ductile and brittle deformation and form an imbricated antiformal stack cropping out from below the Infratatric Inovec Nappe. The imbricated structure is a result of accretionary-subcretionary processes during the Late Cretaceous – Early Tertiary subduction of the Vahic oceanic crust.

Tatricum

The ***Tatricum*** represents the outermost and lowermost superunit of the Slovakocarpathian tectonic system. In the main, it includes as well as the Mesozoic cover rocks, and the pre-Alpine crystalline basement. The Tatric complexes occur in the core mountains of the Tatra-Fatra Belt. On deep-seismic transects, the Tatricum forms a tabular, slightly convex, about 10 km thick upper-crustal body, passing southwards to the primary Fatric basement, rooted in the lower crust below the Veporic wedge (Tomek, 1993). At deeper levels, the Tatric thick-skinned sheet probably overrides the Penninic-Vahic oceanic complexes, being itself overlain by thin-skinned Fatric and Hronic nappes, as well as by overstepping Tertiary sediments and volcanics. The Tatric superunit as a whole, is internally less differentiated compared to the Veporicum. Besides Late Tertiary extensional fault structures (mainly the marginal faults of the core mountain horsts), limited northvergent overthrusts along the northern edges of the inner zone of the core mountains (Tribeč Mts., Ďumbierske Nízke Tatry Mts., High Tatra Mts.) are documented. These originated by positive inversion of Jurassic extensional normal faults (Dumont et al., 1996) at the transition between the original South-Tatric Swell (with shallow-water Tatric successions) and the northward-located Šiprúň Trough (deep-water Šiprúň succession, designated also as the Fatra succession by Maheľ, 1986). Major overthrusts, however, are present at the northern edge of the Tatric sheet, where Tatric partial nappe units overthrust various complexes of the so-called Infratatricum (e.g. the Tatric Bratislava Nappe overriding the Infratatric Borinka Unit – Plašienka, 1990; Plašienka et al., 1991).

East of the High Tatra Mts., NW of the Branisko Horst and SW of the Pieniny Klippen Belt, the Tatric complexes most probably form a wedge into the substratum of the Levoča Paleogene Basin. A similar situation is in the west, in the western part of the Danube Basin substratum. Here, only the basement units adjacent to the Malé Karpaty Mts. and Hainburg Hills, and possibly also in the Leitha Mts. of the easternmost Alps may be considered as Tatric. No typical Tatricum occurs in the Eastern Alps; it is replaced by the Lower Austroalpine (Unterostalpin) units, which can be seen as a parallel to Carpathian Infratatricum as a lower and frontal, imbricated part of the Tatricum. These are directly overthrust by the Middle Austroalpine basement units, i.e. Veporic in the Carpathian terminology.

The smooth mid-crustal suture between the Tatric sheet and underlying Vahic complexes also played an important role later, after formation during the Early Paleogene. Since it represented a crustal inhomogeneity coinciding with the ductile-brittle transition, it was considerable reactivated during the Miocene extension of the Danube Basin area. Listric extensional faults, steep at shallow levels resulting from rigid complexes of the Tatric basement, and gradually flattening in the ductile middle crust, were detected by structural investigation and seismic profiling (Tomek et al., 1987;

Ratschbacher et al., 1990, 1991; Tari et al., 1992; Horváth, 1993; Tari, 1996; Fig. 6). This crustal structure was probably responsible for splitting of the Tatric sheet into a system of rising (core mountain horsts) and sinking (grabens) blocks in the Neogene extensional regions, mainly in western Slovakia (Kováč et al., 1997b).

The ***Tatricum*** as a whole, consists predominantly of pre-Alpine crystalline basement complexes and Late Paleozoic – Mesozoic sedimentary cover. Late Paleozoic complexes are mostly related to the Infratatric units. The Tatric crystalline basement was little affected by Alpine deformation and metamorphism. The basement was not substantially disturbed and preserves in part Variscan internal structure and radiometric ages. The Tatric sedimentary cover is autochthonous to subautochthonous with respect to the basement.

The pre-Alpine, mostly *Variscan crystalline basement,* contains medium- to high-grade metamorphosed volcano- sedimentary complexes intruded by numerous differentiated granitoid plutons (e.g. Petrík et al., 1994; Petrík, 2000). In some areas of the crystalline basement, especially in the Western Tatra Mts., a Variscan nappe edifice has been documented (Kahan, 1969; Janák, 1994). It was presumed that the Variscan nappe structure played an important role in distribution and relationships of metamorphic complexes within the pre-Alpine Tatric, as well as Veporic basement (Putiš, 1992; Bezák, 1994; Bezák et al., 1997b).

The Alpine nappe structure of the frontal Tatric parts (including the Infratatricum) is best documented in the Malé Karpaty Mts. (Plašienka et al., 1991). Here, besides the monotonous gneissic *Pezinok Complex* intruded by the Bratislava Massif, the Tatric basement of ***Bratislava Nappe*** comprises thick low-grade Early Paleozoic volcano-sedimentary successions as well (*Pernek, Harmónia, Doľany Complexes*) – cf. Putiš (1987), Plašienka et al. (1991). The Meso-Variscan (about 350 Ma) *Bratislava granitoid Massif* bears characteritics of the S-type anatectic granites or granodiorites, with abundant pegmatite and aplite veins. The relatively younger *Modra Massif* (about 320 Ma), is composed of I-type granodiorites to tonalites, which penetrated into higher structural levels, being surrounded by a contact metamorphic aureola in the Lower Paleozoic volcano-sedimentary complexes (Cambel & Vilinovič, 1987). Tonalites also make up the *Tríbeč Massif* (Petrík & Broska, 1994). The Tatric Panská Javorina Nappe in the middle – Bojná Block of the Považský Inovec Mts. consists of a gneiss-amphibolite-migmatite complex intruded by the granitoids of the *Bojná* and *Duchonka Massifs* (Putiš, 1983).

The *Tatric sedimentary cover* is Mesozoic (Lower Triassic – lower Turonian); immature terrestrial clastics, probably of the Late Permian age, occur at the base of the cover sequences only locally (*Devín Formation* in the Malé Karpaty Mts., *Meďodoly Formation* in the Tatra Mts. – Vozárová & Vozár, 1988). Subdivision of Triassic sediments into three distinct sequences, as in the Germanic Basin, is typical. Scythian strata in the thickness of 100–200 m, are represented by terrigenous, fining-upward continental siliciclastics usually directly overlying the pre-Alpine basement. Lower Scythian fluvial *Lúžna Formation* is composed of quatzose sandstones, and a few conglomerates and siltstones that are interpreted as semiarid piedmont sediments of ephemeral braided river systems fed by northwestern continental sources ("Vindelician Land" – cf. Fejdiová, 1977; Marschalko, 1978; Mišík & Jablonský, 1978, 2000; Michalík, 1994). The Upper Scythian *Werfen Formation* is composed of variegated sandstones, siltstones, shales and, in the upper part, also evaporites (dolomite, gypsum, rauhwacke). The Middle Triassic shallow carbonate ramp is represented by the *Gutenstein Formation* with many features of a hypersaline environment, submarine slumping and vermicular structures generated by seismic events (Mišík, 1968, 1972, 1978, 1986). It is overlain by a partly hypersaline dolomitic complex of the *Ramsau Formation* with dark shale intercalations in its upper part. The maximum thickness of the carbonate complex is about 500 m. The Upper Carnian – Norian *Carpathian Keuper Formation* includes mostly terrigenous clastic sediments of intracontinental depressions: variegated shales, siliciclastic sandstones, occasional conglomerates, a few evaporites - altogether not more than 80 m thick. Due to erosion during the Lower Jurassic rifting, Rhaetian shallow-marine sediments are rarely preserved. The distinct, but only to the Tatra Mts. restricted, *Tomanová Formation* is a 10–20 m thick limnic sequence of dark shales and light quartzose sandstones with continental flora and Dinosaur footprints (Michalík et al., 1976).

The Jurassic facies were greatly diversified in the Tatric area. Paleogeographically, they are divided into the **North-Tatric Swell** (mostly a part of the present Infratatricum), **Šiprúň Trough** and **South-Tatric Swell** related to the Vysoká-Manín units of the Fatricum. The syn-rift Lower Jurassic sediments are represented by biodetritic and sandy limestones and sandstones (*Trlenská Formation, Baboš Sandstone*) and in the Šiprúň Trough also by the hemipelagic *Allgäu (Janovky) Formation* ("Fleckenmergel", about 200 m thick). Middle and Upper Jurassic strata are chiefly represented by deep-water pelagic facies (cherty and siliceous limestones and radiolarites – Polák, 1978; Bujnovský & Polák, 1979; Polák & Ondrejíčková, 1995). An existence of the Jurassic – Early Cretaceous North Tatric (Lungau) Ridge was interpreted based on the sedimentary record, mainly from Tatric successions of the Malé Karpaty Mts. (Plašienka et al., 1991). Following a remarkable early Jurassic erosion, partly up to the pre-Alpine crystalline basement level, sedimentation starts in the Middle Liassic (*Dudziniec Formation*), or more frequently in the Upper Liassic carbonate breccias (*Pleš Breccia* in the *Kuchyňa* and *Devín Successions* – Michalík et al., 1993a, 1994), and in the swell *Kadlubek Succession* by condensed *Adnet Limestones*. Middle Jurassic is represented by calciturbidites of the *Slepý Formation* (especially in the *Orešany Succession*, where they reach more than 300 m in thickness), Late Jurassic by pelagic silicites (*Ruhpolding Formation*) and nodular and marly limestones (*Tegernsee Formation*). These contain, however, several allodapic intercalations, which are also present in the Lower Cretaceous *Staré Hlavy Formation* (Michalík et al., 1993a). A similar diversification of the South Tatric Swell is recorded in the Jurassic – Early Cretaceous successions in the Tatra Mts. (cf. Mahel', 1986).The Late Malm – Lower Cretaceous sequence is formed by the Biancône-type platy limestones with chert nodules of the *Oberalm* and *Lučivná Formation* (up to 300 m thick; Polák & Bujnovský, 1979). Bioclastic limestones were widespread during the Barremian, even terrigenous allodapic sandy limestones can be found to surround the North-Tatric Swell (*Solírov Formation* – Jablonský et al., 1993). In the area of the South-Tatric Swell (High Tatra Mts.), platform *Urgonian Limestones* accumulated, together with slope deposits representing products of their erosion (Mišík, 1990). Small bodies of hyaloclastite basanitic lavas occur locally in Barremian and Aptian sediments. Synorogenic turbidite sediments with dominance of terrigenous siliciclastic material, together with bodies of exotic conglomerates (*Poruba Formation*, up to 300 m thick) were deposited during the Late Albian and Cenomanian. The hemipelagic sedimentation ended as late as in the Early Turonian. The overall thickness of the sedimentary cover is about 2000 m.

The ***Infratatricum*** is the frontal, imbricated part of the Tatric sheet cropping out in the western part of the tatra-Fatra Belt. The Borinka Unit of the Malé Karpaty Mts., the Inovec Nappe of the northern part of Považský Inovec Mts. and the Kozol Unit in the Malá Fatra Mts. can be ranged into the Infratatric units (Plašienka et al., 1997c). All these units are autochthonous (subautochthonous) with respect to the proper Tatric units. Their deeper substratum outcrops only in the Považský Inovec Mts., where it is formed by the Belice Unit of presumed Vahic origin. Substantial portions of the Lower Austroalpine complexes occurring in the easternmost part of the Eastern Alps (Wechsel and Grobgneiss units), including the Semmering Fold System, may be considered as a westward prolongation of the Infratatric units (Pahr, 1991; Häusler et al., 1993). The Infratatric units form a recumbent fold system and basement partial nappes at the tip and at the lower edge of the frontal Austroalpine-Slovakocarpathian superunits, where they directly overlie the Penninic-Vahic complexes. In more recent times they-crop out in elevated structures – tectonic windows and half-windows. The nappe thrust planes are accompanied by ductile shear zones originating in conditions of low-grade metamorphism (cca 250–300 °C; Putiš, 1991;Plašienka et al., 1993; Plašienka, 1995a).

The Infratatric basement is exposed only within the ***Inovec Nappe***, being composed mainly of micaschists, and some amphibolites and metagranotoids (Putiš, 1983). It is covered by the thick Upper Paleozoic *Kálnica Group*, consisting principally of Permian immature continental clastics (Putiš, 1986; Vozárová & Vozár, 1988), in the same way as the *Stráňany Formation* of the ***Kozol Unit*** in the Malá Fatra Mts. Both are overlain by the Scythian *Lúžna* and *Werfen Formations* and by the Middle Triassic carbonate complex. Upper Triassic formations are generally missing due to erosion during the Jurassic rifting. Jurassic rocks are extensively present in the ***Borinka Unit*** of the Malé Karpaty Mts. where they are composed of thick prisms of syn-rift terrigenous marine clastics filling-up an extension halfgraben – the *Prepadlé Formation* (Middle Liassic extraclastic Borinka limestone, carbonate breccias and quartz sandstones), *Korenec Formation* (proximal turbidites), *Marianka Formation* (Upper Liassic anoxic shales and distal turbidites), *Somár Formation* (scarp breccias of crystalline basement material), *Slepý Formation* (Middle – Upper Jurassic calciturbidites) in a cumulative thickness in excess of one thousand metres (Plašienka, 1987; Plašienka et al., 1991).

Veporicum

The ***Veporicum*** represents a middle crustal superunit of the Central Western Carpathians. It covers the southern Tatric margin and it is overthrust by the Gemeric basement. It is exposed in the Vepor Belt. Based on geometric characteristics derived mainly from deep-seismic transects 2T and G1 (Tomek, 1993; Vozár et al., 1998), it may be characterized as a deep-seated, thick-skinned, partly imbricated crustal slice of wedge, to tabular shape. The lower thrust plane of the Veporicum can be connected to the Čertovica Line, which dips southward under an angle of about 25° and disappears in the lower crust somewhere below the southern part of the Gemericum. The upper limiting plane can be derived from the surface Lubeník and Margecany Lines. This plane dips 10–20°, which depicts the Veporic sheet as a nearly wedge-shaped body. It is about 15–20 km thick in its frontal part and up to 30 km thick in the rear part, where it occupies the whole crustal profile (2T cross-section). Towards the east (G1 cross-section), the Veporicum is only about 5 km thick in the northern part and 8–10 km thick in the southern part. In the seismic cross-sections, the inner structure of Veporicum is complex, with numerous reflecting zones, roughly copying its marginal surfaces. These reflectors are probably anisotropic zones (mainly mylonitic) created during the paleo-Alpine (Cretaceous) collisional and post-collisional tectonic events. On the other hand, at least part of the reflections, namely the subhorizontal or slightly northward dipping ones, may be considered as pre-Alpine, reflecting Variscan overthrust and collisional processes (Bezák et al., 1997a).

On the recent erosional surface, Veporicum is mainly built by *pre-Alpine basement* which has a similar composition and pre-Alpine history as that of the Tatricum. Its Late Paleozoic – Mesozoic cover is preserved locally only. The crystalline basement is formed by likely *Early Paleozoic volcano-sedimentary complexes* of low- and medium-grade Variscan metamorphism, but sometimes up to high-grade metamorphosed migmatitic and amphibolite complexes; by the large composite *Vepor Pluton* (e.g. Bezák ed., 1999) and some smaller specific granitoid massives (Hronček, Rimavica and Cretaceous Rochovce granitoid massives – Putiš et al., 2000a; Poller et al., 2001). Terminology, as well as spatial extension of individual Early Paleozoic metamorphosed volcano-sedimentary complexes differs from author to author and it is still not standardized (see Bezák ed., 1999 and references therein). Unlike the Tatricum, the basement of the South Veporicum, in particular was consideralby affected by paleo-Alpine tectonometamorphic processes, especially by low- to medium-grade metamorphism and development of a penetrating subhorizontal mylonitic structure that is superimposed on the Variscan metamorphic features and tectonic relationships of the pre-Alpine complexes (Hók et al., 1993; Madarás et al., 1996; Plašienka et al., 1999; Janák et al., 2001 and references therein).

The sedimentary cover of the northern part of Veporicum – the ***Veľký Bok Unit***, was paleogeographically part of the Fatric area on the southern flanks of the Jurassic – Early Cretaceous Zliechov Basin. It is more-or-less structurally confined to the North Veporic crystalline basement. At present, however. The Veľký Bok Unit occurs in the classic area on the northern slopes of the Kráľovohoľské Nízke Tatry Mts., and in the NW part of the Slovenské rudohorie Mts. (Ľubietová Zone – where it is sometimes called the ***Lučatín Unit***, with western continuation to the area of the Sklené Teplice inlier and basement of the Komjatice Depression of the Danube Basin), as well as in Sľubica and Čierna Hora Mts. (***Hrabkov Unit***). It is composed of Permian – Lower Cretaceous sedimentary sequences, divided into several units, commonly forming large recumbent folds, differing in their lithostratigraphic contents mostly in the Jurassic sequences. Permian clastic formations with a volcanic horizon of the *Ľubietová Group* occur locally in a great thickness (up to 1000 m – Vozárová & Vozár, 1988), directly overlying the North Veporic crystalline basement. Above them, the early Triassic quartzites of the *Lúžna Formation* occur (200–300 m), together with variegated shales and sandstones of the Werfen Formation. The Middle Triassic carbonate complex is built by the *Gutenstein Limestone* and *Ramsau Dolomite*. The Late Triassic is represented by the *Carpathian Keuper Formation* and by the locally preserved Rhaetian *Fatra Formation*. The Triassic carbonate deposits are about 500 m thick.

Jurassic formations of the Veľký Bok and Lučatín units start with syn-rift sandy carbonate sediments, locally with sedimentary gaps and erosion of underlying Triassic rocks. The post-rift formations consist of Middle Jurassic to Lower Cretaceous pelagic facies, i.e. marly, cherty and siliceous limestones, locally also radiolaritic silicites (Plašienka, 1995c; Soták & Plašienka, 1996). The largest thickness, though in tectonically and metamorphically reduced form, is the Neocomian – Lower Albian *Mráznica Formation* (over 1000 m). Younger sediments are not known. In the Hrabkov Unit, Cretaceous sediments are totally absent (Polák ed., 1997).

The ***Foederata Unit*** represents the cover of the southern and central zones of the Veporicum. However, it is preserved rudimentarily only. In the southernmost part of the Veporicum, along the Lubeník Line, only Late Paleozoic and Scythian formations are preserved, called the *Revúca Group*, with a thickness in excess of 1000 m (Vozárová & Vozár, 1988). Part of the Late Paleozoic – Triassic sequence was detached and thrust northward over the Foederata Unit in the form of a thin allochthonous body called the ***Markuška Nappe*** (Plašienka, 1984; Plašienka & Soták, 2001; Madarás & Ivanička, 2001).

The Foederata Unit in the central Veporic zones is built by Permian – Triassic metamorphosed sedimentary complexes composed of Permian – Scythian clastics and a Middle to Upper Triassic carbonate complex. All rocks of the Foederata sedimentary cover are markedly metamorphosed in greenschist facies and underwent ductile deformation (Plašienka, 1993). However, they remained in autochthonous and/or paraautochthonous position in their crystalline substratum.

During the Middle Cretaceous, sinistral transpression was active in the Vepor Belt that generated important fault zones in the SW-NE to WSW-ENE directions dissecting the Veporicum into individual zones. The **Osrblie Fault System** separates the Ľubietová Zone from the Kraklová Zone, the **Pohorelá Fault** divides the Kraklová and Kráľova Hoľa Zones (Hók & Hraško, 1990; Putiš, 1991; Madarás et al., 1994), the **Muráň Fault** (active mainly during the Late Cretaceous and Early Paleogene as a sinistral strike-slip – Marko, 1993) separates the Kráľova Hoľa from the Kohút Zone. Other parallel fault systems are the Divín Fault, connected with the Muráň Fault and the Zdychava Fault Zone in the Kohút Zone. All these fault systems, along with the **Čertovica Line**, which separates the Veporicum from the Tatricum (e.g. Siegl, 1978), and the **Lubeník Line** at the boundary between the Veporicum and Gemericum, are paleo-Alpine, deep seated sinistral transpressive zones. In places accessible to direct observation, they do not show any sign of Neogene reactivation. The same is true of transverse fault systems of NW-SE direction (e.g. the **Mýto-Tisovec Fault**), which was active mainly during the Paleogene.

Since the Veporic and Tatric basement are in many aspects similar in composition, it is difficult to draw a strict line between them to correspond with the Čertovica Line in places where it is covered by thick Tertiary sedimentary and volcanic complexes, e.g. under the Danube Basin fill. Nevertheless, some crystalline rocks are known from boreholes that provide data for distinguishing between the Tatricum and Veporicum. For example, the boreholes in the extension of the Malé Karpaty Mts. and the Považský Inovec Mts. horsts, registered a continuation of their granitoids or metamorphics. On the contrary, in prolongation of the Dubník Plateau (Nové Zámky area), a tonalite was drilled containing dioritic xenoliths, which is typical of Veporic Sihla-type granitoids. However, data are too scarce and, therefore, the Veporicum is generally not separated from Tatricum in tectonic schemes used for correlation with the Eastern Alpine units (similar subdivision cannot be applied in the Eastern Alps). Both units may be considered as an analogue of the Middle Austroalpine Unit.

Gemericum

The Gemericum is the highest basement superunit of the CWC, although in volume it is smaller than the Tatricum or Veporicum and, moreover, it wedges out laterally. It is exposed in the Gemer Belt. Its (at least some) analogues can be found in the Upper Austroalpine units of the Eastern Alps, which include Paleozoic formations; as for instance, the Grauwackenzone (Noric Nappe), the so-called Graz Paleozoic, Gurktal Nappe System and some units in the basements of the Styrian and Danube Basins (Mihályi Ridge etc.) – cf. Neubauer & Vozárová (1990), Balla (1994), Ebner (1992), Tari (1995a, 1996).

During the Variscan cycle, the ***Gemeric Superunit*** represented the southern, outermost parts of the orogen, whereas during the Alpine cycle it formed the innermost zone of the CWC. Paleogeographically, it represents the southern marginal zones of the Slovakocarpathian system, neighbouring the Meliata Ocean in the south. After its closure, the Gemeric sheet was thrust northward above the Veporicum. According to data from deep-seismic profile G1 (Vozár et al., 1996, 1998), the Gemericum is, in its middle part, a wedge-shaped, southward thickening upper crustal body. Its lower limiting plane, dipping about 20°, can be followed from the Margecany Line, which merges with the subvertical Rožňava Fault Zone at about 15 km depth.

The Gemericum forms a system of northward-verging thrust imbrications and partial nappes, the number and terminology of which differs according to various authors. Most frequently, the North Gemeric (Klátov, Rakovec, Črmeľ and Ochtiná tectonic units) and South Gemeric (Gelnica or Volovec and Štós tectonic units) zones are distinguished. The largest one is the ***Volovec Unit***, built up by low-grade metamorphosed, thousands of meters thick, Early Paleozoic volcano-sedimentary complexes (*Gelnica Group*), intruded by the Late Variscan (Permian) *Spiš-Gemer granitoids* (Finger & Broska, 1999). The sedimentary complexes consist of upward thickening flysch megacycles with abundant terrigenous and volcanogenic material. The cycle bases are formed by pelagic silicites (lydites), anoxic shales and, locally, also carbonates (e.g. Snopko, 1967; Grecula 1973, 1982; Ivanička et al., 1989). Their age ranges from Cambrian to Early Devonian. The volcanics (mostly volcanoclastics) are acid to intermediate, less basic in composition (Ivan, 1994; Vozárová & Ivanička, 1996; Hovorka & Méres, 1997). The upper, tectonically separated part of the Gelnica Group, with prevalence of distal turbidites and with basic volcanics, extending in the southern part of the Gemericum, is called the *Štós Formation* (Mello ed., 1997). It is probably Middle to Late Devonian in age. The sedimentary cover of the Volovec Unit is formed by the Permian – Scythian terrigenous *Gočaltovo Group*, composed of the continental Early Permian *Rožňava Formation* and the Upper Permian – Lower Triassic, partly shallow-marine *Štítnik Formation* (Reichwalder, 1973; Vozárová & Vozár, 1988; Vozárová, 1996). In the Nižná Slaná Depression, erosional remnants of Middle-Triassic carbonates occurring below the Meliatic Bôrka Nappe are probably also a part of the Gemeric sedimentary cover (Mello ed., 1997).

The North Gemeric basement is represented by the Rakovec and Klátov units with an oceanic affinity. The ***Rakovec unit*** is built up of low-grade metamorphosed sediments and basic volcanics, probably of Devonian age (Bajaník, 1975; Bajaník et al., 1981; Hovorka et al., 1988). Together with the higher metamorphosed ***Klátov Unit*** (gneiss-amphibolite complex) they probably represent a Variscan oceanic suture (Dianiška & Grecula, 1979; Bajaník & Hovorka, 1981; Hovorka et al., 1984; Spišiak et al., 1985; Faryad, 1990; Radvanec, 1994; Faryad & Bernhardt, 1996).

The North Gemeric Early Carboniferous, is represented by the *Ochtiná* and *Črmeľ Groups* (the first on the west, the latter on the east, both of them about 1000 m thick). They are built of terrigenous marine sediments and carbonate bodies (magnesites), together with basic volcanics, locally also ultrabasics. Their age is Late Viséan – Serpukhovian (Vozárová, 1996). The Upper Carboniferous *Dobšiná Group* lies transgressively on the Early Paleozoic substratum in the northern part of the Gemericum. Besides basal clastics, it includes also shallow-marine sediments, basic volcanics and the regressive paralic sequence. The Permian *Krompachy Group* rests transgressively on various North Gemeric complexes. The basal part consists of unsorted coarse clastics deposited in a terrestrial environment. Higher up they pass into the Upper Permian and Lower Triassic lagoonal-sabkha sediments, accompanied by subalkaline rhyolitic volcanism (Bajaník et al., 1981; Vozárová & Vozár, 1988). Previously, a normal sedimentary transition to overlying carbonate complexes of the "North-Gemeric Mesozoic" had been presumed. Today, however, this *Stratená Nappe* is considered to be part of the Silicicum (Mello ed., 2000). Nevertheless, its nappe position cannot be convincingly documented in many places.

Superficial nappe systems

Fatricum

The Fatricum stands for the units derived from zones between the present-day Tatricum in the north and Veporicum in the south. The term was introduced by Andrusov et al. (1973) for the "Lower Sub-Tatra Nappe" (i.e. the Křížna and analogous units). The ***Fatricum***, defined as a superunit (Plašienka, 1999b), is equal in status to the Tatricum and Veporicum. It includes not only the detached complexes of the Křížna Unit but also their original substratum, and principally, the whole crustal profile of the original Fatric paleogeographic domain, although today this substratum is rarely seen in surface. Tentatively, the majority of the Peri-Klippen Zone units (their pre-Senonian members) can also be included in the Fatric superunit, where the Fatricum is a dismembered superunit of the CWC, the basement of which was to a large extent consumed. The detached sedimentary complexes form essentially the classical Křížna Nappe, which is one of the fundamental units of the Tatra-Fatra Belt of the Slovakian Carpathians.

Three types of tectonic units make up the Fatric Superunit. The first type are units which include the pre-Alpine basement and its Permian – Scythian sedimentary cover (tegument of basement, over 1000 m thick), which form basement duplexes in the rear part of the Fatric nappe system (Jaroš, 1971; Hók et al., 1994). The ***Rázdiel Unit*** in the Tribeč Mts. is a pre-Alpine basement composed of phyllites, mica-schists, amphibolites and mylonitized granitoids. The cover complex consists of the Late Permian, coarse-clastic *Skýcov* and shaly *Slopné Formation*. In all units of this type, the upper part of the tegument is formed by Permo-Scythian quartzose sandstones of the *Lúžna Formation*. The analogous, imbricated ***Staré Hory Unit*** of the Starohorské vrchy Mts. contains an orthogneissic basement and the Permian *Špania Dolina Formation*. In the ***Smrekovica Unit*** of the Branisko Mts., the basement is made up of the pre-Alpine, high-grade metamorphosed *Patria Complex*, covered by the Permian *Korytné Formation* (Polák ed., 1997).

The second type involves the classical ***Křížna Nappe***, i.e. detached units containing mostly Middle Triassic – mid-Cretaceous sedimentary successions of several lithotectonic types (e.g. Andrusov, 1968; Maheľ, 1983, 1986). These are in an allochthonous position over the Tatric cover and are tectonically overlain by the Hronic nappes. The Lower Triassic complexes are composed of the Upper Scythian *Werfen Formation*, forming irregular slices directly above the nappe basis, accompanied by rauhwackized carbonate tectonic breccias (Jaroszewski, 1982; Plašienka & Soták, 1996). The backbone of the nappe is formed by Middle Triassic carbonates. As in the Tatric superunit, the lower Middle Triassic strata are represented by the *Gutenstein Formation*. The special *Vysoká Formation* (200 m) exemplifies a mobile, storm-dominated carbonate ramp with frequent Pelsonian tempestites and tsunamites (Michalík et al., 1992; Michalík, 1997), overlain by the sabcha-type *Ramsau dolomite Formation*. Unlike in the Tatric zones, the upper part of the Ladinian – Carnian dolomite complex is unevenly intercalated by a comparatively thin package of siliciclasic sandstones and shales of the *Lunz Formation* (10–30 m). The Norian *Carpathian Keuper Formation* (up to 300 m) contains fewer clastics than in the Tatric domain and is composed of varicoloured claystones, siltstones, some sandstones, and in places gypsum, but its upper part is dominated by evaporitic dolomites deposited in supratidal lagoons (Al-Jaboury & Ďurovič, 1996). Secondary detachment zones were generated along this incompetent horizon. The *Fatra (Carpathian Kössen) Formation* (about 50 m) of shallow-water fossiliferous limestones reflects the Rhaetian marine transgression and first manifestations of rifting and disintegration of the European Triassic shelf (Michalík, 1977, 1978; Tomašových, 2000). Lagoonal pseudoolitic *Svätý Jakub Limestone* occurs in the southern marginal Fatric zones (Čepek, 1970; Tomašových & Michalík, 2000).

Jurassic – Early Cretaceous deposits belong to two lithotectonic units differing with facies. A substantial portion of the Křížna Unit (***Křížna Nappe s.s., Zliechov Partial Unit***) is built by the deep-water *Zliechov Succession*. It begins with the Hettangian – Sinemurian, terrigenous, littoral to neritic *Kopienec Formation*. Higher up, it passes to the syn-rift, hemipelagic *Allgäu Formation* represented by spotty marlstones and limestones (*Janovky Formation*, "Fleckenmergel", up to 500 m thick) – Gaździcki et al. (1979), Michalík et al. (1982). In the marginal southern developments (*Iľanovo Succession*), related to the North Veporic Lučatín Unit, the Kopienec and Allgäu Formations are replaced by swell facies of red oolitic, crinoidal and nodular limestones (*Hierlatz and Adnet Formations* – Mišík, 1964; Mišík & Rakús, 1964; Čepek, 1970; Bujnovský, 1975; Soták & Plašienka, 1996; Polák et al. eds, 1997). In the Iľanovo Succession, red nodular and marly limestones represent the entire Middle and Upper Jurassic (Biely & Bezák eds, 1997). In the Zliechov trough, the Middle to Late Jurassic sedimentation reflects gradual post-rift thermal subsidence with eupelagic cherty and siliceous limestones, and finally Oxfordian radiolarites (*Ždiar Formation* – Polák & Ondrejičková, 1993; Polák et al., 1998). During the Middle and Late Malm, siliceous, cherty and marly limestones were deposited in the axial zones of the Zliechov Basin (*Jasenina* and *Osnica Formations*), with gradually increasing amounts of terrigenous clayey material during the Early Cretaceous (*Mráznica* and *Párnica Formations*), e.g. Borza et al. (1980), Michalík et al. (1993), Reháková (2000). Allodapic calciturbiditic and slump breccia intercalations occur in several horizons (Michalík & Reháková, 1995; Michalík et al., 1996). The Párnica Formation also includes numerous, though small bodies of submarine *hyalobasanitic lavas* (Hovorka & Spišiak, 1988; Spišiak & Hovorka, 1997) and bodies of olistostromes (*Vlkolínec Breccia* – Jablonský & Marschalko, 1992). Sedimentation in all Křížna units terminated with the Middle Cretaceous (Albian – Cenomanian) turbiditic *Poruba Formation* (Jablonský, 1978). After its deposition, in the Late Turonian, the main nappe overthrust phase is supposed to have occurred. The ***Drietoma Unit***, exposed in the western part of the PKB, is similar to the Zliechov Succession in composition. The Jurassic – Cretaceous section of the Zliechov Succession is up to 2000 m thick.

While the Zliechov Succession makes up a substantial part of the Křížna Unit, the highly diversified Vysoká-type successions form several smaller subunits with various degrees of structural independence with respect to the Křížna Nappe s.s., situated at its front and in the underlying (***Vysoká, Beckov, Belá, Ďurčiná*** and ***Havran***) nappes. Unlike the Zliechov Succession, the *Vysoká Succession*, defined in the Malé Karpaty Mts, is characterized by dominance of Jurassic swell, comparatively shallow-water deposits. Liassic strata are represented by bioclastic (crinoidal) and sandy cherty limestones, Dogger and Malm by massive crinoidal limestones (*Vils Formation*), as well as cherty, siliceous and nodular limestones (Koša, 1998). Early Cretaceous deposits are similar to those of the Zliechov Succession (*Padlá Voda* and *Hlboč Formations)*. In the Barremian and Aptian, thick allodapic bioclastic limestone bodies originated (*Bohatá Formation, Muráň Limestone*), which were derived from adjacent Urgonian carbonate platforms (cf. Borza, 1980; Michalík et al., 1990b, c; Michalík & Soták, 1990; Mišík, 1990; Plašienka et al., 1991; Michalík, 1994). A similar Jurassic – Early Cretaceous succession occurs also in the ***Manín*** and ***Haligovce Units*** of the PKB (Peri-Klippen Zone).

The third type of Fatric units includes detached units containing mostly Lower Jurassic – Middle Cretaceous sedimentary successions, that are recently located externally from the Tatric substratum in the so called **Peri-Klippen Zone** of the PKB (some geologists do not agree with attributing these units to the Fatricum, however). They include also Late Cretaceous sedimentary sequences. The Drietoma (Bošáca), Manín, Klape and Haligovce units and, some other units in the Pieniny Klippen Belt should perhaps be included here.

The evolutionary tectonic model of the Křížna Nappe (Plašienka & Prokešová, 1996; Plašienka, 1995b, 1999b) assumes that the principal Zliechov Unit was formed at the expense of a wide basinal area floored by continental crust strongly stretched and thinned during Early Jurassic rifting. The lithologically variable succession resulted in a mechanical stratification of the nappe complexes, which contain three important décollement horizons: Werfenian, Keuper and the base of the flysch sequence. The first one is the most important, nearly all Křížna complexes were detached along it. The significance of the other two increases towards the frontal parts of the nappe system. Complexes below the Werfenian décollement remained mostly confined to the underlying basement as its tegument (Jaroš, 1971); massive Triassic carbonates form the "basal buttress" and the well-bedded Jurassic to Lower Cretaceous sequences constitute the incompetent core of the nappe. The uppermost flysch complex exhibits the highest mobility; it is mostly tectonically denuded in the rear and accumulated in the frontal nappe parts.

The inversion of the Zliechov Basin and generation of the Křížna Nappe system occurred in mid-Cretaceous times. The Zliechov Basin was progressively shortened through underthrusting of its basement and tegument complexes below the Veporic thrust wedge. The sedimentary filling was detached along the lower décollement horizon and formed an initial fold-and-thrust stack prograding outwards. Simultaneously, terrigenous flysch prisms (Poruba Formation, Klape Unit), fed by rising hinterland units, were deposited in the piggy-back basins, as well as in the foreland Tatric areas. After the complete elimination of the Zliechov basin substratum, the Tatric and Veporic margins collided and the detached Krížna stack was pushed over the frontal South Tatric ramp, from which the frontal Fatric elements (Vysoká and Manín-type), with slope- and ridge-related sedimentary successions, were torn off. In the Late Turonian, gravitation caused northward diverticulation sliding of the Fatric nappe elements from the South Tatric over the unconstrained basinal northern Tatric areas. The Klape Unit, composed of mid-Cretaceous flysch complex, was the foremost diverticulation. Some frontal, mostly Manín- and Vysoká-type related units were emplaced as the second diverticulation. The Klape and Manín sheets glided farthest, up to superposition over the later subducted oceanic crust of the Vahic domain north of the Tatricum. They were immediately followed by the principal nappe sheet, the Krížna Nappe s.s., with its dominant basinal Zliechov succession, in which the emplacement event is recorded by extensional structures superimposed on older, compressional structures (Prokešová, 1994). Finally, the frontal elements of the backstop Veporic basement wedge overrode the southern Tatric basement and cover – former northern passive margin of the Zliechov Basin, along with local imbricated basement duplexes detached from the original Zliechov Basin substratum.

Hronicum

The term Hronicum was introduced by Andrusov et al. (1973) for the superficial detachment nappes named originally as the "Middle (i.e. Choč) Sub-Tatra Nappe". They attributed to the Hronicum the lower, Šturec Nappe, built up by the Čierny Váh Succession and the upper, Choč Nappe (s.s.) formed by the Biely Váh Succession. However, structural independence of such defined monofacial nappes has not been proved and Hronic units are today mostly called the "Choč Nappe (s.l.)" (or Choč polyfacial "stem" nappe – Mahel', 1979, 1986). The division of Hronic nappes undergoes continuous changes depending on criteria used, which are either lithofacial, structural or combined. Some successions with a predominance of the reef Wetterstein Limestones are also considered a part of the Hronic superunit (e.g. the Nedzov, Strážov and Tlstá nappes – Polák et al., 1996; Kováč & Havrila, 1998). Some authors, however, consider these successions to be a part of the Silicicum, or, formerly "Gemerides" – equivalent to the "Upper (i.e. Strážov) Sub-Tatra Nappe" (Andrusov, 1968).

The ***Hronic Superunit*** represents the highest nappe system in the Tatra-Fatra Belt and along the northern margin of the Vepor Belt, where it forms numerous nappe outliers overlying the Fatric units. The Upper Austroalpine Mesozoic nappe systems in the Northern Calcareous Alps and beneath the Vienna Basin fill (Upper Bajuvaricum and Tirolicum: Lunz, Göll and Ötscher Nappes) are analogous to the Hronicum. They are related to the nappes in the northern part of the Malé Karpaty Mts. (Veterlín, Havranica, Jablonica and Nedzov Nappes). In the Northern Calcareous Alps, however, the typical Hronic member – the Upper Paleozoic Ipoltica Group, is absent.

The Hronicum is a large system of unmetamorphosed superficial sedimentary nappes which originated in the southern zones of the Slovakocarpathian system, i.e. from the northern passive margin of the Meliatic ocean, underlain by a continental crust. They were detached at the base of the Upper Paleozoic detrital succession; but in the northern parts of the CWC, the Triassic carbonate complex is detached along the horizon of Upper Scythian shales and marlstones. The nappes underwent some brittle deformation and represent thin-skinned, detachment cover nappes. In their original Cretaceous form, they probably formed thin tabular bodies subhorizontally covering the entire Tatra-Fatra Belt. They are internally less dissected, but the portions containing stiff reef bodies usually form independent partial thrust units (e.g. the Strážov Nappe). Along the northern margin of the CWC, in the vicinity of the PKB, the Hronic nappes are largely affected by superimposed transpressional and transtensional deformations with syn- to post-tectonic sedimentary cover (Gosau Group).

The basal part of the Hronic nappe system in the southern parts of the Tatra-Fatra Belt, is represented by the several thousands meters thick Upper Paleozoic – Scythian *Ipoltica Group*. Basement slices – mylonitized pre-Alpine granitoids ocassionally occur at the nappe sole (Vozárová & Vozár, 1988), which is usually marked by a thick layer of rauhwackes (carbonate crush breccias). The Upper Carboniferous (Stephanian) *Nižná Boca Formation* consists of a regressive detrital lacustrine-deltaic sequence of dark-grey sandstones, conglomerates, sandy shales and dacitic volcanoclastics (50–500 m thick). The rift related, fluvial-lacustrine, red-beds type *Malužiná Formation* (deposited in an arid climate) with extensive basaltic volcanism, probably lasted the whole of the Permian and is up to 2000 m thick. It is formed by variegated, mostly red, clayey and sandy shales, siltstones, sandstones and conglomerates, locally with evaporites. These rocks are arranged in upward fining cycles forming three regional megacycles. Synsedimentary basaltic and andesitic volcanics ("melaphyres"), comprising huge lava flows generated during two eruption phases (Vozár, 1997), represent continental tholeiites indicating a continental rift environment. The Lower Triassic is represented by the Lower Scythian *Benkovo Formation* of platy quartzose sandstones (max. 250 m) and Upper Scythian *Šuňava Formation* of variegated shales and sandstones, in upper parts with marlstones and sandy limestones (100–200 m).

The Middle Triassic strata are comparatively thick and differentiated into numerous facies representing various shelf environments – from tidal flats and reef platforms up to pelagic basins. There were several subsiding and elevated zones within the Hronic sedimentary area (Dobrá Voda basin, Nedzov-Strážov platform, Biely Váh basin, Čierny Váh platform – Kováč & Havrila, 1998), which were later inverted to create numerous partial units within the Hronic nappe system. The Anisian carbonate ramp with restricted platforms (*Gutenstein, Annaberg, Ramsau, Steinalm* and *Gader Formation*, up to 500 m) was partly destroyed during the Pelsonian rifting event (recorded by the Farkašovo carbonate slump breccia – Michalík, 1979), which ultimately led to the formation of subsiding pelagic basins (*Zámostie, Reifling, Partnach Formation*; see e.g. Masaryk et al., 1993, their thickness is around 100–200 m) rimmed by carbonate clastic aprons (*Raming, Göstling Formation*) of a material derived from neighbouring, reef-cored prograding platforms that kept pace with subsidence (*Veterlín, Wetterstein Formation*, up to 1000 m thick – Michalík et al, 1993b; Polák et al., 1996). During the middle Carnian, the intra-shelf basins were completely filled with up to 600 m thick dark shales and siliciclastic turbidites of the *Lunz Formation* (Marschalko & Pulec, 1967) during a short-term (less than 2 Ma) humid climatic event (Michalík, 1994). In the Norian and Rhaetian, the overall carbonate platform conditions were re-established (*Hauptdolomit, Dachstein, Norovica Formation*, 200–400 m). Locally, Rhaetian fossiliferous marlstones and limestones with tempestite beds filled channels in tidal flats (*Hybe Formation*, Michalík, 1973).

Two lithotectonic successions have usually been distinguished within the Middle and Upper Triassic Hronic complexes: the Čierny Váh and Biely Váh Successions. The *Čierny Váh Succession* is characterized by a predominance of the ramp and platform carbonates, mainly dolomites. The *Biely Váh Succession* shows diversified, mostly basinal facies starting from the late Anisian and shallow-water facies during the late Carnian to Rhaetian. The Biely Váh Succession represents fills of intra-shelf depressions, which originated by upper Anisian rifting aborted later (Michalík, 1994), probably related to opening of the Meliata ocean. The *Bebrava Succession*, defined by Mahel' (1979, 1986), comprises a thick *Wetterstein Formation* dominated by dolomites; in other aspects, it is close to the Čierny Váh Succession. The Middle to Upper Triassic carbonate platform complexes reach a thickness of up to 2000–3000 m.

In Early Liassic times, a hiatus is though to have occurred in the Hronic area, which was followed by deposition of Upper Lias and Dogger, partly condensed swell lithofacies, e.g. *Hierlatz, Adnet, Klaus* and *Vils Limestones* (Kullmanová & Kochanová, 1976; Mahel', 1985; Uchman & Tchoumatchenko, 1994). The Upper Jurassic stage is represented by pelagic basinal limestones (*Oberalm Formation* – Ondrejíčková et al., 1993) with intercalations of allodapic calciturbidites – *Barmstein Formation* (Mišík & Sýkora, 1982). During the Early Cretaceous, a sequence of pelagic marly and cherty limestones was deposited, followed by the Hauterivian turbiditic siliciclastic *Schambach* and *Rossfeld Formations* (Jablonský, 1992; Michalík et al., 1996), which terminate sedimentation in the Hronic superunit.

Silicicum

The ***Silicic Superunit*** includes the structurally highest unmetamorphosed nappes, restricted to the Vepor and Gemer Belts of the CWC, as well as to the Meliata Belt of the IWC (***Drienok, Muráň, Vernár, Stratená*** and ***Silica-Aggtelek Nappes, Szőlősardó*** and ***Bódva Nappes*** in the Aggtelek Karst and Rudabánya Mts. of northern Hungary). The highest nappes of the core mountains (Nedzov, Strážov and Tlstá nappes) are sometimes considered as belonging to the Silicicum. According to their lithostratigraphic contents the Silicic nappes correspond to the Juvavic nappes of the Northern Calcareous Alps. Their palinspastic position is uncertain; the facies relationships support a proposed original position at the northern passive margin of the Meliatic Ocean; structural investigations however indicate the southern margin position.

The Silicic units form internally less complicated nappe plates, detached at the basis of a thick Triassic carbonate platform complex, usually along the Upper Permian – Lower Scythian evaporitic horizon. In places, however, slices of Meliatic oceanic rocks were found at the base of Silicic nappes, incorporated into evaporitic mélanges (Réti, 1985; Havrila & Ožvoldová, 1996; Horváth, 2000; Vojtko, 2000). In the Slovak Karst and Slovenský raj (Stratenská hornatina, Galmus) areas, the Silicic nappes were dissected by later transpressional movements along deep-seated wrench faults (e.g. the Rožňava and Muráň Faults) to a system of partial structures and blocks (Mello ed., 1997, 2000).

The Silicicum contains sedimentary complexes deposited from the Late Permian until the Late Jurassic; the largest portions are occupied by huge Middle to Upper Triassic carbonate complexes, however. The sole of the Silicic nappes is represented by the Upper Permian detrital-evaporitic *Perkupa Formation*, overlain by Lower Triassic variegated sandstone-shaly (*Bódvaszilas Formation*) and marlstone-limestone (*Szin Formation*) complexes, as thick as 400 to 800 m. Rhyolite volcanics occur in the Szin Fm. in northern partial units of the Silicic nappe system (Drienok, Muráň, Vernár Nappes – Slavkay, 1981; Broska et al., 1993). The Anisian carbonate ramp (*Gutenstein Formation*) and platform (*Steinalm Limestone*), some 500–600 m thick, were partly destroyed by a strong Pelsonian rifting event, which produced intra-shelf basins with pelagic sedimentation prevailing over carbonate resediments (*Schreyeralm, Reifling, Nádaska, Raming Formation*); locally siliciclastic turbidites occur as well (Lunz, Reingraben Formation). Thin intercalations of altered tuffites are known from the Ladinian sequence. However, the Silicic units are dominated by a thick Middle – Upper Triassic carbonate platforms reinforced by huge prograding. 1000–2000 m thick, reef bodies surrounded by peri-reef bioclastic aprons (*Steinalm, Wetterstein, Tisovec-Waxeneck, Furmanec Formation*). Barrier reefs passed to back-reef lagoonal flats (*Dachstein, Hauptdolomit, Bleskový Prameň Formation*; e.g. Mello ed., 1997, 2000). Toward the south (Slovak-Aggtelek Karst), Middle Triassic platform carbonates are overlain by basinal and slope pelagic limestones and marlstones (*Aflenz, Pötschen, Hallstatt, Zlambach Formation*). The southernmost partial units presumably belonging to the Silicic system (Szölösardó and Bódva Nappes in northern Hungary), are marked by a predominance of pelagic facies as early as the Middle Triassic (subsequent to the Pelsonian rift event), for example the Ladinian Hallstatt-type *Bódvalenke Limestone* and silicites deposited near the CCD (*Szárhegy Formation*). These facies would indicate a transition to the Meliata-Hallstatt oceanic trough (e.g. Kovács, 1992).

After the Early Jurassic hiatus, swell-condensed *Adnet* and *Hierlatz limestones* were deposited over the Upper Triassic platform sediments. In basinal areas, hemipelagic sediments of the *Allgäu Formation* accumulated continuously since the Late Triassic (Rakús, 1996; Mello ed., 1997). The Middle to Late Jurassic subsidence led to deposition of deep-water shales and radiolarites with terrigenous admixture. In the Slovak Karst area bodies of chaotic breccias (olistostromes) were also found (Sýkora & Ožvoldová, 1996). The youngest dated sediments are Oxfordian radiolarites. The Jurassic members are, however, poorly preserved; their overall thickness amounts to several tens of meters. From the secondary occurrences, as are for example clasts in Senonian and Tertiary conglomerates, shallow-water Upper Jurassic limestones are known.

Relics of the Silicic Nappes-related Senonian *Gosau Group* sediments occur at several places (Poniky, Šumiac, Dobšiná Ice Cave, Gombasek, Miglinc), preserved along younger fault structures. They are formed by fresh-water limestones, variegated conglomerates, rudist limestones, pelagic marlstones (Campanian) and clayey fillings of paleokarst cavities (Mello ed., 1997, 2000).

Paleotectonic evolution of the Central Western Carpathians

The CWC represent a complex tectonic system that have evolved since the Mesozoic. The precursors of the recent compressional tectonic units originated during Early Jurassic rifting when the Triassic carbonate platform of the North Tethyan shelf was disrupted. On its remains, new diversified sedimentary areas arose. The extension and accompanying subsidence in some zones led to the complete breakup of the continental crust and creation of the Penninic Basin, underlain by an oceanic crust. The extension regime and basinal subsidence continued up to the Middle Cretaceous when, after closure of the Meliata Ocean, a compressional regime started, resulting in basement shortening and generation of the north-vergent nappe structure. The shortening affected mainly the zones underlain by attenuated continental crust (Zliechov and Šiprúň troughs) and prograded from south to north (in recent coordinates), simultaneously with synorogenic flysch sedimentation. The climax of the Cretaceous paroxysm took place during the Turonian. At that time, nappe overthrusts of huge rock masses occurred at near-surface levels.

As late as the Late Cretaceous, the South Penninic (Vahic) oceanic realm was incorporated into the contraction zone. At the Cretaceous/Paleogene boundary, the Oravic Units were involved, i.e. recent constituents of the Pieniny Klippen Belt. The Paleogene subduction of the Penninic oceanic zones was propbably accompanied by subcrustal erosion that led to the foundation of the fore-arc Central Carpathian Paleogene Basin. The shortening moved as far as the outer edge of the CWC, where complex structures of the Považie-Pieniny Belt were formed, with a typical klippen morphostructure. The later Neogene evolution was controlled by subcrustal processes driven by subduction of the oceanic substratum of the Flysch Belt, accompanied by expulsion of the Central West Carpathian units from the area of Alpine collision.

3.1.3. Internal Western Carpathians

The term Inner (sensu Maheľ, 1986) or **Internal Western Carpathians** (IWC, sensu Plašienka, 1999b) is used for the units extending south of the inferred suture after closure of the Meliatic ocean. These units have some features common with the units of the Southern Alps and/or Dinarides

(***Hungarocarpathian Tectonic System***, cf. Fig. 7). The position of the Meliatic Suture plays a key role in separation of the IWC from the CWC. Since part of the Meliatic complexes are superimposed on the Gemericum in an apparent north-vergent nappe position (Bôrka Nappe), the main suture is obviously placed immediately south of the Gemericum (Fig. 8 and 9). It is designated as the "**Rožňava Suture**" (Rožňava-Šugov sensu Kozur & Mock, 1997). Practically an identical structure was named by Grecula (1973) as the "Carpathian-Pannonian Suture", from which the Gemericum was though to have been expulsed during the Alpine (Cretaceous) orogenesis; the Rožňava Fault Zone then represents its superficial expression. The Rožňava Suture is, however, largely covered by the Tornaic and Silicic nappes. One of the possible variants of its continuation to the areas covered by Tertiary sediments and volcanics is shown in Fig. 8. The westward prolongation of the Meliatic Rožňava Suture is expressed along the geophysically defined anomalous linear or zonal deep-seated boundaries or discontinuities – Plešivec, Diósjenő, Hurbanovo and Rába Faults. In the Alps, the suture after the Meliata-Hallstatt ocean was destroyed by the Tertiary collision and its remnants were carried by the Upper Austroalpine nappes of the Northern Calcareous Alps as far as the front of the orogen (Florianikogel Nappe, salinary ophiolite mélanges of "Haselgebirge" at the sole of the Juvavicum).

The inferred course of the Meliatic Suture outlines also the boundary between the Central and Internal Western Carpathians. The rock complexes within the Rožňava Suture are composed mostly of scraped-off oceanic sediments forming a fan-shaped accretionary complex, which separates the crustal blocks of different development, composition and structure (see the seismic cross-section G1 – Vozár et al., 1996, 1998). However, the precise boundary between the CWC and IWC cannot be drawn. It cannot be drawn eeven along along the discrete Rožňava Fault s.s. Zones south of the Gemeric basement exposures, which are underlain by the Meliatic oceanic complexes, will be ranged to the IWC here. They encompass the Slovenský kras Mts. and the north Hungarian mountains e.g. Aggtelek, Rudabánya, Szendrö, Bükk, Uppony, Darnó (built up by Tornaicum, Meliaticum and Bükkicum), Transdanubian Range (Transdanubicum, i.e. Bakonyicum), Igal-Bükk Zone and Zemplinicum in the east. The southern limits of the IWC can be seen along the Mid-Hungarian Lineament that separates them from the microcontinent Tisia (Tisza-Dacia sensu Csontos, 1995).

The above definition of the IWC corresponds to the original definition of the Pelso Megaunit by Fülöp et al. (1987). Later on, the "Gemer-Bükk Unit" was also assigned to the **Pelso Block** (e.g. Kovács, 1992), and the whole megaunit was considered as a Tertiary block, which was expulsed from the Alpine realm during the Paleogene collision and was welded to the Western Carpathians during the Oligocene – Lower Miocene only. However, this is in contradiction to the surface structure of the Vepor-Gemer Belt of the CWC where a pre-Tertiary contact of the Veporic and Gemeric units is well documented. Moreover, the northern boundary of the escaping Pelso block – the Rába–Hurbanovo–Diósjenő Lineament cannot be, in the light of structural and paleomagnetic investigations, considered as a large-scale Miocene sinistral strike-slip. The Miocene escape embraced not only the Pelso block, but the CWC block as well, i.e. the entire "North Pannonian Unit" of Csontos et al. (1992), later renamed the "AlCaPa" microcontinent (Csontos, 1995; Fodor et al., 1999). This feature testifies to the Cretaceous welding of the CWC and the Pelso Megaunit, and speaks for the assignment of the Pelso Megaunit to the Western Carpathians, a concept favoured here, despite that both the CWC and Pelso belong to considerably different Mesozoic paleogeographic zones. The last redefinition of the Pelso Megaunit, or "Pelsonia Composite Terrane" by (Kovács et al., 2000) entails, to some extent, a return to the original definition by involving only units occurring on the Hungarian territory. The contact (vague in the cited work) with the Western Carpathian units was considered to be located along the northern boundary of the "Aggtelekia Terrane". However, this boundary seems to closely follow the political Hungarian/Slovakian border, which is no way solves the problem. If this were so, Pelsonia would be more or less a synonym for the IWC, although Hungarian authors accept its affiliation to the Western Carpathians only occassionally (e.g. Árkai et al., 1995 for the Bükk Mts.).

Principal units of the Internal Western Carpathians

Meliaticum

Units of the Meliaticum represent the deepest elements of the Slovenský kras (Slovak Karst) structure. Parts of the Meliaticum are thrust northward over the Gemericum as the ***Jaklovce Unit*** (unmetamorphosed ophiolite mélange – Mock et al., 1998), recently situated in the so called North-Gemeric Syncline, and the high-pressure (12 kbar) metamorphosed ***Bôrka Nappe*** as a transitional Gemeric-Meliatic element (Faryad, 1995a, b, 1999; Mello et al., 1998). The ***Meliata Unit s.s.*** (Jurassic accretionary flysch complexes with radiolarites, olistostromes, melanges and ophiolitic bodies – Kozur & Mock, 1973, 1995, 1997; Kozur, 1991; Mello ed., 1997) outcrop in tectonic windows from beneath the Tornaic and Silicic nappes in the western parts of the Slovak Karst area. Fragments of rocks, considered to be Meliatic, occur locally at the sole of Silicic nappes where they are incorporated into Perkupa Evaporite Formation (in the Bódva Valley in northern Hungary, but also in the Stratená Mts.).

Tornaicum

Tornaicum (or Turnaicum, South Rudabányaicum according to Kozur & Mock, 1997) is defined as a rootless nappe system consisting of several partial units with sediments from Middle Carboniferous to Late Triassic (probably up to Jurassic), overlying the Meliaticum and underlying the Silica Nappe (Mello ed., 1997). In the western part of the Slovak Karst Mts. it builds the ***Slovenská skala Nappe***. The ***Turňa Nappe*** outcrops from below the Silica Nappe in the Turňa Valley. In Hungary Tornaicum occurs mostly in the northern part of the Rudabánya Mts. (***Komjáti Nappe*** – Fodor & Koroknai, 2000; Less, 2000). Tornaic elements were found also in the Alps, together with the Meliaticum. Middle to Upper Triassic complexes are crucial in the definition of Tornaic units: Early Anisian platform carbonates (mainly *Steinalm Limestone*); from the Late Anisian on, only pelagic limestones are known as the *Žarnov, Nádaska, Reifling and Pötschen limestones*. The variegated Carnian sediments, mainly shales, marlstones, sandstones and, locally, volcanics representing the climatically induced detrital "Raibl event", are typical elements.

The Tornaic units display a complex fold-and-thrust structure, forming a common Jurassic accretionary complex together with the underlying Meliaticum. Therefore, the boundaries between these units are often very uncertain. At most places, the Tornaic rocks are low-grade, but relatively high-pressure (about 7 kbar – Árkai & Kovács, 1986) metamorphosed.

Bükkicum

The name is derived from the Bükk Mts. In Hungarian terminology it is usually called the Bükkium (e.g. Árkai et al., 1995). The Bükkicum builds the eastern part of the Pelso Megaunit (Fig. 8). On the surface, it can be found in Bükk, Uppony and Szendrő Mts., with some relations with units of the Rudabánya Mts. Typically, the Bükkicum includes Paleozoic and Triassic – Jurassic sedimentary, few volcanic complexes with an affinity to Dinaridic units, which underwent just a low-grade Alpine metamorphism.

The structure of the Bükk Mts. provoked and still gives rise to many controversial opinions. Recently, the concept of Csontos (1988), with some modifications, is mostly accepted, proposing that Bükkicum consists of two fundamental units – the Bükk "Paraautochthon" and the Mónosbél-Szarvaskő nappe system.

The Bükk "Para-autochthon" (Fennsíkum in terminology of Kozur & Mock, 1998) consists of a Paleozoic – Jurassic succession of a passive continental margin.The complexes of the Uppony Mts. and the "North-Bükk Anticlinorium" include mainly Silurian shales, Devonian – Lower Carboniferous platform carbonates, Middle Carboniferous flysch, Lower Permian red beds, Upper Permian and Lower Triassic shallow-water carbonates, Middle Triassic platform carbonates and calc-alkaline volcanics, Carnian detrital Raibl Beds and Upper Triassic platform carbonates. Jurassic deep-water shales and silicites occur in several synclines in the southern part of the mountains.

The ***Mónosbél-Szarvaskő nappes*** (partly corresponding to the Bátor Nappe sensu Kozur, 1991) contain only Jurassic rocks – dissected ophiolitic complexes, deep-water shales, radiolarites and olistostromes with blocks of Triassic oceanic rocks. It is thought that these southvergent nappes were derived from a Jurassic back-arc basin, which arose north of the Bükkicum due to the subduction of the Meliata Ocean. The nappes were thrust over the Bükk "Para-autochthon", most likely during the Late Jurassic/Early Cretaceous. In the entire zone, no Cretaceous sediments are known, except for Senonian conglomerates of the *Gosau Group* occurring at Nekézseny. According to radiometric dating, however the low-grade Alpine metamorphism is of Early Cretaceous age (Árkai et al., 1995).

Transdanubicum

The Transdanubicum is a large tectonic unit occupying the western part of the Pelso block, which outcrops in the Transdanubian Range (Balaton Hills, Bakony Forest, Gerecse Mts., Vértes Mts., Buda Hills and Csővár inselbergs east of the Danube). Below the Tertiary cover, this unit extends as far as the Hurbanovo-Diósjenő Line in the north and the Rába Line in the northwest and the Mid-Hungarian Lineament in the south (Fig. 8). It consists of weakly metamorphosed Lower Paleozoic and unmetamorphosed Upper Paleozoic and Mesozoic complexes covered by Tertiary complexes.

The pre-Alpine complexes outcrop in a few places near Lake Balaton. They occur also in the substratum of the Danube Basin in the vicinity of the Rába Lineament (Fig. 5), and consist of low-grade metamorphosed slates and phyllites with interbeddings of metavolcanites and limestone. The age of the series is Ordovician to Early Carboniferous; the age of the metamorphism is Variscan. In the small Velence Mts., some *Late Variscan granitoids* also occur, with a subalkaline geochemical trend. They are similar to some CWC granitoids, e.g. Hrončok and Turčok granites. The pre-Permian succession is terminated by Upper Carboniferous conglomerates.

The Upper Permian to Neocomian sedimentary series represents a passive continental margin succession (e.g. Haas & Budai, 1995, 1999; Császár & Haas, 1984; Trunkó, 1996). The Upper Permian sediments consist of terrestrial clastic and lagoonal evaporitic rocks, the marine *Dinnyés dolomite* occurs in the east. A general transgression at the Permian/Triassic boundary resulted in shallow-marine sedimentation on a peneplained relief. Intertidal sediments, such as dolomites, calcareous sandstones and limestones (*Alcsútdoboz Limestone*) and marls (*Arács* and *Csopak Formations*) represent heteropic marine lithofacies. During the Middle Triassic, shallow-water, lagoonal carbonates were deposited (e.g. *Megyehegy Dolomite, Felsőörs limestone*). Later on, in the Ladinian, thin-bedded, cherty, sometimes bituminous limestones appear, with thin tuffaceous "Pietra verde" intercalations (*Buchenstein Formation*), which record an extensive rifting event. In the Vértes, Gerecse and Buda Mountains the platform *Budaörs Dolomite* was deposited during the Middle Triassic. The thickness of the Lower – Middle Triassic sequence varies between 2000–2400 meters.

Significant paleogeographic changes took place during the Late Triassic. Influx of a fine terrigenous material ("Raibl event") resulted in the deposition of the Carnian *Veszprém Marl*, which occurs above the basinal limestones as well as the platform carbonates. The thickness of the whole formation changes from several metres up to 800 m in basinal successions. In the eastern Csővár–Buda area marls are replaced by basinal cherty limestones and dolomites (*Mátyáshegy Formation*). In the Upper Carnian and Norian, almost the whole Transdanubian Range became the place of a shallow-water carbonate platform deposition. The most widespread formation is the 1000–1500 m thick *Hauptdolomit*. The Hauptdolomit is overlain by the Upper Triassic (Norian – Rhaetian) *Dachstein Limestone* of 500–600 m thickness. Cyclic sedimentation is characteristic of this shallow-water, peritidal platform limestone. The total thickness of the Upper Triassic strata can reach 2000–2300 metres.

The Triassic/Jurassic boundary is not reflected by a facies change within the Dachstein Limestone complex. In the Jurassic, the sedimentary environments were differentiated into elevations with comparatively thin, discontinuous and condensed lithofacies, and basinal areas with relatively thick, continuous successions showing less condensation.

Throughout the Liassic, nodular, cherty limestones occur, with interbedded *Hierlatz Limestone* and "Ammonitico Rosso" limestones and marls (*Isztimér, Pisznice Formation*). The pelagic carbonate sedimentation is continuous up to the Middle Jurassic, when siliceous marls and bedded radiolaritic cherts occur (*Lókút Formation*). Calcareous sediments reappear again as Upper Jurassic Ammonitico Rosso (*Pálihálás Formation*) limestones and white pelagic limestone and cherty marls (*Szentivánhegy, Mogyorósdomb Formation*). The minimum thickness of Jurassic strata is a few tens of metres, the thickest of those attains 400–420 metres.

In the Bakony Mountains, calcareous sedimentation was continuous from the Jurassic to the Lower Cretaceous (cherty limestones, marls – *Mogyorósdomb Formation, Sümeg Marl*, crinoidal *Tata Limestone*). On the other hand, in the Gerecse Mountains (northern part of the Transdanubian Range) a siliciclastic flysch sequence represents the Lower Cretaceous strata: marls (*Bersek Marl*) and turbiditic sandstones (*Lábatlan Sandstone*) and conglomerates with ophiolite material (e.g. Császár & Árgyelán, 1994). Jurassic and Cretaceous rocks do not occur in the Buda Mountains.

After the first Mesozoic compressional deformation in the Transdanubian Range during the Albian, a new sedimentary cycle began with fresh-water and brackish calcareous claystones (*Tés Formation*), locally with bauxite lenses. Reef limestone (*Zirc Formation*) sedimented on elevations, overlain by shallow-marine marls ranging up to the Cenomanian also appears. The total thickness of Lower Cretaceous formations in the Transdanubian Range is from a few hundred up to 1400 metres.

The surface structure of the Transdanubian Range is rather simple, dominated by a large synclinorium with some reverse faults on its flanks, which originated before deposition of the Upper Cretaceous sedimentary cover (Balla & Dudko, 1993) and was overprinted by Tertiary transversal faults. However, according to Horváth (1993) and Tari (1995b), the Transdanubicum possesses a nappe structure. The original thrust planes were reactivated during the Miocene extension as low-angle normal faults, e.g. the Rába Fault as well. On the other hand, some authors have interpreted the Rába Lineament as a deep, steep crustal boundary with a strike-slip character (Balla, 1994). The Transdanubian block, though influenced by the Paleogene back-thrusts and the Neogene transtensional tectonics, represents a comparatively rigid block within the Pannonian basin system.

Zemplinicum

The ***Zemplinicum*** is represented only by pre-Tertiary rocks of the Zemplín Mts. on the surface. It has a controversial position, belonging either to the Veporicum or to the Tisia terrane, and consists of a high-grade crystalline basement of probably Variscan age, thick Upper Paleozoic complexes and remnants of Triassic sediments. Along its NE boundary in the basement of the Neogene East Slovakian Basin, the Zemplinicum is in contact, either with the Ptrukša Zone (possible continuation of the Fatricum), or directly, with the Iňačovce-Krichevo Unit (Vozár et al., 1996; Figs. 8 and 9).

Paleotectonic evolution of the Internal Western Carpathians

The IWC units came from the Triassic – Jurassic zones of the Meliata-Hallstatt Ocean and from zones south of it. The northern, Triassic – Jurassic passive margin is probably represented by the Silicic and Gemeric units. The southern margin, active since Jurassic, was formed by the Tornaic, Szarvaskő back-arc basin, Bükkic and Transdanubic units. The rifting and spreading of the Meliata Ocean were probably a result of back-arc extension of a weakly consolidated Variscan crust within the supra-subduction upper plate of the Paleotethys Ocean. The Meliatic subduction of southern polarity was accompanied by back-arc rifting and ended in the Late Jurassic, followed by collision of its margins. The collisional zone has a double vergent structure – the northern, Central Carpathian branch developed during the Cretaceous as a prograding north-verging nappe system, whilst the southern, IWC branch possessed southern vergency of principal structures during the Cretaceous, when the oceanic crust of the Szarvaskő back-arc basin was obducted over the Bükkicum. In the Late Cretaceous, the IWC underwent another compressional regime, with only rudimentarily preserved (except the Transdanubian Range) Gosau sediments. In the Paleogene, a retro-arc Buda Basin arose due to a transfer of the compressional stresses from the northern margin of the CWC. During the whole Tertiary, the IWC were affected mostly by transpressional and later by transtensional tectonics.

3.1.4. Senonian – Paleogene overstep complexes of the Central and Internal Western Carpathians

The principal arrangement of the tectonic units of the Central (except the Považie-Pieniny Belt) and Inner Western Carpathians originated during the Late Jurassic to mid-Cretaceous age, when the final formation of the nappe structure took place. This structural pattern is overstepped by several basin systems of Late Cretaceous to Tertiary age. They are assigned as "post-nappe" or "post-tectonic" complexes, although in some areas (northern margin of the Tatra-Fatra Belt, Slovak Karst) the Senonian – Paleogene deposits were still strongly affected by the meso-Alpine (Senonian – Early Miocene) deformation.

In inner zones of the Central Western Carpathians, south of the Považie-Pieniny Belt, only a few occurrences of the Senonian *Gosau Group* sediments are known, located in the Pohronie valley at Šumiac village and at the Dobšiná Ice Cave. However, they represent remnants of an originally extensive marine channel crossing the CWC area from northern Hungary, which was interpreted based on drilling of the pre-Tertiary basement in southern Slovakia (cf. Mišík, 1978). Other small occurrences of Senonian sediments are known from the Slovak Karst area (Gombasek) and from the Uppony Mts.

Large areas covered by Senonian sediments occur in the western part of the Transdanubian Range (Bakony Mts.). They represent a new sedimentary cycle after the Albian deformation and Late Cenomanian – Late Santonian hiatus. This succession (more than 1000 m thick) starts with bauxites and terrestrial detrital succession with fluvial, limnic and parallic coal measures (*Ajka Coal Formation*). These sediments are overlain by a marly sequence in the basinal areas, whereas rudist-bearing platform limestones (*Ugod Formation*) developed in elevated areas. In the latest Cretaceous, these platforms were buried by pelagic-pelitic-carbonate sediments (*Polány Marl*).

The Hungarian (Buda) Paleogene basin is situated along a SW-NE strike-belt, extending into the southern part of Slovakia (Štúrovo). The Paleogene deposition started in South Bakony with continental bauxite deposits during the Paleocene to Early Eocene. The bauxites are overlain by Upper Eocene neritic nummulitic limestones and marls. In northern parts, the Dorog coal measures were deposited at that time. An overall thickness of the Transdanubian Eocene rarely exceeds 200–400 m. Upper Eocene andesites occur near Recsk.

In most parts of the Transdanubian Range, the Eocene sedimentation was followed by the so-called "infra-Oligocene denudation". Only in the SE part of the basin, *Tard Clay* and marginal *Hárshegy Sandstone* sedimented, together with coal deposits (Buda Hills and surroundings of the Bükk Mts). In the western part, eroded Eocene rocks are unconformably overlain by brackish and fresh-water Upper Oligocene deposits, reaching a maximum thickness of 700 to 800 m. The new, Oligocene transgression reached the area in the Late Kiscellian. First, coal beds were formed in a thickness of 200 m in the Esztergom area. This was overlain by littoral sandstones of 100 m thickness and then by deep-water *Kiscell Clay* (*Číž Formation*) 60 m thick. During the Egerian, deep-water deposition continued in the form of *Szécsény Schlier* (*Lučenec Formation*). The average thickness of the Upper Oligocene strata is 250 m. In the northernmost parts, the Kiscellian beds are covered by the Egerian marine schliers and Eggenburgian sandstones. The Egerian deep-water sedimentation changed to Eggenburgian shallow-water siltstones and sandstones (*Fiľakovo Formation*). In the uppermost parts of the formation, some brackish layers appeared. The Eggenburgian sedimentation was terminated by deposition of the terrestrial *Bukovinka Formation* (*Zagyvapálfalva Formation* in Hungary).

The **Central Carpathian Paleogene Basin** probably covered the entire Tatra-Fatra Belt and a considerable part of Vepor Belt of the CWC in the Eocene and Oligocene. In northern Slovakia (Orava region, Poprad Depression, Levoča Mts. and Šarišské vrchy Mts.), its sediments, called the *Podtatra Group*, are 3000 to 5000 m thick. In SW Slovakia, only erosional remnants of this group were preserved in the northern part of the Pezinské Malé Karpaty Mts. (Buková Furrow) and in the NE part of the Bánovce Depression. The Podtatra Group is divided into four formations. The basal *Borové Formation* consists of carbonate conglomerates and nummulitic limestones, as well as huge prisms of the *Súľov Conglomerate* in the fringe areas. This transgressive formation gets younger from the north, from the Pieniny Klippen Belt, towards the south and, simultaneously, from the west (Early – Middle Eocene, Malé Karpaty Mts.) to the east (Late Eocene – Early Oligocene, Levoča Mts.). It also indicates the direction of the Eocene transgression. The overlying *Huty Formation* dominated by dark shales with Mn-rich layers, reflects the rapid subsidence of the basin and becomes a the flysch-like turbiditic *Zuberec Formation*, forming a substantial part of the basin fill. The highest member are thick bodies of massive, amalgamated sandstones of the *Biely Potok Formation* which, however, do not occur in western Slovakia.

The Senonian – Paleogene basins of the CWC originated in a fore-arc position at the edge of the CWC, reinforced by the stiff Tatric basement, probably due to subcrustal erosion during subduction of the South Penninic (Vahic) oceanic crust and later of the North Penninic (Magura) Zone (Wagreich, 1993).

3.2. Eastern Alps

The tectonic subdivision of the Eastern Alps differs in certain aspects from that of the Western Carpathians, hence a different terminology is used. The main zones are: the **Molasse Zone** (foredeep), **Flysch Zone** (both units pass into the External Western Carpathians), **Northern Calcareous Alps** (corresponding to the outermost zone of the CWC – the Považie-Pieniny Belt, but they do not have direct equivalents in the Carpathians, excepting the northern part of the Malé Karpaty Mts.) and the **Central Eastern Alps** (built by the Austroalpine tectonic system linked to the Slovakocarpathian system of the CWC). A correlation scheme of pre-Tertiary units of the Alpine-Carpathian-Pannonian Junction Zone is presented in Fig. 13.

3.2.1. Molasse Zone (Eastern Alpine Foredeep)

The Molasse Zone forms a foreland basin, varying in width, at the front of the Alpine orogen south of the Bohemian Massif. A substantial part of the molasse basin was, together with the underlying platform, overthrust by nappe units of the inner Alpine zones, namely the Flysch Zone and the Northern Calcareous Alps. Based on the degree of deformation, the Molasse Zone can be divided into three zones:

1. **Foreland molasse** (undisturbed) lying autochthonously on the platform foreland.
2. **Disturbed molasse** (folded successions, steeply inclined at the southern margin).
3. **Subalpine molasse** (strongly folded, imbricated, para-autochthonous to allochthonous) at the contact with the Flysch Zone (e.g. the Waschberg Zone).

The molasse sediments were deposited in the Late Eocene to Early Miocene in an overall thickness of 1000–4000 m. They comprise sediments from continental to relatively deep-marine and from fine-grained to coarse clastic ones. The lower part of the succession is characterized by material derived from the Alpine foreland (Bohemian Massif), whereas the upper part includes an increasing amount of terrigenous material derived from the uplifted Alps. The succession can be divided into the *lower fresh-water and lower marine molasse* (Late Eocene – Middle Oligocene), and the *upper marine and upper fresh-water molasse* (Middle Oligocene – Middle Miocene). The Late Eocene stage is represented by thin lacustrine, lagoonal and shallow-marine sediments, the Early Oligocene by anoxic shales and Middle Oligocene by pale marly limestones to marlstones. The terrigenous material of the lower molasse came mainly from the foreland. Egerian sediments are composed of sandy marls ("Schlier"), siltstones and sandstones, locally also conglomerates, with material coming predominantly from the Alps, as in Eggenburgian marls and sandstones. The Ottnangian deposits comprise marls, sands and conglomerates and the brackish *Oncophora Beds* in the east. The Karpatian *Laa*

Formation, restricted only in the eastern part of the Molasse Zone at the Alpine orogenic front, terminates the marine deposition. The upper fresh-water molasse is locally represented by Sarmatian – Pannonian sands and gravels.

3.2.2. Flysch Zone of the Eastern Alps

The Wienerwald flysch deposits (Fig. 10) belong to the Rhenodanubian Flysch Belt of the Eastern Alps, comprising the Greifenstein, Kahlenberg and Laab nappes. The Laab Nappe can be correlated with the Biele Karpaty Unit (part of the Magura Superunit); the Greifenstein Nappe used to be paralleled with the Rača Unit (Eliáš et al., 1990).

The ***Laab Nappe*** involves the *Kaumberg Formation* (Coniacian – Campanian), 300 m thick "dark shales" (Maastrichtian), the *Hois Formation* (Paleocene, up to 500 m thick) and the *Agsbach Formation* (Eocene, 500 m thick). From NW, the Laab Nappe is lined by the **Schottenhof Zone**, which is composed of Middle Triassic to Lower Cretaceous klippen, probably of Helvetic derivation. The other Klippen belt – the **St. Veit Klippen Zone** near Vienna belongs already to the Penninic Zone (Schnabel, 1992).

The ***Kahlenberg Nappe*** is formed by the *Gault Flysch* deposits (Albian), "red and green shales", the *Reiselsberg Sandstone* (Cenomanian – Turonian) and the *Kahlenberg Formation* (Santonian – Campanian, 500 m thick). The *Sievering Formation* (Maastrichtian, 700 m thick), like the above mentioned klippen belts, has no unambiguous equivalent in the Moravian territory. A South Penninic position, together with the **Ybbsitz Klippen Unit** has been suggested by several authors (e.g. Faupl & Wagreich, 1992, 2000).

The ***Greifenstein Nappe*** (Sauer et al., 1992, Egger, 1992) comprises the *Wolfpassing Formation* (Hauterivian – Barremian), *Gault Flysch* (Albian), "lower variegated shales", *Reiselsberg Sandstone* and variegated shales of the *Seisenburg Formation* (Cenomanian – Turonian, 100 m thick), the *"Zementmergel" Formation* (Santonian, 500 m thick), variegated shales of the *Perneck Formation* (Santonian, 100 m thick), the *Altlengbach Formation* (Maastrichtian – Paleocene, 1000 m thick) and the *Greifenstein Formation* (Paleocene – Eocene, 500 m thick).

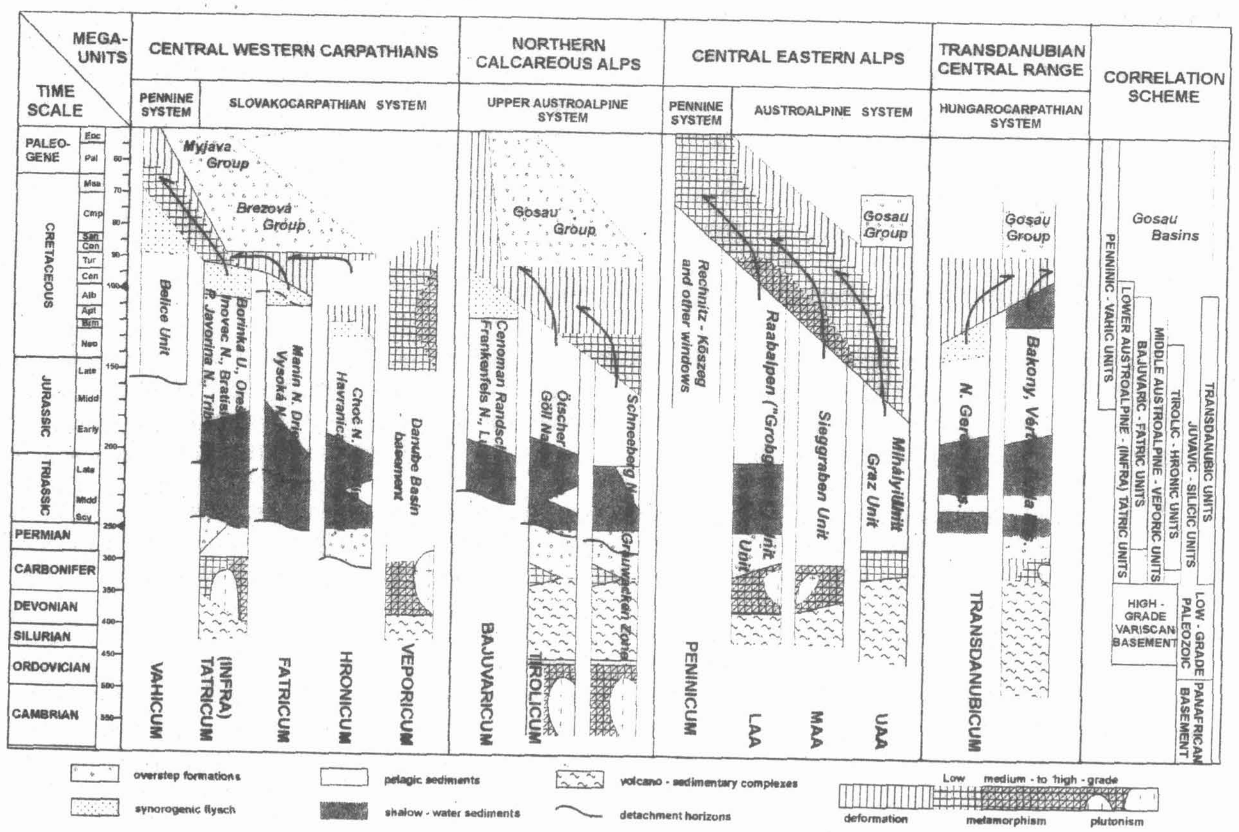


Figure 13. Correlation scheme of the units in the Alpine-Carpathian-Pannonian junction zone.

3.2.3. Northern Calcareous Alps

The **Northern Calcareous Alps** (NCA) form a 40–50 km wide and more than 500 km long, E-W trending fold-and-thrust belt, built of extensive sedimentary nappes designated as the ***Upper Austroalpine Units*** (Oberostalpin). The NCA are dominated by huge Mesozoic carbonate complexes. Further eastward, the NCA units submerge below the Neogene sediments of the Vienna Basin and crop-out again at the northern part of the Malé Karpaty Mts. (Biele hory Mts., Brezovské Karpaty Mts. and Čachtické Karpaty Mts.), where Carpathian terminology is used.

The structure of the NCA involves several Mesozoic cover nappe systems. The lower – ***Bajuvaric*** nappes occur in the external (northernmost) part of the NCA, overlain by the nappes of the ***Tirolicum*** and the highest nappes to the south, the ***Juvavicum*** (Tollmann, 1976). The southern rim of the NCA consists of low-grade metamorphosed Paleozoic volcano-sedimentary complexes called the ***Grauwackenzone***. This zone represents the Paleozoic basement of southern parts of the NCA, presumably of the Tirolic nappe system (e.g. Schweigl & Neubauer, 1997), and/or of the Upper Juvavic nappes (Hamilton et al., 1990; Wessely, 1992). The Senonian – Paleogene sediments of the *Gosau Group* cover a considerable portion of the NCA structure. Though, they partially seal Lower to mid-Cretaceous nappe structures, and they are overprinted by younger, Tertiary thrusts. This documents the complex polyphase processes of shortening and nappe stacking in the NCA (e.g. Peresson & Decker, 1996).

Geological structure of the Northern Calcareous Alps

Bajuvaricum

The ***Bajuvaricum*** forms a very narrow, outer zone in the eastern NCA, called the ***Frankenfels-Lunz imbricated nappe system*** (Wessely, 1992), which is overthrust directly onto Flysch units. It consists of Triassic complexes of a dissected carbonate platform, with typical *Gutenstein, Reifling, Lunz, Opponitz, Hauptdolomit* and *Kössen Formations*. This development is close to the Biely Váh Succession of the Hronic nappe system in the CWC. The Triassic strata are covered by a complete Jurassic – Lower Cretaceous succession, with the Lower Jurassic *Allgäu Formation* (Kieselkalk) or *Hierlatz Limestone*, *Klaus Limestone*, the Upper Jurassic *Ruhpolding Radiolarites*, *Neocomian marlstones* and, in the outermost slices, by the Middle Cretaceous synorogenic turbidites of the *Losenstein Formation* (so-called ***Cenoman-Randschuppe***). The latter is an analogue of the Poruba Formation occurring in the Fatric and Tatric units of the CWC. These formations are discordantly overlain by the *Gosau Group* of the **Giesshübl Syncline** (Wagreich & Marschalko, 1995). This group is formed by Upper Turonian-Senonian-Paleocene (chiefly coarse-grained) terrigenous formations. In the lower part they are lacustrine, whereas the upper parts are marine. The Giesshübl Syncline displays a complex thrust structure and separates the Bajuvaric units from the higher nappes of the Tirolicum. It reflects the large extent and importance of the meso-Alpine shortening within the NCA.

Tirolicum

The ***Tirolicum*** at the eastern margin of the Eastern Alps is represented by the ***Ötscher Nappe System***, consisting of the ***Reisalpen, Unterberg*** and ***Göll nappes***. They comprise various mixed facies of Triassic carbonate platforms, with typical reef-lagoonal, thousands of meters thick carbonate complexes of the *Wetterstein* and *Plattenkalk-Dachstein Formations*. The Tirolic nappes in the basement of the Vienna Basin are linked to the Malé Karpaty nappes, such as the Veterlín, Havranica and Jablonica nappes (Hamilton et al. 1990, Wessely 1992). The *Gosau Group* of the **Glinzendorf Syncline** on top of Tirolic nappes includes limnic deposits.

Juvavicum

Opinions on the inner structure and position of the ***Juvavic nappes*** are now contradictory, since some slices of oceanic rocks, attributed to the Meliaticum, were found at their base (***Florianikogel Unit*** – Mandl & Ondrejičková 1991, Kozur & Mostler 1992). The Juvavicum itself consists of two nappes: the lower, ***Mürzalpen Nappe***, is characterized by the presence of Upper Triassic basinal *Hallstatt Limestones*, the upper, ***Schneeberg Nappe***, displays thick Triassic *reef complexes.* The Juvavic nappes are also partly covered by Gosau sediments of the **Grünbach Syncline**. The Juvavicum as a whole (together with the Meliatic slices), forms nappe remnants covering the Tirolic units in the southern parts of the NCA.

Grauwackenzone

The ***Grauwackenzone*** is a narrow belt rimming the NCA in the south. At the eastern margin of the NCA, however, it is submerged below Neogene deposits of the Vienna Basin. In this area it wedges out and does not appear further NE-ward in the CWC. The easternmost corner of the Grauwackenzone is represented by narrow slices of three higher mid-Cretaceous nappes (Neubauer et al., 1994). The lower, ***Silberberg Nappe***, consists mostly of the Alpine *"Verrucano"* (Upper Carboniferous – Permian clastics), the middle, ***Kaintaleck Nappe***, consists of *mica-schists* and *amphibolite* slices and the highest, **Noric Nappe**, comprises mainly *Lower Paleozoic green-schists, phyllites* and *porphyroids* and *Upper Paleozoic "Verrucano"*. The latter, together with the Scythian clastics, form the stratigraphic basement of the Triassic carbonate complexes of higher nappes of the NCA (Neubauer et al., 1994).

Paleotectonic evolution of the Northern Calcareous Alps

The present complex structure of the NCA originated from a polyphase tectonic evolution during the Late Jurassic, Cretaceous and Tertiary. The major nappe structure was formed during the Late Jurassic to Early Cretaceous eo-Alpine orogeny, when the NCA units detached from their basement and overrode the Lower and Middle Austroalpine crystalline complexes. During the Senonian and Paleogene, this substratum was covered by the Gosau Group sediments. During the Eocene to Oligocene overthrusting of the entire Austroalpine system onto the Penninic units occurred. At that time, the Mesozoic units of the NCA outran their basement and in the final neo-Alpine period they were thrust over the Flysch Belt and the foredeep molasse complexes, as far as the platform (Bohemian Massif), as indicated by the Berndorf-1 borehole in the examined area (Fig. 14).

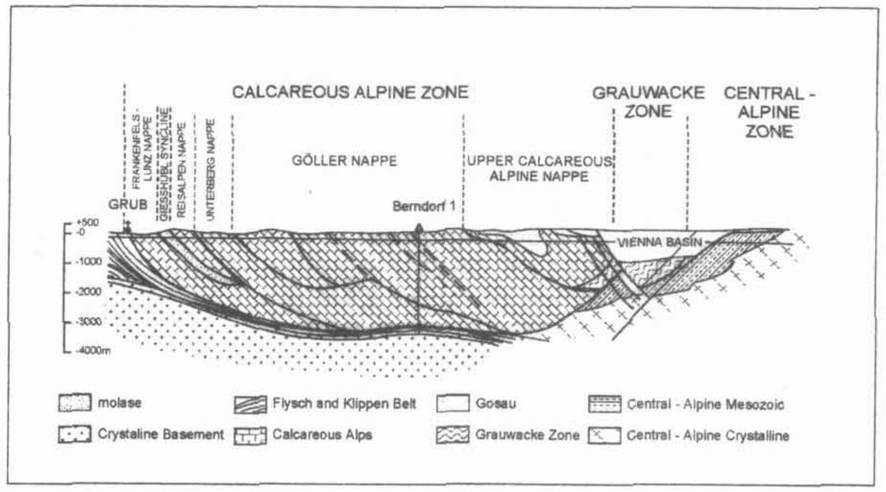


Figure 14. Overall cross-section through the eastern part of the Northern Calcareous Alps and the deep Berndorf-1 borehole (Wessely, 1992).

The Cretaceous – Paleogene shortening was accompanied by dextral transpression and the origin of a complex fault system, during formation of the front of the Austroalpine orogenic wedge (Linzer et al., 1995). The subsequent Miocene shear movements along the NCA were sinistral, due to the eastward extrusion of the central Eastern Alps (e.g. Ratschbacher et al., 1991; Decker et al., 1994; Linzer et al., 1995; Fig. 15). At that time, an important lateral displacement line originated along the southern margin of the eastern NCA. This line, designated as the **SEMP Line** (Salzachtal-Ennstal-Mariazell-Puchberg), together with sinistral strike-slip faults along the seismoactive Mur-Mürz-Leitha fault system within the central Eastern Alps, accommodated a considerable portion of the extrusion movement of the Eastern Alps, and played an important role during the formation of the Vienna Basin.

3.2.4. Central Eastern Alps

Central Eastern Alps

The **Central Eastern Alps** (CEA) represent the widest and morphologically highest zone of the Eastern Alps. They are composed mainly of the pre-Alpine basement complexes and remnants of their Mesozoic cover, both being affected by Alpine metamorphic recrystallization, which form several nappe systems (Fig. 16).

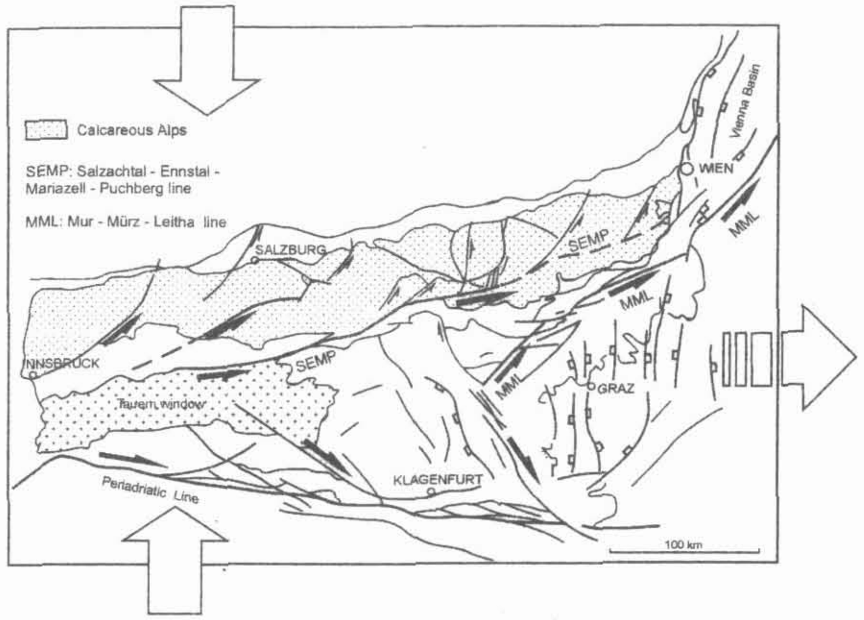


Figure 15. Principal Neogene fault system of the Eastern Alps enabling tectonic extrusion of the Western Carpathians from Alpine domain (modified after Decker et al., 1994).

Penninicum

The ***Penninicum*** is the structurally deepest element of the CEA. It occurs in tectonic windows beneath the Austroalpine nappes, e.g. in the Tauern window. The Rechnitz-Köszeg, Bernstein, Möltern and Eisenberg windows are present at the eastern margin of the CEA (Fig. 16). The Penninic complexes comprise Jurassic – Cretaceous deep-water oceanic sediments and fragments of their oceanic crust – dismembered ophiolites (e.g. Pahr 1991, Koller & Höck 1992). The oceanic successions contain predominantly dark calcareous shales (*Bündnerschiefer*), limestones, silicites and scarce conglomerate layers. The ophiolite complexes consist of serpentinites, gabbros, plagiogranites, basalts and their tuffs (and/or hyaloclastites) and ophicarbonates. Most of the Penninic units underwent a complex deformation and metamorphism, with preserved bodies of HP metamorphosed basalts (glaucophanites). The Penninic windows themselves represent Late Tertiary extensional metamorphic core complexes. In Hungary, the oldest Penninic rocks are the *Kőszeg Quartz Phyllites*, a formation over 500 m thick. Somewhat younger are the *Velem Calcareous Phyllites* with lenses of the *Cák Conglomerate* (500–600 m). These two formations are covered by the *Felsőcsatár Greenschists* and serpentinites, representing remnants of an ophiolite suite exceeding 500 m in thickness. The succession is most likely in an overturned tectonic position and was affected by low-grade Alpine metamorphism. The age of this succession is older than Early Cretaceous, most probably Jurassic.

Lower Austroalpine

The ***Lower Austroalpine*** (Unterostalpin) units occur above the Penninic units over large areas in the easternmost part of the Alps. They are represented by pre-Alpine (Variscan) crystalline complexes and their Permian – Triassic sedimentary cover (e.g. Tollmann, 1977, 1978; Pahr, 1991; Neubauer et al., 1992). The crystalline complexes comprise several metamorphosed volcano-sedimentary formations intruded by Variscan granitoids. They are divided into two principal Alpine nappe units: the lower, Wechsel Unit, and the higher, Semmering (or Raabalpen) Unit.

The main portion of the ***Wechsel Unit*** is built-up by the *Wechsel Complex*, represented by monotonous albitic gneisses at the base and by more variegated metavolcano-sedimentary complexes in the upper part. The polymetamorphic *Waldbach Complex* (mica-schists, orthogneisses, amphibolites) overlies the Wechsel Complex along its southern margin. The Wechsel Unit has only rudimentarily preserved Permian – Triassic cover.

The ***Semmering Nappe System*** covers the Wechsel Unit that crops out in the tectonic windows (Fig. 16). The sole of the Semmering nappes is represented by the *Raabalpen Crystalline Complex* (in other terminology *Grobgneiss* or *Eselsberg Complex*). In this complex, migmatitized paragneisses, mica-schists and phyllonites predominate; however, granitoid massifs of several types are the most widespread; all of them are of Late Paleozoic age. The crystalline complexes were formed in the Variscan period, but during the Alpine orogeny they were extensively deformed and retrograde metamorphosed again. At fronts of the Lower Austroalpine nappes around Semmering, some younger cover members (Permian – Scythian clastics, Middle Triassic carbonates and Upper Triassic lagoonal sediments of the Carpathian Keuper type) are present in recumbent folds (Tollmann, 1977).

In Hungarian territory, Lower Austroalpine rocks occur near Sopron. They can be divided into two complexes: The *Fertőrákos Group* (an analogue of the Wechsel Unit in Austria), consists of a thick complex of mica-schists, overlain by thick amphibolite schists. These successions only occur near the Fertő Lake (Neusiedlersee). The *Sopron Group* (an analogue of the Austrian Grobgneiss Unit) is formed by various types of gneisses and mica-schists. The Lower Austroalpine rocks were affected by high-grade metamorphism during the Variscan Orogeny and by later Alpine overprint.

The Lower Austroalpine nappe system is overlain by a thick Neogene cover of the Little Hungarian Plain (Danube Basin). Its SW margin continues parallel with the Répce river (Répce Line) where it comes into contact with the Upper Austroalpine nappes.

Middle Austroalpine

The ***Middle Austroalpine*** (Mittelostalpin) is represented in the easternmost part of the Alps exclusively by the ***Sieggraben Unit***, building up some small nappe outliers over the Grobgneiss Complex (Fig. 16). Further to the west, however, the Middle Austroalpine crystalline complexes become the main part of the Austroalpine units of the CEA. The Sieggraben Unit consists of polymetamorphosed crystalline complexes with Alpine eclogites (Neubauer et al., 1999; Putiš et al., 2000b).

Figure 16. Tectonic sketch of the easternmost part of the central Alps (Pahr, 1991).

Upper Austroalpine

The ***Upper Austroalpine*** (Oberostalpin) rocks do occur on the surface in Hungarian territory. Below Neogene deposits of the Little Hungarian Plain (Fig. 5), the belt runs in a SW-NE direction between the Répce and Rába lineaments. The Middle Austroalpine is thrust over the Lower

Austroalpine units there. The unit is represented by rocks of *Rábamente Complex* (comparable with the Grazer Paläozoikum in Austria). Its stratigraphic content, however, occurs only sporadically. Above the *Nemeskolta Sandstone* (over 400 m thick), phyllitic and metavolcanic series about 500 to 700 m thick occur. These siliciclastic deposits are locally covered by the *Bük Dolomite* with a thickness of more than 200 m. The age of this group is Early Paleozoic, most probably Silurian and Devonian. This unit underwent very low-grade to low-grade Alpine metamorphism (Balla, 1994; Tari, 1995a).

Paleotectonic evolution of the Central Eastern Alps

The compressional Alpine tectonic evolution of the Austroalpine units of the CEA started in the Late Jurassic to Early Cretaceous with the suturing of the Meliata-Hallstatt ocean (Faupl & Wagreich, 2000). Fragments of this suture probably exist in the Sieggraben Unit. During the Middle Cretaceous (eo-Alpine orogeny), the collisional shortening prograded to the lower Austroalpine units and the basement nappe structure originated (Neubauer et al., 1992). It terminated by the uplift of the Lower Austroalpine metamorphic domes (e.g. the Wechsel Dome). In the meso-Alpine stage (Late Cretaceous to Paleogene), the Austroalpine nappe system has been thrust over the subducted Penninic oceanic units.

The neo-Alpine (Oligocene – Miocene) tectonic evolution of the eastern corner of the CEA was strongly influenced by Miocene extension, related to origin of the marginal Neogene basins during the eastward extrusion of the Carpathian-Pannonian units from the area of the Alpine collision (e.g. Decker, 1996 – Fig. 17). The basin-forming processes were, on the other hand, accompanied by uplift and unroofing of Penninic metamorphic domes, documented by structural (Ratschbacher et al., 1990) and termo-chronological studies (Dunkl, 1992). The original paleo- and meso-Alpine thrusts were reactivated as extensional and transtensional flat normal faults, that accommodated the majority of extensional movements below the adjacent basins (Ratschbacher et al., 1990; Horváth, 1993).

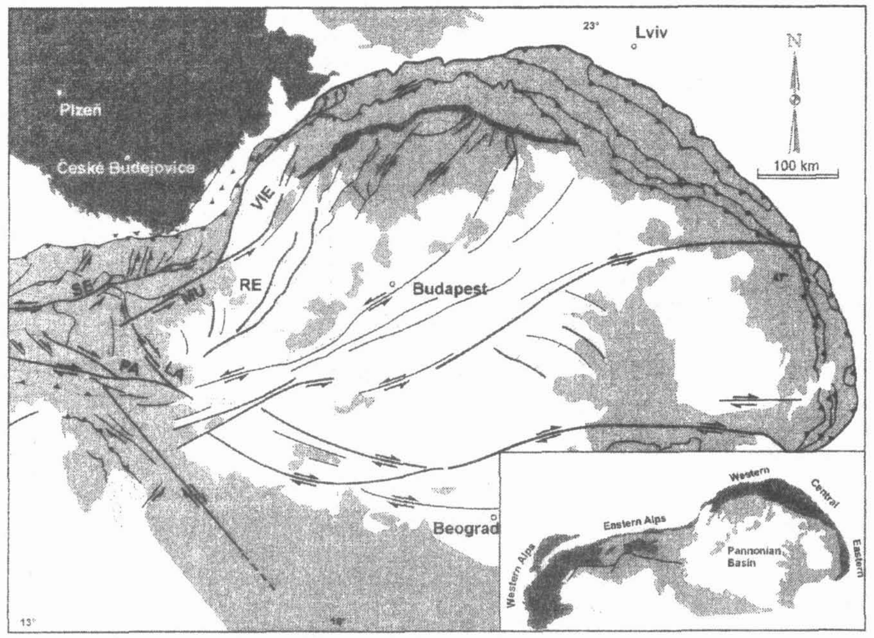


Figure 17. Tectonic map of the Eastern Alpine-Carpathian-Pannonian area with the most important faults and their Neogene kinematics (Decker, 1996).

Explanations: VIE – Vienna Basin, RE – Rechnitz window; fault systems: SE – Salzach-Ennstal, MU – Mur-Mürz-Leitha, PA – Peri-Adriatic system, LA – Lavanttal.

4.

NEOGENE BASIN SYSTEMS IN THE ALPINE-CARPATHIAN-PANNONIAN JUNCTION AREA

The largest basins, situated in the Eastern Alpine-Western Carpathian-Pannonian junction zone, are the .Vienna and Danube basins (Fig. 18). They can both be characterized as intramontane depressions, recently separated by horsts of the Malé Karpaty Mts. and Leitha Hills. Nevertheless, till the Middle Miocene they had a common evolution (Kováč et al., 1988, 1993a, b, 1997a, b). The maximum thickness of sediments is up to 5500 m in the Vienna Basin and over 8500 m in the Danube Basin (Kilényi & Šefara, 1989).

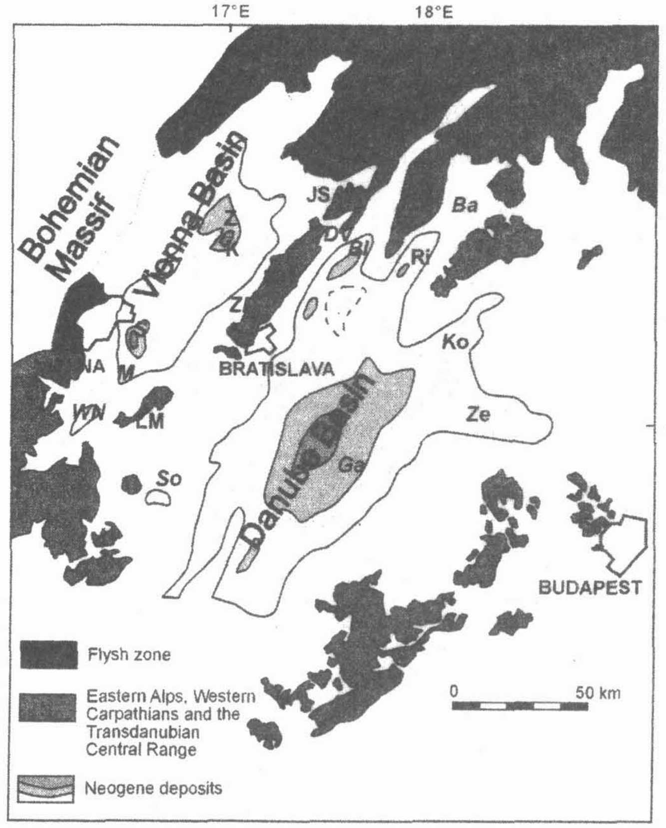


Figure 18. Schematic map displaying the position of the Vienna and Danube basins in the Alpine-Carpathian-Pannonian junction zone (Lankreijer et al., 1995).

Explanations: MK – Malé Karpaty Mts., PI – Považský Inovec Mts., Tr – Tribeč Mts, LM – Leitha Mts.
Vienna Basin: WN – Wiener Neustadt Basin, M – Mitterndorf Graben, S – Schwechat Depression, Z – Zistendorf Depression, K – Kúty Furrow, JS – Jablonica-Senica Depression, ZP – Zohor-Plavec Graben, DV – Dobrá Voda Depression.
Danube Basin: Ba – Bánovce Depression, Bl – Blatné Depression, Ri – Rišňovce Depression, Ko – Komjatice Depression, Ze – Želiezovce Depression, Ga – Gabčíkovo Depression.

The **Vienna Basin** (Dolnomoravský úval Valley, Záhorie Lowland and Vienna Basin) represents a transtensional pull-apart basin including systems of depositional lows and highs. The elevated blocks along the western and eastern margins of the basin are separated from deep depressions by faults with a considerable movement amplitude (Fig. 19). In the central part of the basin, a sigmoidal elevated zone diminishing southward and northward occurs (**Spannberg-Matzen Ridge** – Wessely, 1988; Sauer et al., 1992).

The Pre-Neogene basement of the north-western parts of the Vienna Basin comprises the Eastern Alpine and Outer Carpathian Flysch Zone, forming the accretionary prism at the paleo-Alpine orogene front (Eliáš et al., 1990). The basement of the central and north-eastern part of the Vienna Basin is built-up by nappe complexes of the NCA (Wessely, 1992). The substratum of the eastern margin of the basin is formed by the CWC and CEA complexes, separated from the previous ones by the **Leitha Fault System**.

The **Danube Basin** (comprising the Slovakian Danube Lowland and Hungarian Little Hungarian Plain) comprise in the northern part some smaller basins - depocenters (Fig. 18), forming finger-like promontories between the West Carpathian core mountains. From the west to the east, these are the **Blatné, Rišňovce** and **Komjatice Depressions**. Parallel to the front of the Transdanubian Range in the eastern part of the basin, the **Želiezovce Depression** is situated. The central, deepest part of the basin is called the **Gabčíkovo Depression** (Vass et al., 1990), which, according to seismic data, is as deep as 8500 m (Hrušecký, 1999). The basement relief of the central and southern portions of the basin is characterized by several elevations of NE-SW to NNE-SSW directions, separating the depressions at the western and eastern sides. In Slovak territory it is the **Úľany Ridge** in the southern prolongation of Považský Inovec Mts. horst and in Hungary the **Mihályi Ridge** (Fig. 19).

The pre-Neogene basement of the Danube Basin (Fig. 5) consists of units of the Tatra-Fatra and Vepor Belts of the CWC in its northern part (Fusán et al., 1987). The western part is floored by the Central Alpine units and the SE part by complexes of the Pelso Unit (Fülöp et al., 1987).

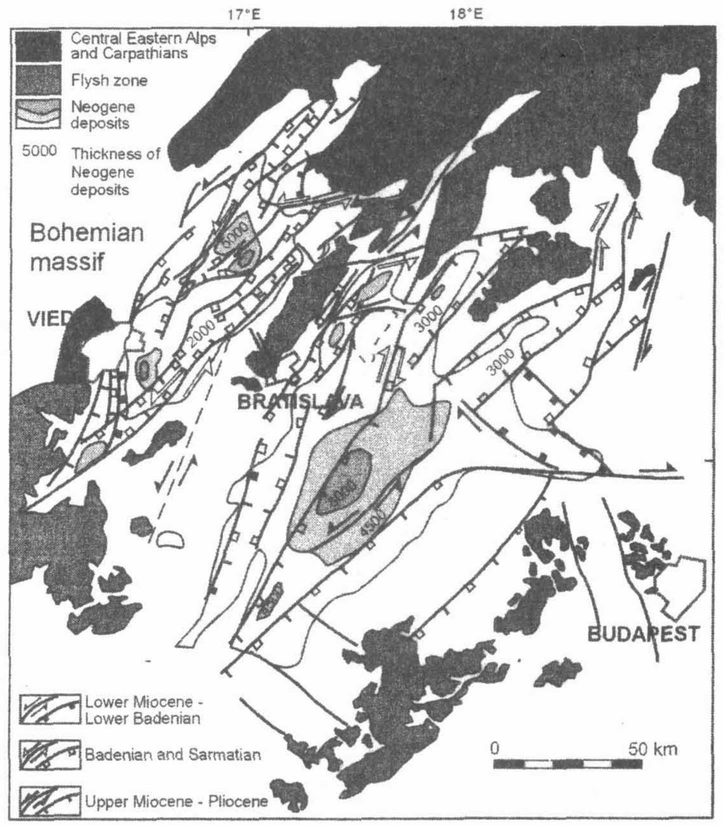


Figure 19. Outline of evolution of the main fault systems and depocenters of the Vienna and Danube Basins (after Lankreijer et al., 1995).

4.1. PALEOGEOGRAPHIC AND TECTONIC EVOLUTION OF THE VIENNA AND DANUBE BASINS

Three main tectonic periods were distinguished in the evolution of the basins, each of them corresponding to a certain tectonic regime and paleostress field orientation. An overall N-S and W-E depocentre migration in these basins (Vass et al., 1988), documents the influence of changing tectonic position of the basins during the Carpathian orogene collision with the North European Platform and the Neogene back-arc rifting. This migration is also reflected in the geothermal gradient that increases from the SE margin of the Vienna Basin toward the centre of the Danube Basin (Král et al., 1985).

Early Miocene

Structural and paleogeographical analysis documents a common Early Miocene evolution of the recent Vienna Basin, northern part of the Malé Karpaty Mts., NW part of the Danube Basin (Blatné Depression) and the Bánovce Depression situated in the east (Kováč et al., 1989a, 1991, 1993a, b, Nemčok et al., 1989, Marko et al., 1990, 1991, Fodor et al., 1990). Opening of Eggenburgian depocentres was controlled by dextral strike-slips oriented in ENE-WSW direction and NW-SE oriented normal faults. Structural reworking of the studied area was also influenced by N-S sinistral strike-slips and NE-SW oriented back-thrusts (Fig. 19). The transpressional regime with a NW-SE oriented main compression axis resulted in small size of the basins and in slow subsidence (Nemčok et al., 1989, Kováč et al., 1989b, Marko et al., 1991, Fodor, 1995).

The **Eggenburgian transgression** (22 Ma), advancing eastward from the Alpine foredeep, crossed the flysch accretionary wedge in the northern part of the present Vienna Basin and from there it extended along the front of the Central Western Carpathians, following the Pieniny Klippen Belt. The northern margin of the E-W trending Lower Miocene basin was built up by elevated flysch nappes of the Magura Group (Kováč et al., 1989a, b). The southern margin comprised the uplifted Alpine and Central Western Carpathian units belonging recently to the basement of the southern part of the Vienna Basin, Danube Basin and Malé Karpaty Mts. (Kováč et al., 1991; Seifert, 1992). The Eggenburgian and Ottnangian sediments of the Vienna Basin overlying the Alpine and Western Carpathian Flysch Zone were deposited in a piggy-back basin. Deposits overlying the Central Carpathian units accumulated in wrench-fault furrows (Fig. 20).

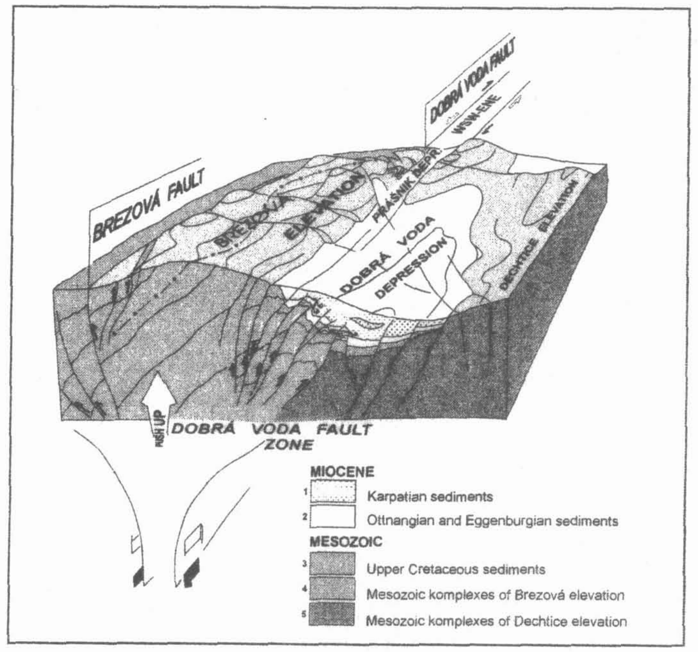


Figure 20. Outline of origin of the Dobrá Voda Depression as a wrench-fault-furrow along ENE-WSW trending faults (Kováč et al., 1989b).

At the end of the Lower Miocene, during the **Karpatian** (17.5 Ma), important paleogeographical changes took place in the zone between the Eastern Alps and Western Carpathians. In the Eastern Alps, the final north-vergent nappe overthrust at the orogen front came to halt. Unlike this area, foreland-ward advancement of the accretionary prism of the External Western Carpathian still continued, having been induced by subduction-collision processes (Tomek & Hall, 1993). NE-ward extrusion (escape) of the Central Western Carpathian lithospheric fragment initiated activity of a large NE-SW directed wrench zone at that time, within which the Vienna pull-apart basin opened (Nemčok et al., 1989; Vass et al., 1990; Kováč et al., 1993a; Decker et al., 1993, 1994; Fodor, 1995). This evolutionary period was characterized by the N-S oriented principal compressional axis of the paleostress field, which was registered also in the NW portion and on the western flanks of the Danube Basin (Fig. 19).

Sinistral horizontal displacements played the principal role in the evolution of the Karpatian Vienna Basin (Figs. 19 and 21), particularly along the Malé Karpaty Mts. and the Magura nappe front (Roth, 1980; Fodor et al., 1995). At that time, the subsidence rate increased and the basin extended southwards. Pelitic-psammitic sediments of the basinal facies exceed 2000 m thickness in the central and northern portions of the basin (Špička, 1969; Jiříček & Seifert, 1990). Southwards, these sediments pass into psammitic-pelitic, upward thickening facies, covered by large fluvial-deltaic conglomerate fans of the *Aderklaa Formation*, an equivalent of the more northerly deposited *Jablonica Conglomerates* (Kováč, 1986; Wessely, 1988).

In the northern part of the Danube Basin, NE-SW oriented sinistral strike-slips played the most important role in the pre-Tertiary basement of the western basin margin at that time (Fig. 19). Activity of these faults caused opening of the Blatné Depression and depressions in its central part, along the NW margin of the Transdanubian Range (Hrušecký, 1999). Simultaneously, at the northern part of the recent Malé Karpaty Mts., gradual closure of the Dobrá Voda and Jablonica depressions (now belonging to the northern part of the Malé Karpaty horst structure) took place along the ENE-WSW oriented back-thrusts (Kováč et al., 1993a). In the southern (Hungarian) part of the Danube Basin, N-S

to NNE-SSW oriented listric detachment faults located along the western margins of the basin played the dominant role during opening of sedimentary areas (Tari et al., 1992, Horváth, 1995).

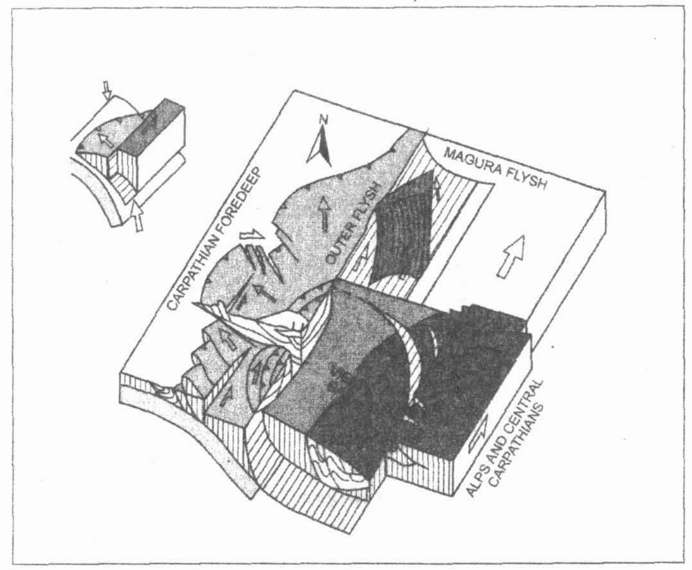


Figure 21. Pull-apart mechanism of the Vienna Basin opening (after Fodor et al., 1995).

In the Danube Basin, the Karpatian sediments are preserved in the NW part in the Blatné Depression area and further at its western margin, in the more southerly situated Sopron area in Hungary. Part of the Karpatian and Lower Badenian terrestrial deposits is also preserved along the Répce and Rába faults, following the western edge of the Transdanubian Range units. In boreholes in the Györ area, the thickness of red coloured sediments reaches up to 500 m. This NE-SW oriented strip of Karpatian and lowermost Badenian sediments continues also into Slovak territory (Hrušecký, 1999).

Middle Miocene

The **Early Badenian** transgression from the Mediterranean area reached the Carpathian region through the Pannonian back-arc basin via the Transdinaric corridor, situated in present day Slovenia. The sea covered the whole Vienna Basin and reached the SE margin of the Danube Basin through the Novohrad area.

The Early Badenian evolution of the Vienna Basin continued under the influence of the N-S oriented main compression axis (Nemčok et al., 1989). Sedimentation represented an independent sedimentary cycle at that time, which was reflected in the marginal parts of the basin by an angular unconformity between the Karpatian and Badenian sediments. The steep morphology of the eastern margin of the basin is documented by thick delta fans, alluvial cones and debris fans up to 400 m thick, deposited on the slopes of the Leitha Hills (Leithagebirge) and Malé Karpaty Mts. during the Early and Middle Badenian (Vass et al., 1988; Sauer et al., 1992).

The oblique collision of the Western Carpathians in the Early Badenian was accompanied by their counter-clockwise rotation (Túnyi & Kováč, 1991). During this period, a break in sedimentation occurred in the NW part in the Blatné Depression of the Danube Basin. In the more southerly situated Želiezovce Depression, the tectonic subsidence was restricted to this period, with a relatively rapid deposition. The opening of the depression was, according to structural analysis, accompanied by a compression oriented in NNW-SSE to NW-SE direction (Vass et al., 1993). The NW-SE oriented normal faults played a principal role in the basin evolution. Some activation of N-S and NNE-SSW directed sinistral strike-slips cannot be excluded, as well as activation of dextral horizontal displacements of WSW-ESE direction (Kováč & Hók, 1993).

During the Middle Miocene, the oblique collision between the North European Platform (Bohemian Massif) and the western part of the Carpathians continued (Jiříček, 1979; Csontos et al., 1992). Movement of the West Carpathian lithospheric fragment turned to the NE, as documented by the principal compressional paleostress vector oriented in NE-SW direction (Nemčok et al., 1989; Csontos et al., 1991). Lower Miocene sediments between the Vienna Basin and the northern part of the Danube basin (Jablonica and Dobrá Voda Depressions) were incorporated into the uplifting horst structure of the Malé Karpaty Mts. (Kováč et al., 1991). Formation of the depocentres in the Vienna and Danube basins during the Middle Miocene was influenced by a transtensional tectonic regime in the back-arc domain (Fig. 6).

Activity of the NE-SW to NNE-SSW oriented normal faults increased mainly in the central parts of both basins (Kováč et al., 1993c). In the depocentres of the Vienna Basin (e.g. Zistendorf, Gajary and Kúty Depressions), pelitic-psammitic Badenian and Sarmatian sediments reach a maximum thickness of 2500 to 3000 m (Jiříček & Seifert, 1990).

At the northern margin of the Pannonian area, the evolution of the depocentres was above all influenced by the ENE-WSW directed sinistral strike-slips and NE-SW oriented normal faults. The Blatné Depression is characterized by a rapid subsidence during the Middle and Late Badenian. In the Rišňovce Depression, an increased subsidence has been recorded in the Sarmatian, whereas in the Komjatice Depression it occurred later, during the Late Miocene. Maximum thickness of **Middle** to **Upper Badenian** sequences of the northern part of the Danube Basin is represented by 2000 to 3000 m thick pelitic-psammitic development (Adam & Dlabač, 1969). During the **Sarmatian**, 600 to 1200 m thick psammitic-pelitic sequences were deposited in the northern portion of the Danube Basin (Biela, 1978). In the central part of the Danube Basin, terrestrial sediments (300–400 m thick) are overlain by the Badenian pelites, coralline algal limestones and sandstones (overall thickness about 200–300 m). Pelitic-psammitic Sarmatian deposits reach a thickness of only cca. 100–400 m, which points to a slowing down in activity of normal and listric faults of the NNE-SSW to NE-SW direction in this period, or to crustal updoming above an astenospheric diapire.

Late Miocene

The **Late Miocene** was characterized by southward shift of the depocentres of the intramontane depressions. This post-rift stage of evolution is characterized by an extensive thermal subsidence, namely in the Danube Basin. At this time, the Vienna and Danube basins were filled with sediments transported by rivers from the Alpine-Carpathian orogen. In deltaic and lacustrine environments, clays and sands were deposited, reaching about 1000 m thickness in the Vienna Basin, whereas in the Gabčíkovo Depression of the Danube Basin they are as thick as 3500 m (Adam & Dlabač, 1969; Jiříček & Seifert, 1990; Vass et al., 1990).

Pliocene

During the **Pliocene**, the uplift of the Eastern Alps and Western Carpathians accelerated, which resulted in erosion of the Miocene sediments in the northern parts of the basins. Subsidence in the central and southern parts led to a further accumulation of fluvial and lacustrine sediments in the Vienna and Danube basins. The best exmples are the Mittendorf and Zohor-Plavec Grabens in the Vienna Basin and the Gabčíkovo Depression in the Danube Basin, where the Pliocene sediments are up to 1200 m thick (Gaža, 1984).

4.2. SUBSIDENCE ANALYSIS AND STRUCTURAL-TECTONIC EVOLUTION

The origin of the Vienna Basin is usually considered as a typical example of upper crustal thin-skinned tectonics with extensional deformation of the Carpathian Flysch Belt nappes and contemporary formation of a pull-apart basin (Royden, 1985). About 50 km of sinistral horizontal displacement along marginal faults of the basin is presumed (Roth, 1980).

The increasing importance of the thermal subsidence with distance from the orogenic thrust front (Royden & Dövényi, 1988) indicates, however, a change from upper crustal thin-skinned extension close to the thrust front, to entire lithospheric extension predominantly in the Pannonian back-arc basin. Application of the pure shear model (McKenzie, 1978) may explain the accelerated subsidence due to an extensional phase, whereas the gradually decreasing subsidence could be attributed to thermal basin collapse.

Subsidence analysis of the Vienna and Danube basins (Lankreijer et al., 1995) supports the model of non-uniform, asymmetric extension (Wernicke, 1985), where both crustal and lithospheric extension are present. Crustal extension and transtension were accommodated by horizontal displacements, whereas lithospheric extension utilized a mechanism of reactivation of older deep-seated listric faults (Tari et al., 1992), simultaneously accommodating a rotating paleostress field (Nemčok et al., 1989; Csontos et al., 1991).

Taking into account MOHO depth, lithosphere thickness, heat flow and thickness of the Miocene sediments in the Vienna and Danube basins (Babuška et al., 1987; Meissner & Stegena, 1988; Dövényi & Horváth, 1988; Jiříček & Seifert, 1990; Becker, 1993), the best explanation of the evolution of both basins is a model of low-angle extensional faulting.

Subsidence curves of the Danube Basin are also in accordance with the model of asymmetric extension (Wernicke, 1985), along the SE dipping fault system at the western margin of the basin (Fusán, et al. 1987; Dank & Fülöp, 1990; Tari et al., 1992). Asymmetric extension along this fault system (Fig. 6) also explains the absence of a thermal phase in the Blatné Depression or absence of an initial extensional phase in the more eastern Rišňovce, Komjatice and central Gabčíkovo Depressions.

A block tilting process on an eastward dipping listric fault, as well as along smaller fault branches reaching the surface, has been seismically documented for the evolution of the central and southern parts of the Danube Basin (Györfy, 1992; Horváth, 1995).

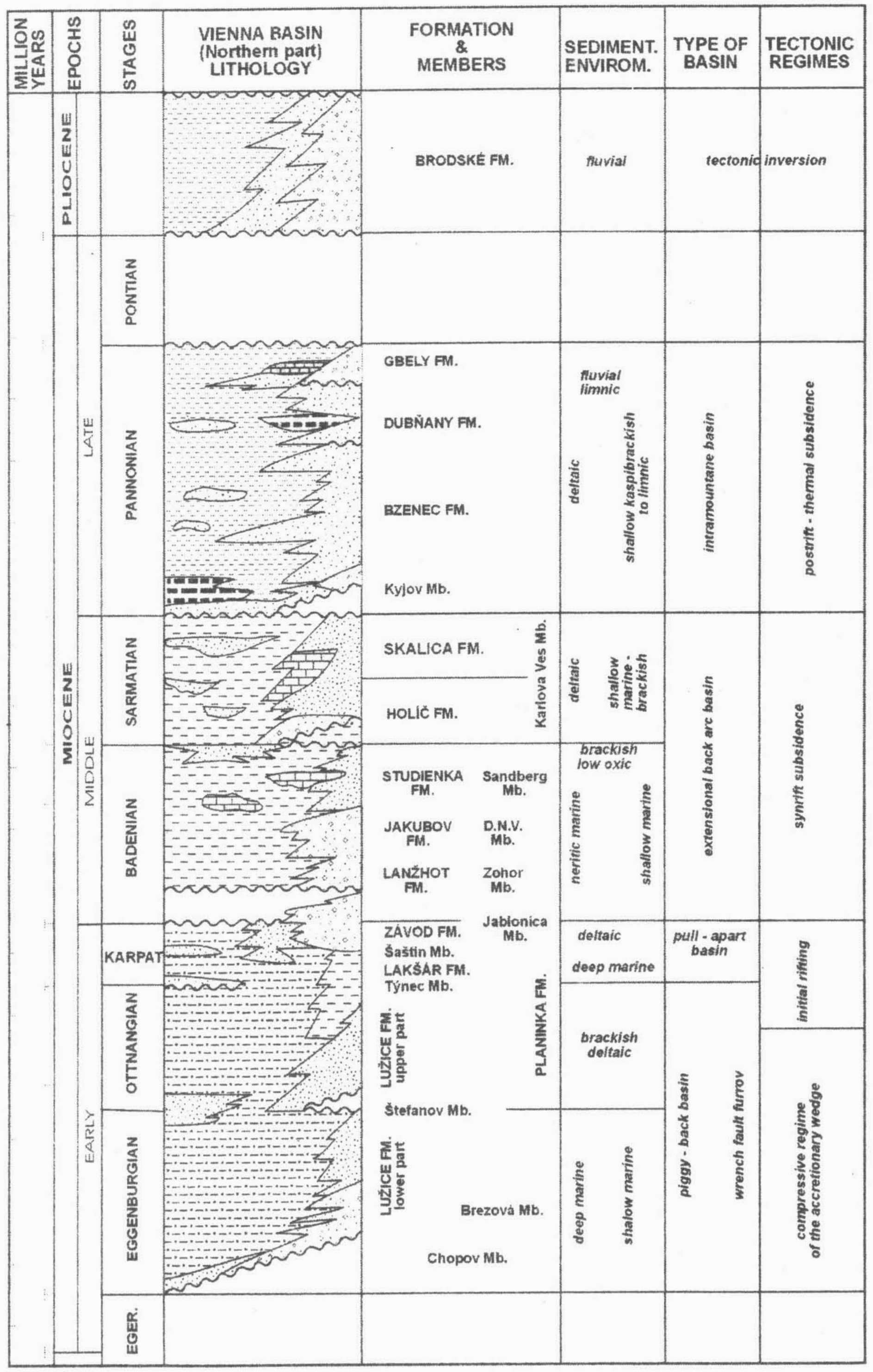


Figure 22. Lithostratigraphy and tectonic evolution of the Vienna Basin.

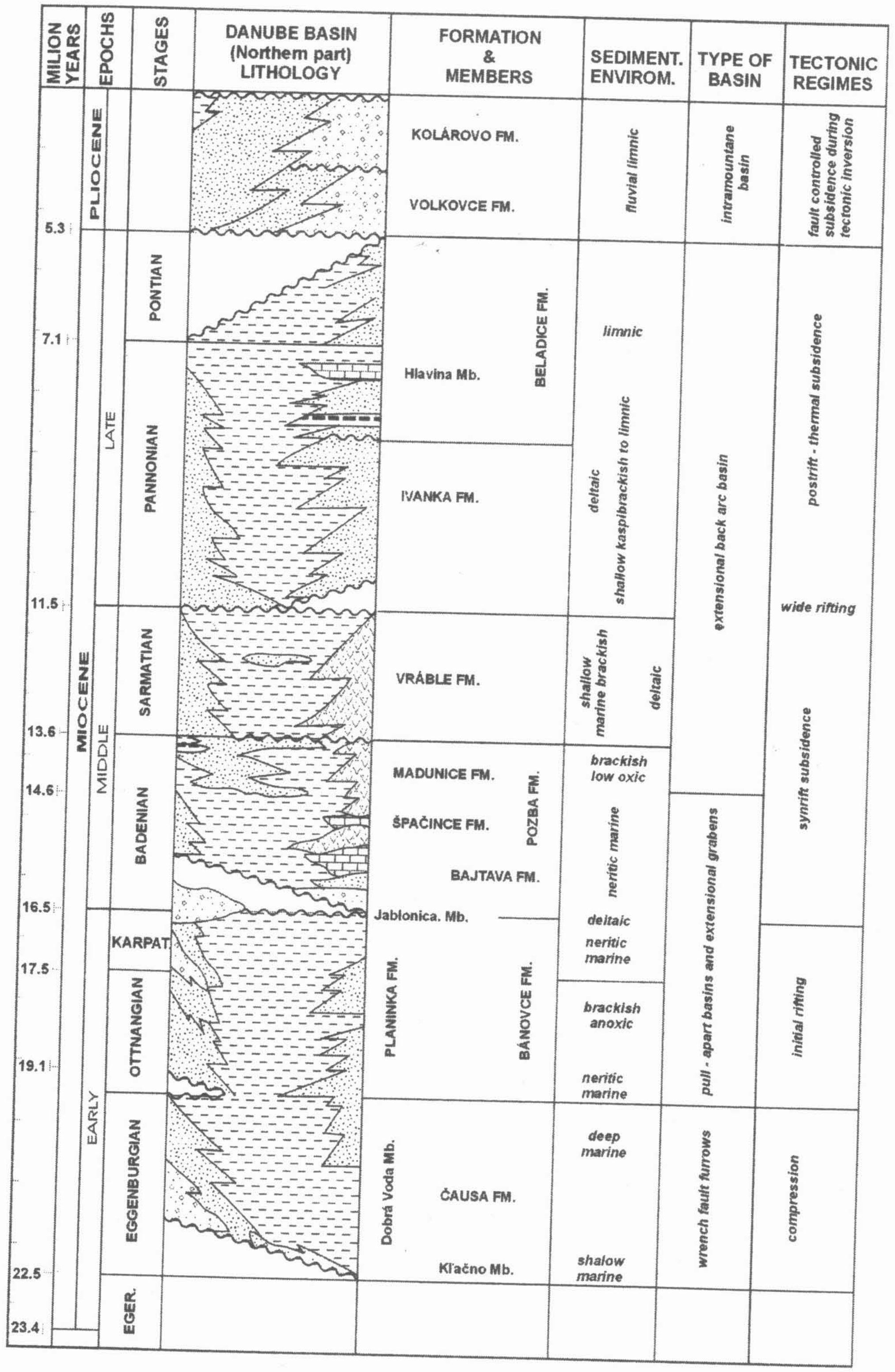


Figure. 23. Lithostratigraphy and tectonic evolution of the Danube Basin.

5.

NEOGENE VOLCANIC COMPLEXES

Tertiary volcanics with a clear affinity to the subduction process in the External Western Carpathians and to the back-arc extension connected with the astenospheric updoming, are situated along the inner side of the mountain range. These calc-alkaline and alkaline neovolcanics form volcanic, subvolcanic to intrusive, basaltic, intermediate to acid magmatic rocks and their pyroclastics of Neogene to Pleistocene age (Fig. 24a, b).

Based on the age, spatial distribution and geochemical-petrological character, four basic genetic types of neovolcanics have been be distinguished (Konečný et al., 1983; Konečný & Lexa, 1984; Lexa et al., 1993).

5.1. AREAL TYPE OF DACITIC TO RHYOLITIC VOLCANISM

Areal type of dacitic to rhyolitic volcanism (Eggenburgian – Early Badenian). It represents relatively widespread covers of tuffs and ignimbrites with groups of extrusive dome in the source areas. Their thickness varies from tens to hundreds of meters, exceeding 1000 m in the central part of the Pannonian Basin. From the petrological point of view, they originated from crustal anatectic melts due to overheating of the continental crust as a result of mantle updoming in the extensional lithospheric regime.

5.2. AREAL TYPE OF ANDESITIC VOLCANISM

Areal type of andesitic volcanism (Early Badenian – Early Pannonian). This type covers the largest area and involves several stratovolcanoes with alternating effusive and extrusive volcanic rock types. Some stratovolcanoes are also buried below the younger infill of the Danube Basin. This type of volcanism appeared during the Early Badenian in the western and north-western part of the Pannonian Basin. In the Central Slovakian Neovolcanic area it continued in several stages till the Early Pannonian. Petrographically, the pyroxenic-amphibole andesites and their pyroclastics are dominant. Since the Sarmatian, acid volcanic rocks of rhyolite to rhyodacite composition occurred as well (*Jastrabie Formation*). This calc-alkaline, mainly intermediate volcanism, may be related to the subduction of the oceanic basement of the Magura Zone of the External Western Carpathians under the continental Tatric-Veporic plate.

This stage of the calc-alkaline volcanism is associated with the main portion of the ore veins, stockworks and metasomatic ore deposits of noble metallic (Au-Ag), polymetallic (Ag-Cu-Pb-Zn) and low-temperature (Sb-As) types, as well as numerous deposits and occurrences of industrial minerals (secondary quartzites, perlites, opals, clay minerals and building-stones).

5.3. ANDESITE ARC-TYPE VOLCANISM

Andesite arc-type volcanism (Late Badenian – Sarmatian). Its products are sparely distributedalong the Pieniny Klippen Belt (Horné Sŕnie, Pieniny Andesite Line in Poland); in Moravia they are also found in the Flysch Belt (Uherský Brod). Larger occurrences are found in eastern Slovakia (Slanské vrchy Mts., Vihorlat Mts.), where they formed a chain of stratovolcanoes. Basaltic and pyroxenic andesites (with trachybasalts) resulted from subduction of the Krosno-Moldavian oceanic crustal substrate of the External Western Carpathians.

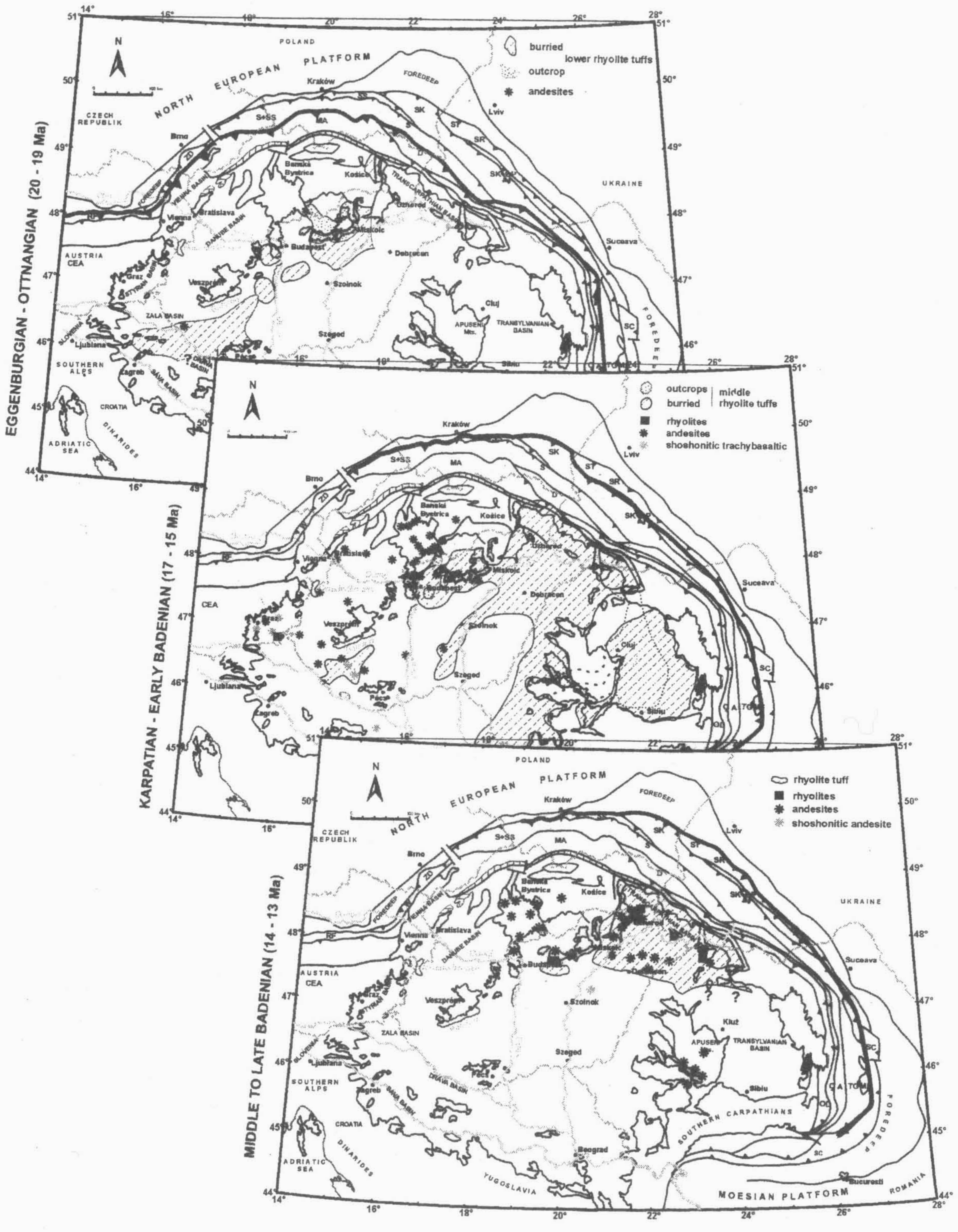


Figure 24a. Early to Middle Miocene volcanism in the Carpathian- Pannonian region.

5.4. Post-orogenic alkaline-basaltic to basanitic volcanism

Post-orogenic alkaline-basaltic to basanitic volcanism (Pannonian – Pleistocene). It represents relatively small occurrences of basaltic volcanics involving diatremes, maars, scoria cones and lava flows. This type of volcanic activity started in the Burgenland area in the west during the Pannonian and continued through the Danube Basin and Transdanubian Range as far as the South Slovakian-

North Hungarian (Novohrad) Basin. Its Pliocene to Pleistocene occur are known in the area from Fiľakovo to Salgótarján, as well as in the vicinity of Zvolen, Nová Baňa and Banská Štiavnica. The lava flows and a scoria cone overlying the Hron River terrace near Brehy at Nová Baňa appears to be the youngest example of the volcanic activity. Their age has been determined as ca 530 Ka (Šimon & Halouzka, 1996). Geotectonically, they are regarded as products of a post-orogenic extensional stage, characterized by mantle updoming connected with penetration of the basaltic magmas, through fault-weakened zones of the thinned crust up to the surface.

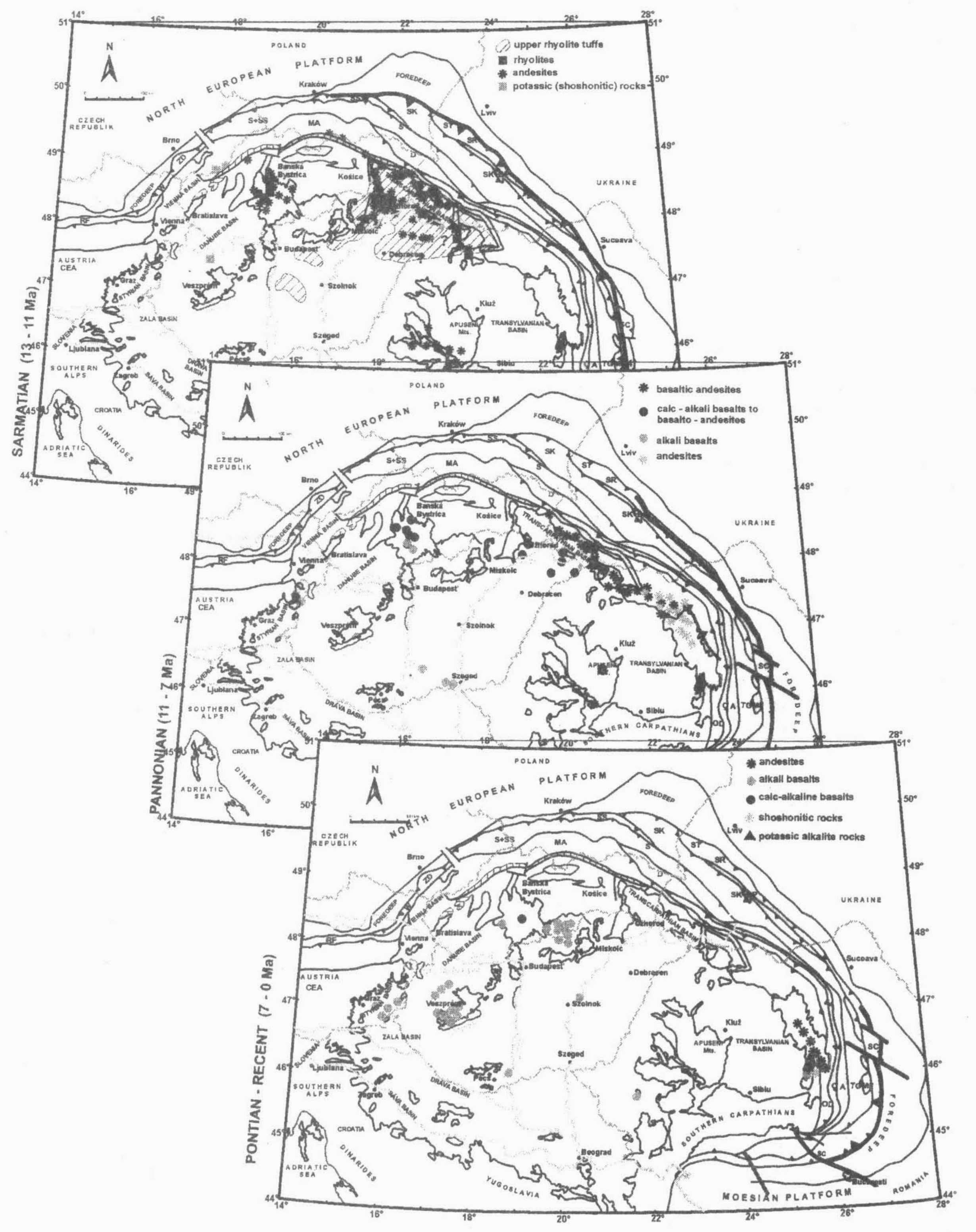


Figure 24b. Late Miocene to Quaternary volcanism in the Carpathian- Pannonian region.

6.

QUATERNARY OF THE WESTERN CARPATHIANS IN RELATION TO THE EASTERN ALPS AND PANNONIAN BASIN AREA

Quaternary deposits in the western part of the Carpathians, as well as in neighbouring parts of the Eastern Alps and the Transdanubian Central Range, occur mostly in intermontane depressions and in river valleys. The fluvial accumulation is mostly displayed in terrace development (river terrace systems). In the mountains (so called the mountain Quaternary), the Quaternary is less represented (less dissected slope and alluvial deposits). The highest mountains (in Slovakia – the Tatra and Low Tatra Mts.) form an exception, in that the Pleistocene glaciers resulted in larger glacier Quaternary features (valleys with stone/boulder moraines, gravely sands, and sandy gravels of glacifluvial fans or terraces).

The places with the largest Quaternary accumulations are the areas geologically belonging to Pannonian Neogene Basin System, i.e. lowlands and lowland depressions on the Alpine-Carpathian orogenic margin (Fig.25). The Quaternary deposits here are quite extensive. They consist of relatively thick deposits which are locally continuous, genetically and stratigraphically miscellaneous and divided.

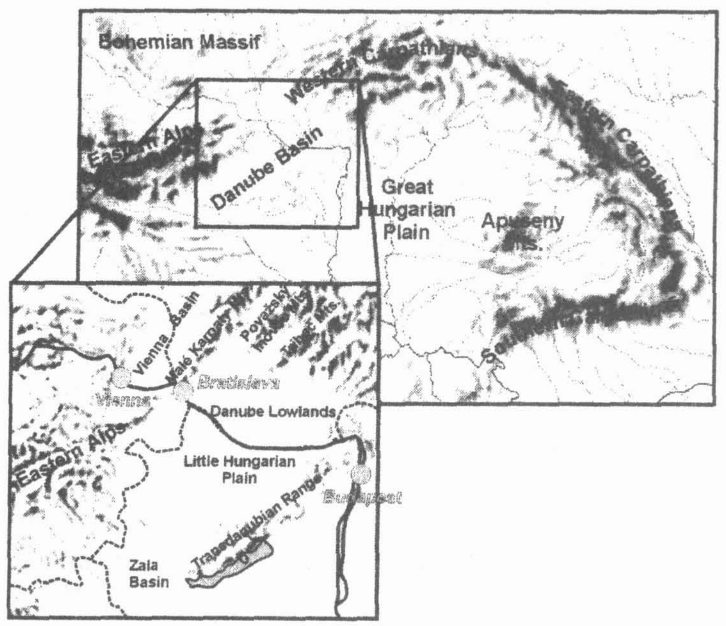


Figure 25. Map of the East Alpine-West Carpathian-Pannonian junction area (1:1000 000)

6.1. LITHOGENETIC TYPES OF QUATERNARY IN THE ALPINE-CARPATHIAN-PANNONIAN JUNCTION ZONE

Glacigenic type represents the Pleistocene valley glacial sediments in the form of moraines, mostly from the last glacial period (moraine lines are mostly preserved). The sediments are mostly poorly sorted, and consist of very course stone-chips (or rocks) up to subangular boulders (or blocks), always mainly poorly rounded (angular to subangular). Pebble material from older glaciations is a little smoother and deeply weathered. In Slovakia, the most important glacigenic deposits are in the valleys

of the High Tatra, West Tatra and Belá Tatra Mountains; in the Low Tatra Mts., they are only found in the highest valleys, mainly on the northern slopes, less on the southern slopes.

Glacifluvial type represents fore-glacier alluviated accumulations from glacier valleys, deposited in valleys or on their mostly depressional forelands of mountains. Sediment material is locally variable in grain size, rounding and composition, and consists mainly of subangular coarse gravels, very coarse pebbles and boulders, sometimes with angular-subangular blocks. This type of deposit is found in the High Tatra Mts. (mainly on its southern foreland – in the Poprad Depression and in the eastern part of Liptov Depression); in the West Tatra Mts. (mainly on its southern foreland in the central part of the Liptov Depression and to a lesser extent in the northern foreland of Roháče Mts., in Zuberec-Habovka Depression in Orava territory). Other occurrences are found in the Low Tatra valleys (mainly the northern foreland in the central part of the Liptov Depression and some on its southern foreland in the central part of the upper Hron Valley).

Fluvial type of Quaternary deposits in the Carpathians and in the Eastern Alps is mostly related to intermontane depressions and river valleys (with dominant river terraces). In the lowlands of the examined area - (1) in the Vienna Basin Dolnomoravský úval Valley to Záhorie (Bor) Lowland, and (2) in Danube Lowland and Little Hungarian Lowland, they occur as terraced open river valleys, as well as superimposed (colmatational) sequences. In the central (Gabčíkovo) depression of the Danube Lowland's basin (the only active basinal development of the alluvion during the whole Quaternary until Recent time in Slovakia), there the maximum thickness of Quaternary fluvial deposits is up to 500 m.

The terrace development of fluvial sedimentation was often influenced by the climate. *The superimposed colluvial (or colmatational) development* (depression and basinal) is usually induced (directly or indirectly) by neotectonic vertical movements on faults. Lithologically, the fluvial sediments (from Pleistocene glacial and cool periods) represent mainly various, well-sorted gravels and sands, of variable grain-size, from subangular (angular) through poorly rounded to rounded pebbles. In grain size they can be as large as boulders or blocks (Danube).

The main **river terrace systems** of the Eastern Alpine-West Carpathian-Pannonian junction zone are *in the valleys of the river Danube and its tributaries (lowlands of Vienna and Danube Basins)*.

In Austria, well developed terraces stretch from the Vienna Basin: valley section from "Vienna Gate" in the Vienna Forest (Wienerwald) in Vienna, on both sides of the river as far as the Lower Pleistocene terraces on the boundary between Alps (Leitha Hills) and the Carpathians (Hainburg Hills) and the "Carnuntum (Bruck) Gate" near Parndorf (Parndorfer Platte). The Plenipleistocene deposits of the Danube on the Austrian/Slovak boundary continue on the right bank of the Danube to "Devín Gate" in the Malé Karpaty Mts. (Hainburg, Wolfsthal, to Berg and Kittsee). From Kittsee the low terrace and the youngest middle Danube terrace turns southward and follow the margin of Little Hungarian Lowland. The course of the terraces, which form a lateral wedge into subsiding colmatational fluvial sedimentary development of the Danube in the Hungarian part of the Danube Basin, follows the foothills of the Parndorfer Platte and then crosses the horst, separating the Little Hungarian Lowland and the Holocene depression of the Neusiedl Lake (Neusiedler See) and See-Winkel.

In Slovakia, the Danube terraces form a continuation of the Austrian development in the west (in Bratislava). An important fact is, however, that the earliest known terraces in the Bratislava area (Premindel, Lower Pleistocene) do not belong to the Danube ("Danube Gate" in Bratislava – i.e. present "Devín Gate", as a fault gap which opened as late as in the Cromerian period, i.e. 0.6 Ma ago), but they belong to a former river issuing from the Záhorie Lowland (river basin of ?*Dyje* = *Thaya*). They consist of high terrace accumulations in Lamač-Karlova Ves fault gap (Karlova Ves – Mlynská dolina area) and include similar aged high terrace steps near Devín. Sediments of Plenipleistocene small terrace accumulations in the Devín "depression" indicate the *Morava River* origin (only the two youngest steps are marked by Morava-Danube mixed rock material).

The younger (Plenipleistocene) and real *Danube* terraces on the left river bank are to be found in the southern tip of Záhorie Lowland and mainly at "Devín Gate" (terraces in Devínska Nová Ves and in the section Karlova Ves – Mlynská dolina). Only the middle and low terraces extend as far as the edge of the Danube Basin in the central part of Bratislava City; as well as a low terrace on the right river bank in Petržalka (along the state frontier to the west of Jarovce and Rusovce).

Other Plenipleistocene Danube terraces were formed more recently, after the river has forced its way though the central Gabčíkovo Depression of the Danube Basin (with basinal suprapositional sedimentation). On Slovak territory, they are formed on the left river bank in the section Marcelová-Štúrovo-Chľaba.

In Hungary, the Danube terraces of the same age (as in the opposite left bank) were formed on the right river bank in the section Dunaalmás – Esztergom – Szob. They extend as far as Budapest on both sides of the river. However, the Danube provenance of the earliest (high) terrace accumulations in the valley section from Estergom (Kováčov) to Visegrád "gates" is very questionable. South of Budapest, the Danube sediments arose again in colmatational position.

The northern tributaries (Morava, Váh, Nitra, Žitava, Hron) form typical river terrace systems of the Danube of the Vienna and the Danube Basin lowlands. The oldest terraces in Záhorie Lowland were formed probably by the Dyje (Thaya) River. Younger Plenipleistocene terraces on the Austrian/Slovak boundary in the lowlands were formed by the Morava River. Neotectonic evolution (Riss) in the Danube Lowland along the lower course of the Váh River induced formation of middle terraces. On the other hand, the terraces of Hron River, as the only northern tributary in lowland, developed continuously throughout the Pleistocene. They are characterized by complex (migrating) evolution of its outlet into the Danube River. *Of the southern Danube tributaries*, mainly the youngest terraces of Leitha River are known. Colmatational deposition of Danube Basin took place mainly along the Rába River.

Fluviolimnic type of sediments is represented mainly in accumulations of Quaternary deposits in the lower parts the central Gabčíkovo Depression of the Danube Basin (local lithofacies, e.g. Palkovičovo Formation consisting of fine-grained sandy gravels), or in the basal Quaternary formations (Gabčíkovo Sands in the centre of this depression or Cífer Formation in the Blatné Depression).

Proluvial type (variant of fluvial type) represents accumulations of smaller streams in lowlands at the inflection points of their courses. In such cases, terraced or superimposed (initially only ingressive) alluvial fans were formed.

Aeolian (wind-borne) type of sediments are represented by **wind-blown sands**. As an example, the sands of Záhorie Lowland may be mentioned. Their largest cover is concentrated near Bor (centre of the Bor Lowland), where the wind-blown sands are up to several tens of meters thick. Minor occurrences are also found in the dunes in SE part of the Danube Lowland.

The most important aeolian sediment of lowlands and foothills of uplands and hills is ***loess***. Loess accumulations form flat, wind-blown-filling bodies and sheet covers (they "mask" the underlying relief forms). Fossil soil horizons were commonly preserved in the loess which facilitates the use of pedostratigraphy in their age determination. They are predominantly of Upper Pleistocene age, less commonly of Middle Pleistocene age and, locally, even of Lower Pleistocene age. The loess often contains fauna of tiny terrestrial molluscs, that serve as an indicator for paleoecological and paleoclimatic reconstruction. The loess sequences commonly contain so called loess derivatives, e.g. decalcified loess loams and calcareous resedimented loess-like loams (with admixture of different loams). Washed loess contains a characteristic admixture of sand grains and some coarser clastics. Swamp loess (with increased portion of clay grains) was blown into swamps and marshes. As an example, large occurrences of loess on terraces and uplands of Danube Lowland and Little Hungarian Lowland may be mentioned. They are also found in the lowlands of the Vienna Basin (mainly in the Austrian, Marchfeld area), or on the edge of the Carpathians and their intermontane depressions.

The following Quaternary deposits vary in extent:

Deluvial-gravitational type consists of sediments formed by fine-grained and coarse-grained regolith, undergoing planar transport downslope (coarser clastics, even linear), by slope shaping processes. Falling due to gravitation and washing (with water agent), are the main processes, i.e. without participation of cryogenic (periglacial) processes, glacial activity or slope shaping processes of catastrophic intensity. Washing and falling results in formation of slope loams or variable debris (stone-loamy, loam-stony, stony). They form covers, debris cones and taluses, stone and block fields.

Polygenetic and periglacial sediments. Among them, mud flows (loam-stony) and solifluxion sediments (mud tongues) can be ranked. The results of high-intensity slope-shaping processes are ***landslide deposits*** from the surface and base of sliding slope deformations.

Chemogene-organogenic sediments e.g. travertines, calcareous sinters and tuffas in Slovakia are seen mostly in the Spiš area (Vyšné Ružbachy, Gánovce etc.), Liptov area (e.g. Liptovský Ján, Bešeňová, Lúčky etc.), Horná Nitra area (Bojnice), Zvolen Depression (Sliač), or Ipeľ Upland (Dudince, Santovka, Levice and others). In Hungary, the important travertines are in the Transdanubian central Range (near Dunaalmás, Vértesszőlős, etc.).

Organic sediments consist of humolites – peats and fen peats (peaty loams, fen peat muds). In Slovakia there are peat bogs in the Orava Depression (Suchá Hora, Bobrov peat ex-site on Čierna Orava River), Liptov area (Liptovský Ján, etc.), in the foreland of High Tatra Mts. (Poprad Depression – Spišská Teplica, Spišská belá and others). They are also found in the Danube Lowland (the marsh at Jurský Šúr, a former lake; fen peats from former river-arms swamps in Žitný ostrov "Island", a similar area of former river arms - the "Dead Hron" at the Hron-Danube confluence near Štúrovo; the large swamps of Paríž Brook near Gbelce on Hron Upland etc.) and the Záhorie Lowland (Cerová). In Austrian territory, the fen peats in the Vienna Basin are known (swamps of Moravian Field, Marchfeld) and, also at the edge of the Danube or Pannonian Basin (marshes and swamps in the See-Winkel area near Neusiedl Lake, Neusiedler See). In Hungarian territory, there are similar areas of marsh and swamp in the Little Hungarian Lowland (Kiss Alföld, mainly in the Hanság area).

Quaternary **volcanics (lavas and volcanoclastics)** are found in Slovak territory (basalts) on the margin of Štiavnica Stratovolcano (Brehy, Ostrá Lúka) and in the Cerová vrchovina Hills. In Hungarian territory, the basalts of the Salgóvár Volcanic Complex and Bér Complex in the Transdanubian Central Range are of Lower Pleistocene age; basalts of Plio-Pleistocene age (?) are found on the north coast of Balaton Lake (SW tip of the Bakony Hills).

6.2. QUATERNARY STRATIGRAPHY

Quaternary stratigraphy has undergone an intense development in the last decade. Recent knowledge enabled relative agreement on the Pliocene/Pleistocene boundary, as well as stratigraphic scales of Pliocene and Pleistocene (namely the Lower Pleistocene). Stratigraphic progress was due to wide corelation and utilization of physical dating methods (magnetostratigraphy, geochronology and radiometric age determination). However, a synthesized overview of the actual correlation between stratigraphic scales and Quaternary geochronology (namely Pliocene and Lower Pleistocene) is still lacking in the literature. Therefore, we introduce a graphic overview of this parallelization, integrated with study of regional stratigraphy (division) of the Slovak Quaternary (Figs. 26, 27).

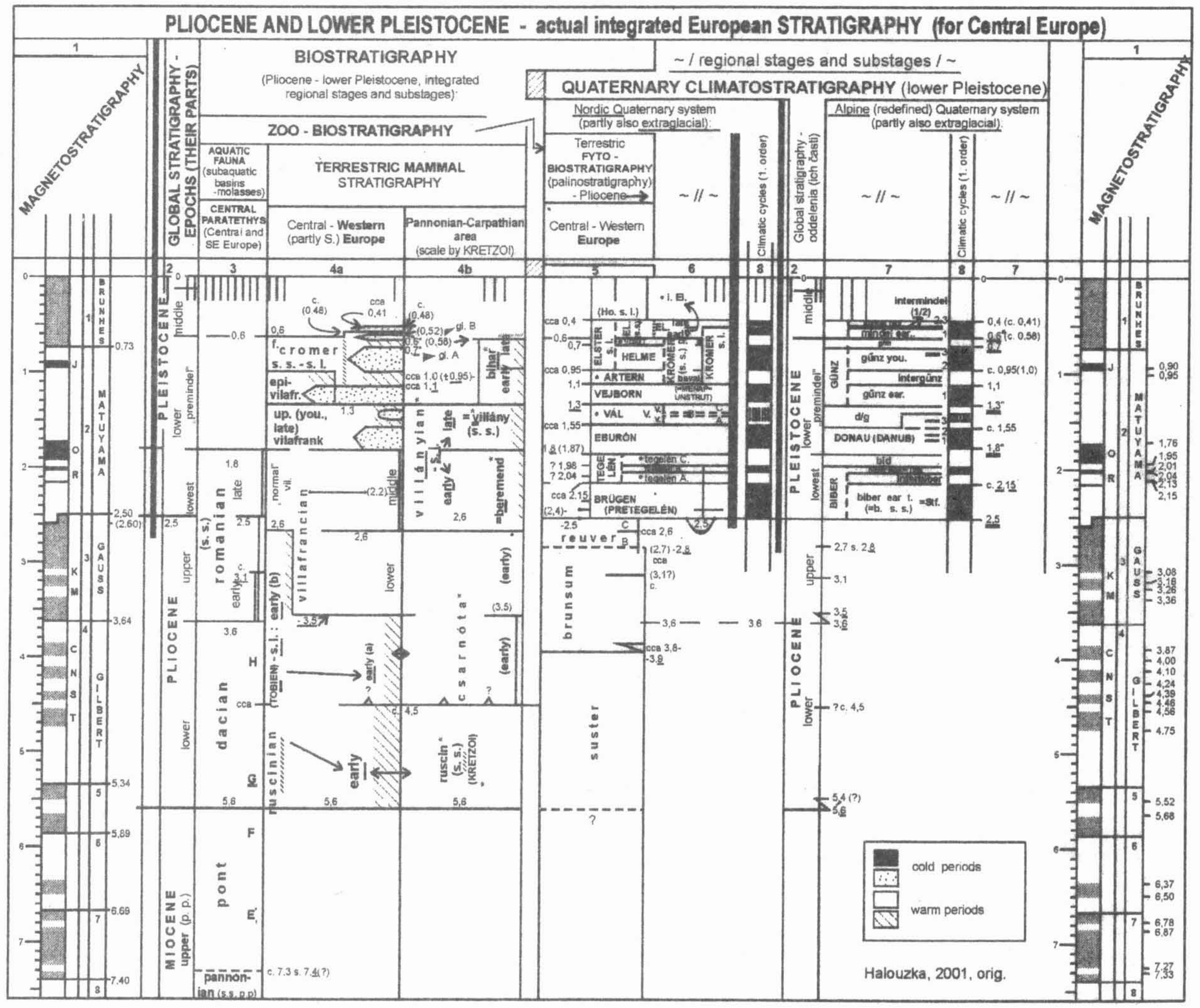


Figure 26. Pliocene and Lower Pleistocene; actual integrated European stratigraphy (Halouzka, 2000 – 2001, orig.)

Quaternary stratigraphic division of the examined area is based on *glacial stratigraphy* (glacigenic and glacifluvial sediments), *fluvial stratigraphy* (fluvial and fluviolimnic sediments, used also for wind-blown sands and loesses, deluvial deposits, as well as travertines and peats); and special *loess stratigraphy* (utilizing *pedostratigraphy* of fossil soils and *ecological biostratigraphy* on the basis of mollusc fauna of terrestric gastropod asemblies), with detailed division of Upper Pleistocene (similar to glacial stratigraphy). *Palynostratigraphy* plays a crucial role from the point of view of peat stratigraphy and other Holocene and Pleistocene organic sediments.

Glacial stratigraphy of the Tatra region (correlated with Polish territory) revealed *4 Pleistocene glaciation periods* (the last, the penultimate and the maximal one and one with so called old glaciation). Further *2-3 oldest glaciations* are indicated indirectly by existence of oldest alluvial terraces and fans with glacifluvial-like sediments, containing material from High Tatra valleys. Three generations of their terrace accumulations overlay the Paleogene basin foreland of the mountains. A complete overview of glacial stratigraphy (the stages) of Slovakia is given in tables (Fig. 28).

Fluvial (basic) stratigraphy is based on age determination of fluvial and other related sediments and their attribution to climatostratigraphic stages reflecting the 1st order of climatic oscillations in the Quaternary. In the field, geomorphological division of fluvial sediments is often utilized (mostly in *terrace formations*, i.e. inversion development). In the Alpine-Carpathian-Pannonian junction area, mainly the European integrated scale of the Alpine system is used mainly, readapted for the extraglacial zone of central and western Europe (Figs. 26, 27, 29). For superpositionally deposited fluvial sediments of Lower, and particularly basal Pleistocene (depressions, basin development), the usual biostratigraphic scale for Central Paratethys basins (regional Pliocene stages – Fig.30), is used.

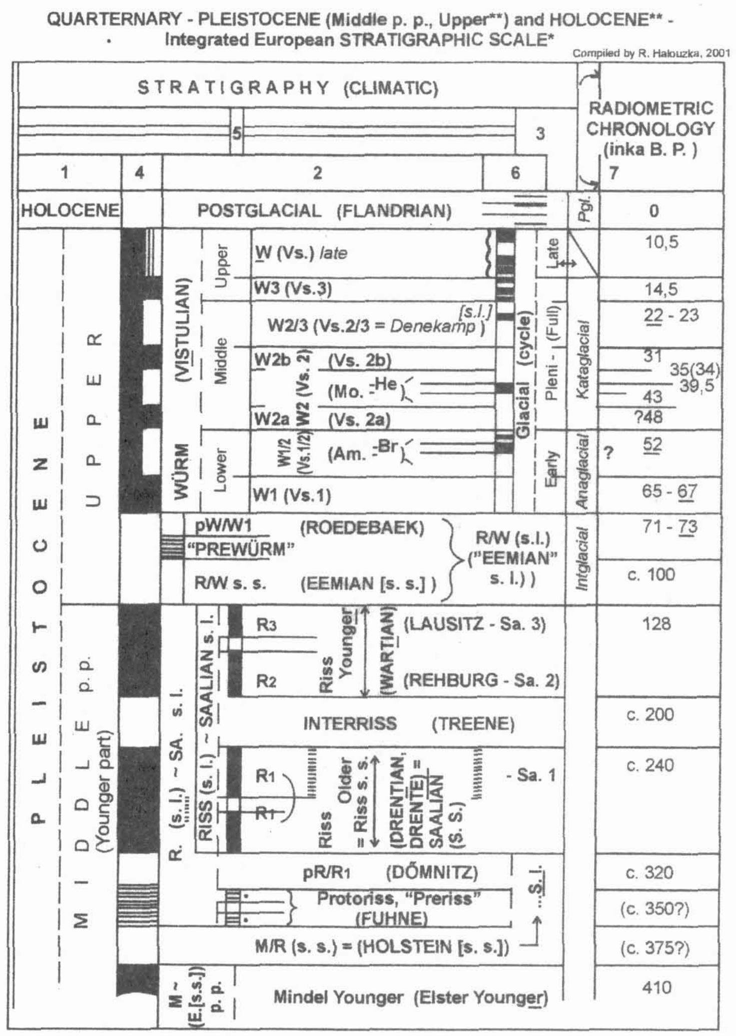


Figure 27. Quaternary – Pleistocene p.p. (Middle, Upper) and Holocene; integrated European stratigraphic scale (Halouzka 2001, orig.)

*/ the both glacial systems in Europe - Nordic and Alpine (redefinated in the extraglacial zone, actually paralelizated and radiometrically dated)
**/ the units for oscillations of the third and fourth order (in Würm and Holocene)

Finds of *fossil mammals* and other vertebrates in fluvial and terrestric sediments can simultaneously be linked to biostratigraphic scales and to the MN zones of the integrated and redefined scale for central and western Europe (in Fig.26 compiled for Upper Pliocene – Lower Pleistocene period in this European region by Halouzka, 2001, mainly according to references, especially according to Fejfar 1976, Fejfar, Heinrich, Lindsay, 1997, Lindsay, 1989, Mein 1989, Suc et al. 1997, Tobien 1970, etc.) or for the regional scale for the Pannonian region (Kretzoi 1969, 1982, Fejfar 1976). As an example, mammal fauna in Quaternary deposits of Slovakia near Strekov in the Hron Upland (Danube Lowland) may be mentioned. In the redefined and integrated "classical" biostratigraphic scale, and according to the MN zones (Mein 1989) (for central and western Europe), the fossil fauna from Strekov is attributed to the MN 17 zone, i.e. to the basal part of Middle

Villafranchian; in Kretzoi's scale for the Pannonian region, it is attributed (analogous to the site Kisláng in Hungary) to basal Beremendian, i.e. to the basis of Lower Villányian. Therefore, it represents the basal part of Slovak Quaternary (in Pretiglian stage).

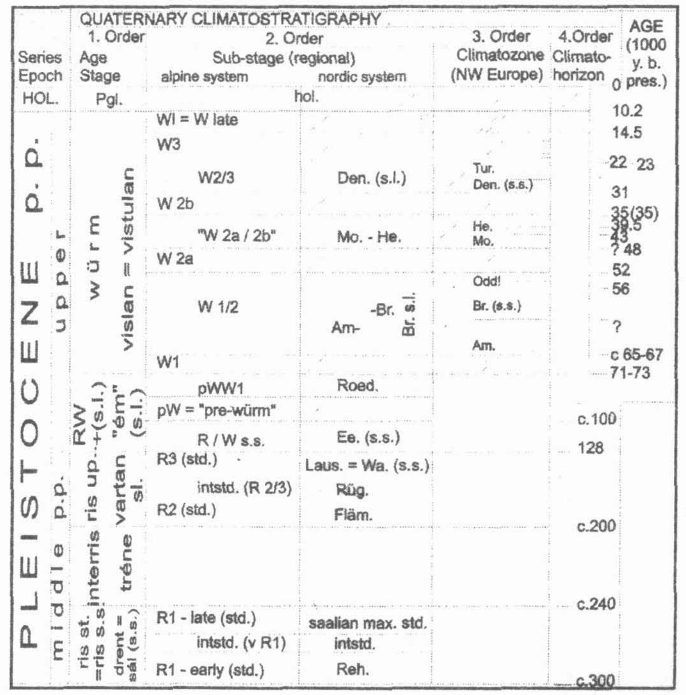
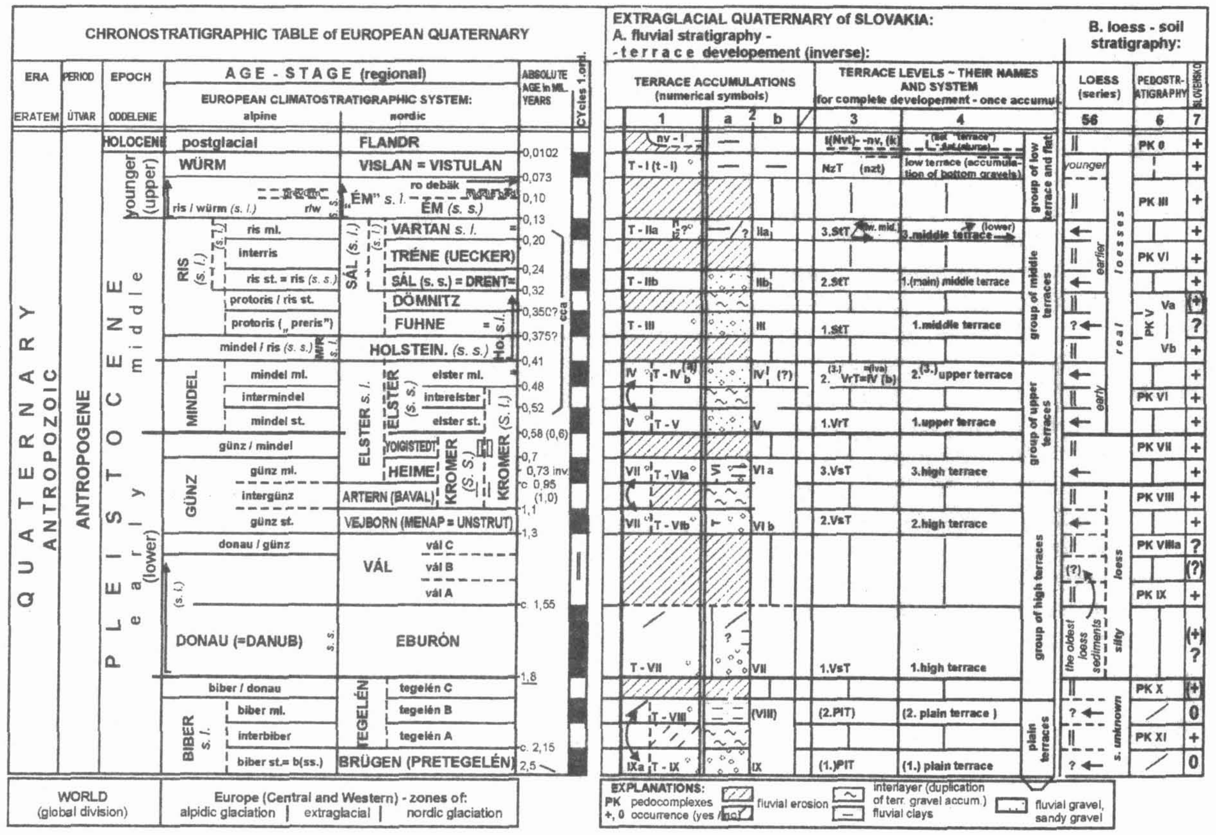


Figure 28. Correlation of European Pleistocene glaciation with Tatra Mts (Reprint from: Halouzka,1992; Halouzka in Schirmer et al., 1995).

Explanations of abbreviations and notes in the table: Pgl. – postglacial; Tur. – Tursac; Den. – Denekamp; He. – Hengelo; Mo. – Moershoofd; Odd. – Odderade; Br. – Brorup; Am. – Amersfoort; Roed. – Roede-baek; Ee. – Eem; Laus. – Lausitz; Wa. – Warta; Rûg. – Rûgen; Fläm. – Fläming; Reh. – Rehburg; std. – stadiál; instd. – interstadiál; pp. – partly; s.s., s.l. – indication of span of the definitions (in parentheses are the original definitions only)

Quaternary – oscilating climatic fluctuations of different orders (corresponding always to climatostratigraphic Quaternary units of the same order) are: 1. order – glacials and interglacials, 2. order – tadials and interstadials (for sections in glacials), resp. so-called calidophfases a frigido-phases (for section in interglacials). Note to categories of 3. order – their species designation (for sections in stadials and interstadials, resp. also in frigidophases and calidophases) with the corresponding categories is nomenclaturally not fixed yet.



EXTRAGLACIAL QUATERNARY of SLOVAKIA: Climatostratigraphical scheme of main succesions of extraglacial sediments of Slovakia (compiled by R. Halouzka, 2000 - 2001)

EXPLANATION OF COLUMNS: (1), (2) - terrace accumulations
(1) - basic type, e.g. once-accumulated, so-called complete (completely differentiated = mountain and cauldron type (intramontane and lowland cauldrons)
(2) - lowland type, mainly twice-accumulated (partly with duplicated accumulations) = type of basinal lowlands
(3),(4) - terrace levels
(3) - abbreviations of names (of terrace levels)
(4) - names of terrace levels and their groups
(5) - succesion of Slovakian loesses (Transdanubia)
(6) - Central European scale (Ložek - Kukla - Smolíková et al.)
(7) - occurrences of loesses and soils in Slovakia

Figure 29. Extraglacial Quaternary of Slovakia - overview of fluvial terrace and loess-soil stratigraphies (Halouzka 2000-2001, orig.)

The updated, selected data of fluvial stratigraphy in Slovakia are shown in tables (Fig. 29). The terrace development documents the river terrace system of the Western Carpathians, valid (with local reduction) also for the lowland terraces of W and SW Slovakia (Záhorie and Danube lowlands) and lowland depressions of southern Slovakia. The stratigraphy of superposition successions of fluvial formations in basin development (Fig. 30), are tabled in the original column for the central Gabčíkovo Depression of Danube Basin in its Slovak part (succession since the base of Quaternary).

Specific to **loess stratigraphy,** is utilization of pedostratigraphic methods for the study of fossil soils in loess sequences. This refers especially to soil micromorphology, determination and analysis of biotopes of mollusc faunas and lithological analyses. At the same time, the results of detailed division of Upper Pleistocene loess sequences mediate the sequence correlation with glacial stratigraphy (i.e. correlated to the first- to second-order climatogenic sequences in both successions).

Synthesis of stratigraphy of so called young loess (Upper Pleistocene loess formation with fossil soil horizons), was compiled on the basis of complex study of numerous instructive profiles in the area of the largest extent of loess in Slovakia, i.e. in the eastern part of the Danube Lowland (Halouzka 1985), together with detailed mapping of Quaternary (Figs. 27, 29).

The oldest loess occurs in the older (Mindel) part of Middle Pleistocene. Loess-like loams (calcareous, pale to clayey-silts) or their analogues of different origin, were found to be as old as the Lower Pleistocene Günz stages (G older). The oldest soils (soil sediments) can be ranked stratigraphically to the D/G interglacial stage, i.e. to PK IX (Svodín, perhaps also Milanovce), without taking into account the undoubtedly older soil (soil sediment) around Bukovec in the upper course of the Ipeľ River, and maybe also, the soil sediment of the Lukáčovce bed (in original position) of Nitra Upland.

6.3. NEOTECTONIC EVOLUTION OF THE REGION (UPPER PLIOCENE – QUATERNARY)

The neotectonic period can be compared with the youngest Cenozoic tectono-sedimentary megacycle, the duration of which dates from Pliocene to Quaternary (Halouzka et al., 1998). Geological data of the Carpathian-Pannonian-Alpine junction area (Slovakia, Hungary, eastern Austria), which is considered to apply to the Bohemian Massif (Czech Republic) as well, show that the latest tectono-sedimentary megacycle in this region started at the beginning of the Pliocene, i.e. at Pontian/Dacian boundary (5.6 Ma B.P.). In the mentioned megacycle, since about the beginning of the Upper Pliocene (i.e. at Dacian/Romanian boundary - 3.6 Ma B.P.), the geological structure of the area turned into "Quaternary" to Recent type. This stage represents a separate *neotectonic era* of Alpine orogen (Halouzka in Maglay edt., Halouzka, Baňacký et al., 1999), see Fig.30.

The neotectonic activity in Slovakia was represented by powerful tectonic movement (also volcanic activity) in several stages. The most distinctive ones were near the beginning of the Quaternary (about 2.5 +/- 0.1 Ma B.P.), then in the Lower Pleistocene (about +/- 1.8 Ma B.P.) and especially at the Lower/Middle Pleistocene boundary (Cromerian period, about 0.7-0.6 Ma B.P.), i.e. about the time of the Matuyama/Brunhes paleomagnetic inversion (Fig. 30).

The neotectonic fault lines differentiated (in various stages of activity) the areas of both systems into their principal structures (neotectonic blocks, positive or negative in mutual relationship), as well as into neotectonic units of a lower order. The dissection of the Pannonian Basin subsystem units (in lowland uplands, plains and in lowland depressions), mainly in the Danube Lowland, was extremely dense. In the West Carpathian subsystem, the neotectonic effect also characterized some of the intermontane depressions (Poprad and Liptov, Orava, Turiec, Zvolen and Slatina Depressions). The reader is referred to the latest publications - to the Neotectonic map of the Danube Region (Wien-Bratislava-Budapest) in 1:200 000 scale, compiled during DANREG project (Halouzka edt., et al., 1998), as well as to the Neotectonic map of Slovakia in 1:500 000 scale and explanations to this map (Maglay edt., et al. 1999).

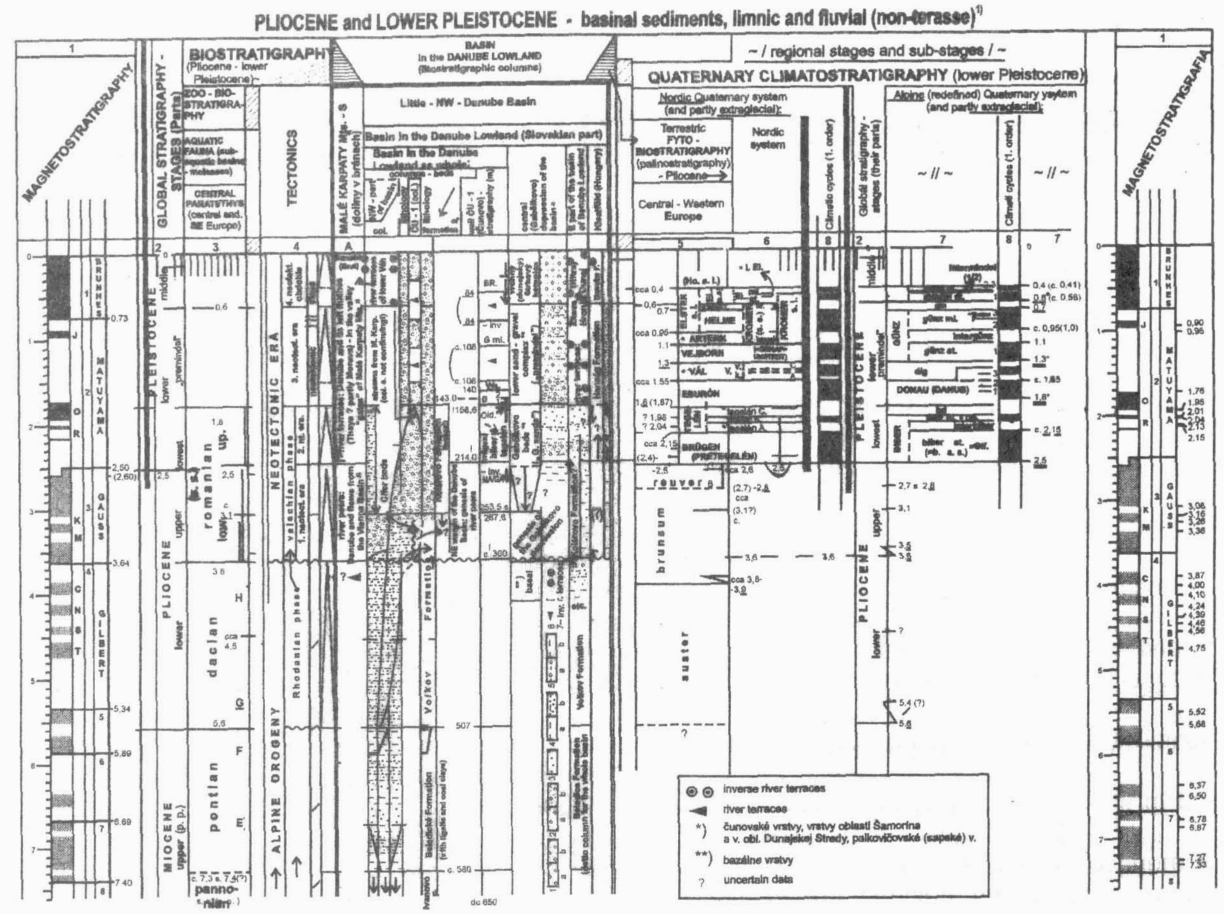


Figure 30. Pliocene and Lower Pleistocene – basinal sediments (limnic and fluvial, non-terrace) in the Danube Basin in Slovakia (Halouzka 2000 – 2001, orig.).

7.

CONCLUSIONS

Lithostratigaphic composition, structural relationships, tectonic position and evolution of principal regional geological units occurring at a junction of the North European Platform (Bohemian Massif), Alpine-Carpathian mountain belt and intramontane Pannonian basin system have been characterized in the present work. Outstanding natural attributes of this area with a peculiar geological structure embracing rock complexes of almost all time levels starting from the Precambrian up to the Quaternary have not allowed us do describe all phenomena and processes in detail, since the extent of this book is limited. Nevertheless, we believe that our overview attempt will find its readers to whom it may serve as a basic information.

Geological structure Alpine-Carpathian-Pannonian junction and the neighbouring slopes of the Bohemian Massif should also serve as an introduction and basis for intended list of important geological localities in this area, as a tool for organization of geological excursions for students of all the four concerned universities, as well as for other universities and occasional scientific meetings.

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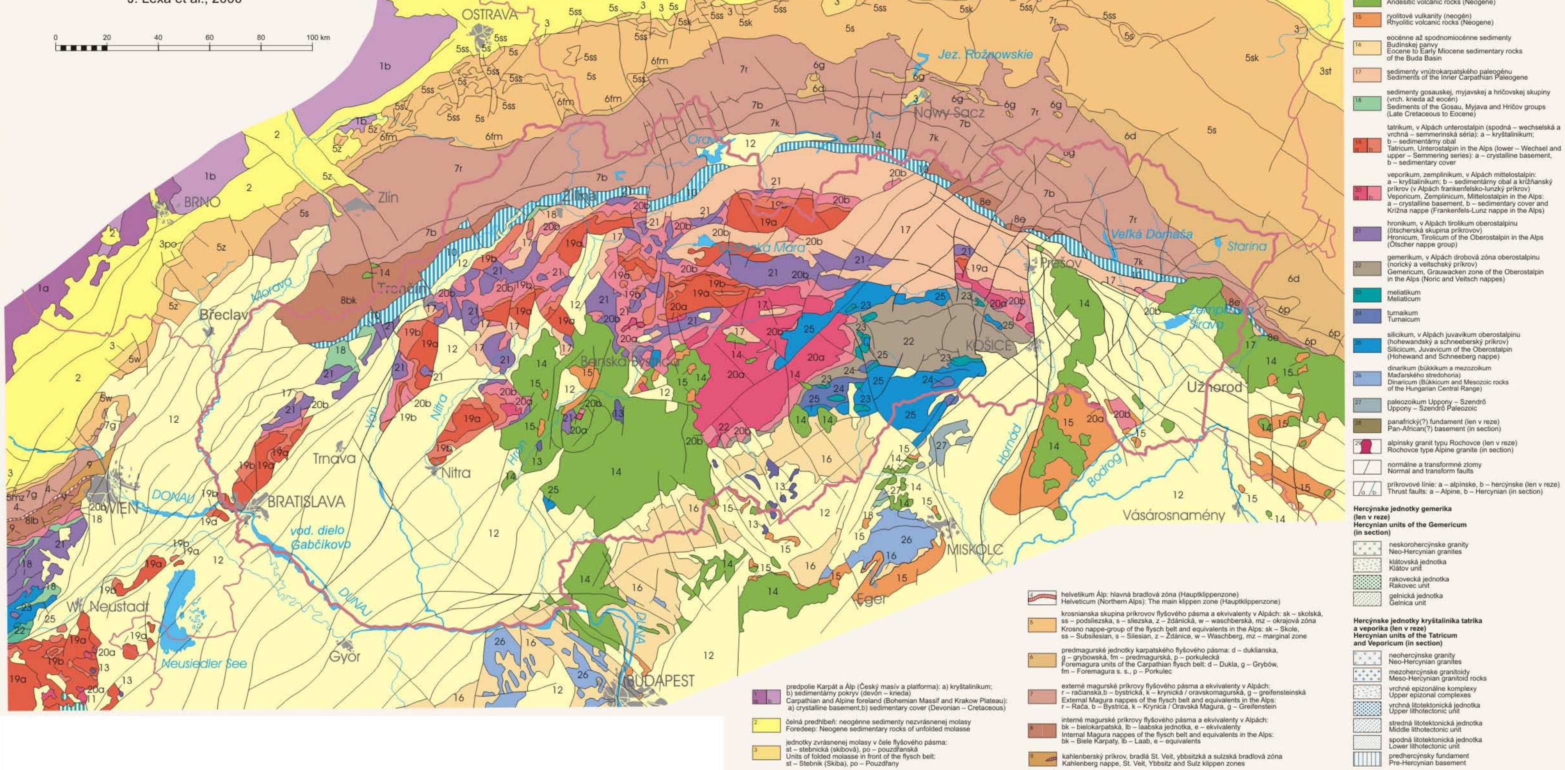
ŠTRUKTÚRNA SCHÉMA ZÁPADNÝCH KARPÁT A PRIĽAHLÝCH ÚZEMÍ

STRUCTURAL SCHEME OF WESTERN CARPATHIANS AND ADJACENT AREAS

J. Lexa et al., 2000



Schematic section of Western Carpathians (Vertical scale exaggerated)