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PALEOTECTONIC EVOLUTION OF THE MALÉ KARPATY MTS. – AN OVERVIEW*

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Abstract: The Malé Karpaty Mts. structure consists of several superposed nappe units comprising pre-Alpine basement, its Mesozoic cover and superficial nappe complexes. Several Paleozoic volcano-sedimentary successions have been distinguished in the Tatric basement. Contrasting metamorphic overprint and different relationship to both the Bratislava and Modra granitoid bodies account for their Late Variscan tectonic approaching. Crustal dissection produced by long-termed extensional tectonic regime controlled Alpine Tatric dismembering into individual basement sheets. Paleo-Alpine superficial nappes were disturbed by Neoalpine back thrust tectonics. Paleogene and Lower Miocene complexes were incorporated into Malé Karpaty Mts. horst structure during Middle Miocene, when the Vienna- and Danube Basins opened.

Key words: Phanerozoic development, sedimentary record, paleodynamics, Alpine-Carpathian junction area.

Introduction

The importance of the Malé Karpaty Mts. in the context of the Eastern Alpine–Western Carpathian correlation is evident. These mountains appear as an isolated island of pre-Tertiary basement between Cenozoic Vienna and Danube-Kiss Alföld Basins, being a significant link of these two so closely related, but so distinct mountain systems. Considering this position, the Malé Karpaty Mts. bear some typical features of both systems, the Carpathian influence being the more pronounced one, however (Maheľ 1983, 1987). Complex structure of the mountains reflects its complicated development, which started hundreds of kilometers far southwards. Rests of Variscan mountains have been overriden by Paleo-Alpine nappe piles. However, their structure has been modified by back-thrusts and by transpressional tectonics. Tectonic escape of the SW part of the Western Carpathians from the Eastern Alpine domain during the Early Tertiary resulted in disintegration of Cretaceous–Paleogene basins. During Late Miocene, their filling together with Lower Miocene deposits was incorporated into the Malé Karpaty horst structure. The aim of this brief overview is to summarize some most important results and ideas, which have been achieved by an intensive research during the last decade.

Penninic

The problem of the presence of Penninic units in the structure of the Western Carpathians has been discussed many times in Slovak geological literature. However, only conceptions presuming the position of Penninic (South Penninic-Vahic) units in front and/or below the Tatricum seem to be consistent with most of the geological data. From this point of view, the units with Penninic affinity should be expected in zones, where the lowermost levels of the Tatric basement are cropping out, except the zones of accreted sedimentary cover of unknown basement (e.g. the Klape Unit of the Peri-Klippen Belt). The Malé Karpaty Mts. are a very good candidate for such a search (Maheľ 1981, 1983, 1987). Nevertheless, in spite that the lowermost unit of the Tatric Nappe edifice – the Borinka Unit shows some features of Penninic affinity, as far as its lithostratigraphical content and inferred paleogeographic setting at the southern flank of probably oceanic domain are concerned, from structural point of view it is still a part of the Tatricum. True Penninic units of oceanic provenance could be expected in a deeper underlier beneath the Borinka and related Lower Tatric units.

Tatricum

The Tatricum appears to be the most extensive tectonic superunit of the Central Western Carpathians, it forms the lowermost basement substratum of the so-called "core mountains" ranging between the Klippen Belt and southerly exposed other basement superunits – the Veporicum and Gemericum. Similarly as those, the Tatricum is a Paleo-Alpine (pre-Gosau) thick-skinned sheet composed of pre-Al-

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pine basement complexes and Upper Paleozoic–Mesozoic sedimentary cover. Compared with the Eastern Alps, the Tatricum may be best correlated with the Lower and Middle Austroalpine units. Recently, four principal tectonic units have been distinguished within the Tatricum of the Malé Karpaty Mountains: the Borinka and Orešany subautochthonous units and the Modra and Bratislava basement nappes (Fig. 1).

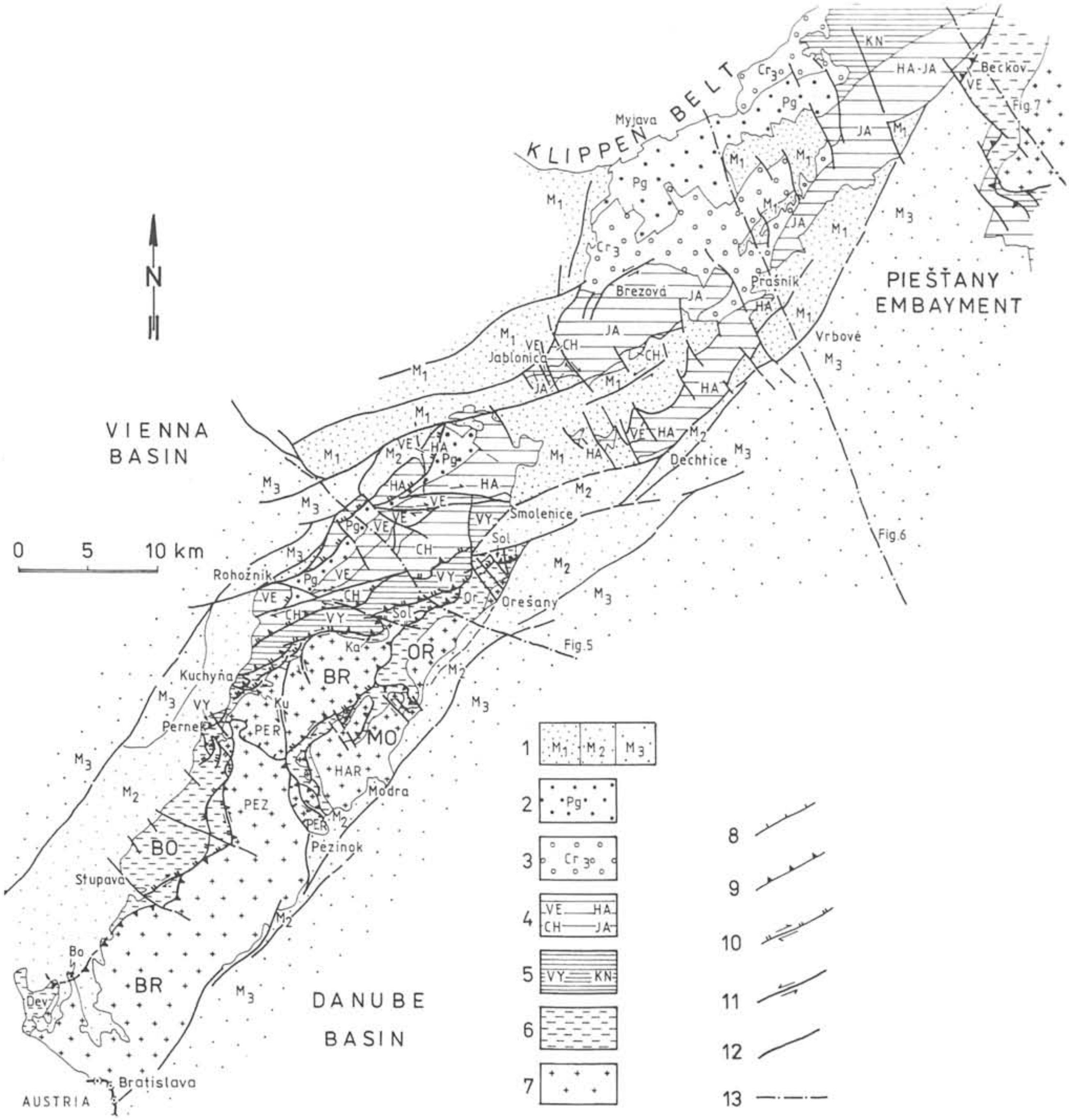

Fig. 1. Tectonic sketch map of the Malé Karpaty Mts.

Variscan units: PEZ – Pezinok Unit, PER – Pernek Unit, HAR – Harmónia Unit.; **Alpine units:** BO – Borinka subatochthonous Unit (comprising only Bo – Borinka Mesozoic Succession), OR – Orešany subautochthonous Unit (comprising PEZ basement and Or – Orešany Mesozoic Succession), MO – Modra Basement Nappe (comprising HAR – basement and Triassic cover), BR – Bratislava Basement Nappe (comprising PEZ and PER basement, Dev – Devín, Ku – Kuchyňa, Ka – Kadlubek and Sol – Solírov Mesozoic Successions), VY – Vysoká cover Nappe, KN – Krížna Nappe, CHN – Choč-Nappe, VE – Veterlín Nappe, HA – Havranica Nappe, JA – Jablonica (and Nedze) Nappe.

1 – Neogene cover (M_1 – Lower Miocene, M_2 – Middle Miocene, M_3 – Upper Miocene – Pliocene); 2 – Paleogene cover; 3 – Upper Cretaceous cover; 4 – Choč-, Lunz- and "higher" nappes; 5 – Vysoká and Krížna Nappes; 6 – Tatric Mesozoic cover; 7 – Tatric Pre-Alpine basement; 8 – Variscan overthrust; 9 – Alpine overthrust AD_1; 10 – Alpine oblique slip reverse faults AD_2; 11 – strike slip faults; 12 – normal faults; 13 – profile lines.

Pre-Alpine basement complexes

Early Paleozoic crystalline complexes of the Malé Karpaty Mts. was divided previously into two "series": Harmónia complex, resting on the Pezinok-Pernek one (Cambel 1954). Putiš in Maheľ et al. (1983) Putiš (1986, 1987), and Plašienka & Putiš (1987) distinguished four lithological units: Pezinok Succession (metamorphosed mantle of Bratislava Massif granitoids), Pernek and Harmónia Succession (metamorphosed mantle of Modra granodiorite body) and Dolany Succession (Fig. 2).

The successions are composed of two formations, named A and B (Doľany S. comprises the A formation only), with very pronounced lateral changes suggesting their relatively independent developments in different parts of the Lower Paleozoic basins. The lower, flysch-like, predominantly pelito-psammitic A formation (Silurian–Lower Devonian), more or less gradually passes into the overlying volcano sedimentary B formation (Lower to Middle Devonian, sensu Planderová and Pahr 1983; Cambel and Planderová 1985) composed of black shales, quartzites, marly shales, carbonates, basalts and their tuffs, locally gabbros and gabbrodiorites.

The **Pezinok Succession** (A_1, B_1) is characterized by: distinct dominance of the A-formation pelites over psammites, with only small basalt bodies and related tuffs; presence of transitional beds between A and B formations; intercalations of marly shales and limestones (the latter being 1–10 *cm* thick) in the basalt complexes. Sporomorphs are almost exclusively of marine origin.

Typical features of the **Pernek Succession** (A_2, B_2) are as follows: pelitic-psammitic beds of A formation with increased proportion of psammites mainly in the upper part of the formation; transitional horizon to B-formation composed of

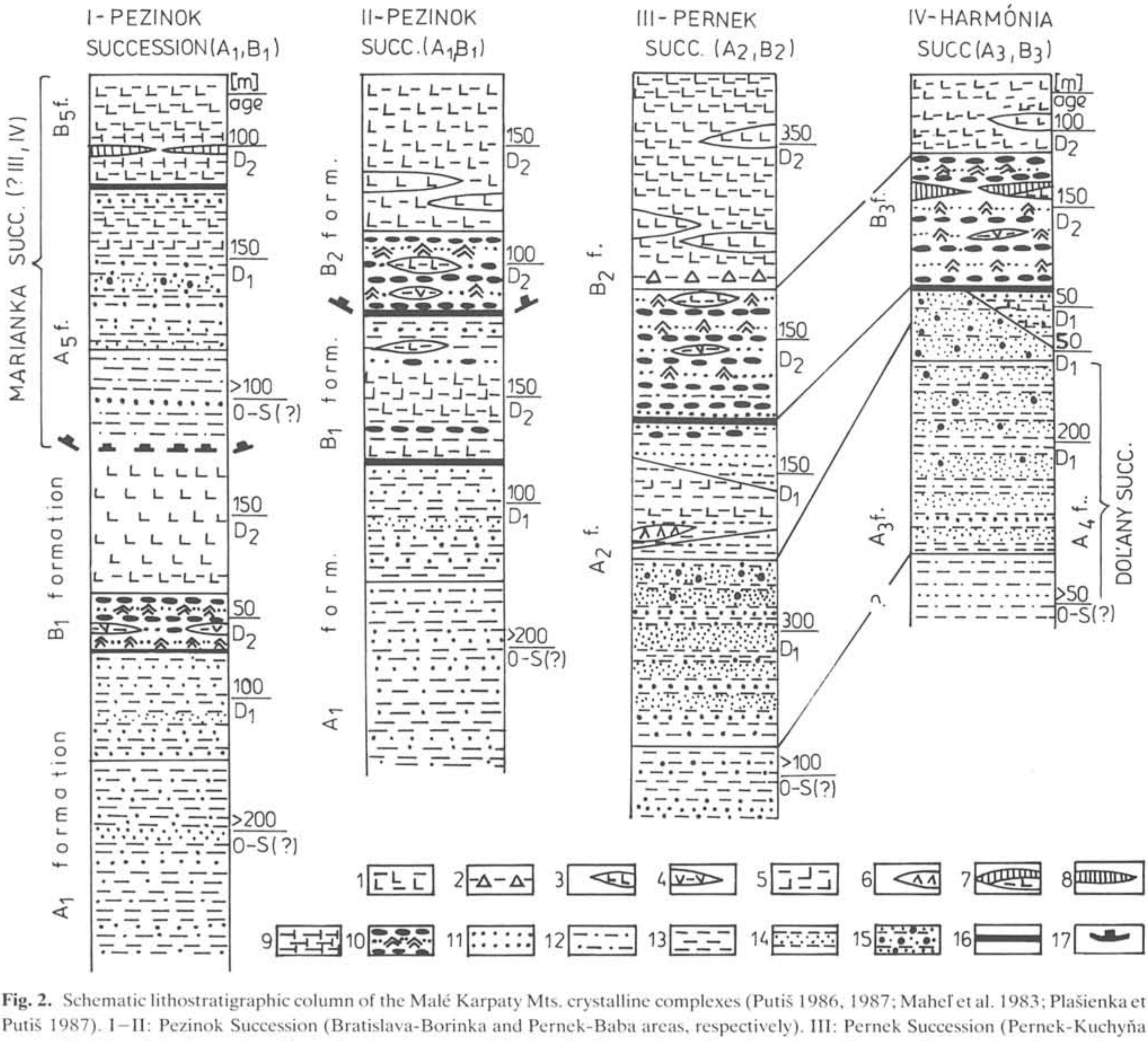

Fig. 2. Schematic lithostratigraphic column of the Malé Karpaty Mts. crystalline complexes (Putiš 1986, 1987; Maheľ et al. 1983; Plašienka et Putiš 1987). I–II: Pezinok Succession (Bratislava-Borinka and Pernek-Baba areas, respectively). III: Pernek Succession (Pernek-Kuchyňa area). IV: Harmónia Succession. Symbols: 1 – basalts and their tuffs; 2 – volcanic breccias; 3 – gabbros, gabbrodiorites; 4 – schists to quartzites with tuffogene admixture; 5 – tuffites; 6 – amygdaloid andesites; 7 – limestones with basalt tuff admixture; 8 – limestones; 9 – marly shales; 10 – bituminous schists and quartzites; 11 – pale quartzites; 12 – clayey sandy shales; 13 – shales; 14 – rhytmic clayey-graywacke sediments; 15 – graywacke sandstones (locally lithic graywackes) intercalated with shales; 16 – the boundary between formations A, B; 17 – tectonic boundary between lithological sequences.

quartzitic and quartzitic-graphitic pelites and psammites with only rare thin bodies of basic rocks and tuffs; thick (150–200 *m*) black shale horizon at the base of the B-formation overlain by a very thick (500 *m*) complex of basalts and their tuffs, locally with small subvolcanic gabbro and gabbrodiorite bodies. Indentified sporomorphs are almost exclusively of marine origin.

The **Harmónia Succession** (A_3, B_3) is characterized by: equal proportion of pelites and psammites in A-formation, except its uppermost psammite – dominated part (with lithic graywackes); virtually no transitional beds between A and B formations; black shales of B-formation contain fairly thick (to 20 *m*) lenticular limestone bodies intercalated in basic tuffs and hyaloclastites, only small bodies of basalts (mostly amygdaloidal) and their tuffs as well as rare tiny gabbrodiorite bodies lie above (Fig. 2). In addition to the marine sporomorph associations, the sequence contains also rich continental types.

The **Doľany Succession** (A_4) is made up only of A-formation whose lower part is dominated by pelites prevailing over psammites, quartzites and/or graphitic-quartzitic members; prominent pelitic-psammitic beds lie above. The succession containing abundant continental sporomorphs along with marine ones has been deposited during the Early Paleozoic in a probably E–W trending basin on a stable, moderately inclined shelf (absence of B-formation).

Like the deposition of the Doľany Succession, that of the Harmónia Succession was, at the beginning, characterized by increased dynamics of its environment (both successions contain similar A-formation with abundant psammites). The relief was later dissected by faults and the basin became generally deeper, with subsequent development of the B-formation (black shales with carbonates, basic magmatism). The Pernek sequence was formed closest to basified continental crust thinned by extension. Intensive basalt volcanism accompanied and also followed the deposition of black shales (B-formation).

Volcanic rocks of both Pernek- and Harmónia successions correspond to slightly differentiated tholeiitic basalts (Grecula and Hovorka 1987) mainly in their relationship to subvolcanic gabbro and gabbrodiorite bodies. The rocks are characterized by low content of REE and by a distinct negative europium anomaly (Cambel and Spišiak 1979).

A few strongly alterated small bodies of almost unmetamorphosed andesite-basalts appear to be subsequent (Late Paleozoic) to the main phase of basalt volcanism. They contain xenoliths of granodiorites.

The Pezinok Succession is likely to have been formed already on the continental (trench?) slope, because of dominance of the flyschoid A-formation, which is, in turn, dominated by pelites (Fig. 2).

The **Marianka** (A_5f, B_5f) **Succession** resembles Pernek-Harmónia-Doľany Successions. Its formation A_5 was an increased content of sandy shales and psammites, in the upper part alternating with basic tuffs and tuffites. The higher B_5 formation consists of basic tuffs and marly shales with a few *cm* beds of limestones.

Apart from lithological differences, the above successions differ one from another also in their metamorphic zonation in connection with their different relationship to two main granitoid bodies (Bratislava Massif: 347 Ma, and Modra Massif: 324–320 Ma, cf. Kantor (1959): K-Ar method; Bagdasaryan et al. (1982): Rb-Sr method; Shcherbak et al. (1988): U-Pb method on zircon).

The succession of Variscan tectono-metamorphic events was as follows:

1) Regional-metamorphic folding F_1 in biotite to biotite-garnet zone, resulting in a general fold-cleavage tectonic style (387 ± 38 Ma – 347 ± 4 Ma, Rb-Sr method, Bagdasaryan et al. 1983).

2) Continuing periplutonic metamorphism, terminated by intrusion of the Bratislava granite-monzonite body with S-type affinity (Cambel and Vilinovič 1987), but preferably in the Pezinok sequence setting. The origin of the regional-periplutonic metamorphic (biotite, garnet, staurolite, chlorite and staurolite- sillimanite) zones (Korikovsky et al. 1984).

3) Intrusion of the Modra granodiorite body with I-type affinity (Cambel and Vilinovič 1987), but only in the environment of the Pernek and Harmónia Successions that were earlier tectonically approached. Cordierite-andalusite-biotite zone of typical contact metamorphism is superimposed on older regional-metamorphic biotite to biotite-garnet zone (Putiš in Maheľ et al. 1983; Korikovsky et al. 1985). A linear intrusion of the Modra granodiorite (steeply dipping tabular body about 5 *km* thick) ascended along a tectonic contact between the adjacent Pernek and Harmónia Successions.

4) Late Hercynian tectonic displacement of the Hercynian Pezinok Unit toward the Pernek and Harmónia ones gave rise to a characteristic fan of steeply dipping (to the N) metamorphic foliations (NW–SE) with steep fold axes (the area between Pezinok and Pernek). This ancient subductional-collisional structure of the Alpine Bratislava Nappe (Maheľ 1980) is cut by flat-lying shear planes (Putiš 1987).

Mesozoic cover units

Mesozoic sedimentary sequences of the Tatricum in the Malé Karpaty Mts. are grouped into several tectono- lithostratigraphical units (Maheľ 1951, 1987; Plašienka and Putiš 1987), here referred to as successions. However, only Jurassic and Lower Cretaceous formations are decisive for such a division, as the Triassic sediments are of uniform continental, lagoonal and shallow-marine character, while the Middle Cretaceous, mostly flysch deposits are of unvaried deep marine character as well. The beginning of the sedimentary record of the pre-Jurassic paleotectonic period, termed as the period of epi-Variscan shelf epeirogenesis, is expressed by scarce Upper Permian terrestrial clastics (**Devín Formation** of Vozárová and Vozár 1988), overlying the Variscan basement. Lower Triassic piedmont alluvial quartzose sandstones (**Lúžna Formation** of Fejdiová 1980) form an extensive 100–200 *m* thick body (Mišík and Jablonský 1978) overlain by rarely preserved variegated "Werfen" shales. Middle Triassic limestone and dolostone complexes represent sediments of a shallow marine carbonate platform rimmed by relics of hypersaline belt (Mišík 1986b). Their maximum thickness reaches about 500 *m*. Upper Triassic sediments (probably in Carpathian Keuper facies?) were completely eroded during the following extensional period. Rare fragments of Rhaetian coquinal limestones were found in Lower Jurassic breccias (Kochanová et al. 1967).

Disintegration of the Triassic carbonate platforms started during the earliest Jurassic. Sedimentary area of the later Tatricum splitted into several deep-marine basins and shallow submarine highs (even emerged zones appeared in some places). Starting from the Lower Jurassic, six distinct units

(Borinka, Orešany, Devín, Kuchyňa, Kadlubek and Solírov Successions) have been distinguished in the Tatricum according to their lithofacies content and inferred paleogeographical settings. This differentiation has been initiated by **extensional tectonic regime** in the Tatric crust. Crustal stretching triggered extensive normal faulting recorded by clastic influx and multiple resedimentary events. Two principal paleogeographic domains were established: the South Penninic (Vahic) Oceanic Basin with the marginal Borinka Succession on the NW and the Šiprúň (Fatra) Trough to the SE, represented by the remaining successions (Fig. 3). Subaeric continental ribbon dividing these two basinal domains persisting more or less during the whole Jurassic and Early Cretaceous could be analogized with the Lungau Swell of the Eastern Alps (Tollmann 1977).

When reconstructing the Mesozoic paleotectonics, we subdivide the period of extensional tectonic regime into three stages:

1) initial rifting (Hettangian–Pliensbachian) with prevailing erosion and a shallow marine, often clastic sedimentation;

2) areal extension (Toarcian–Barremian) marked by breaking of the sedimentary area into numerous basinal and raised zones, mostly pelagic sedimentation, lasting 80 Ma;

3) pre-compressional subsidence (Aptian–Cenomanian) recorded by an uniformly spread siliceous marlstone sequence with bodies of hyalobasanitic lavas (Aptian–Lower Albian – thermal subsidence after maximum crustal stretching) and flysch **Poruba Formation** derived from exotic sources (Albian–Cenomanian flexural subsidence of trench basins in front of compressional orogenic wedge).

The **Borinka Group** (Lower to Upper Jurassic formations only) represents a sedimentary filling of a tilted halfgraben with fault escarpment facing to the NW (Fig. 3). Its marginal zones are indicated by a thick sequence of coarse-grained scarp breccias supplied from the sources on the south (Lower Jurassic **Prepadlé Formation** with predominance of Triassic carbonatic clasts, up to 300 *m* thick; Middle and Upper Jurassic **Somár Formation** composed of breccias dominated by crystalline fragments, at least 500 *m* thick), while turbiditic Korenec Formation (Lower Jurassic, up to 800 *m*) and hemipelagic, partly anoxic **Marianka Shaly Formation** (Toarcian–Bathonian, about 500 *m*) were deposited in the axial parts of the halfgraben (Plašienka 1987). The Borinka Group along with small outcrops of its Triassic basement are the only surface representatives of the subautochthonous Borinka Unit. Lithofacies development of the Borinka Group is unique among all Jurassic successions of the Western Carpathians. Comparable sequences can be found only in the Lower Austroalpinicum units of the Alps, e.g. in those rimming the Penninic Tauern Window (cf. Häusler 1988).

The **Orešany Succession** overlies the pre-Alpine basement and the remnants of deeply eroded Triassic sequence of another subautochthonous – Orešany Unit. Its lithological content considerably differs from the Borinka Group as well as from the other successions. Calciturbiditic sequences

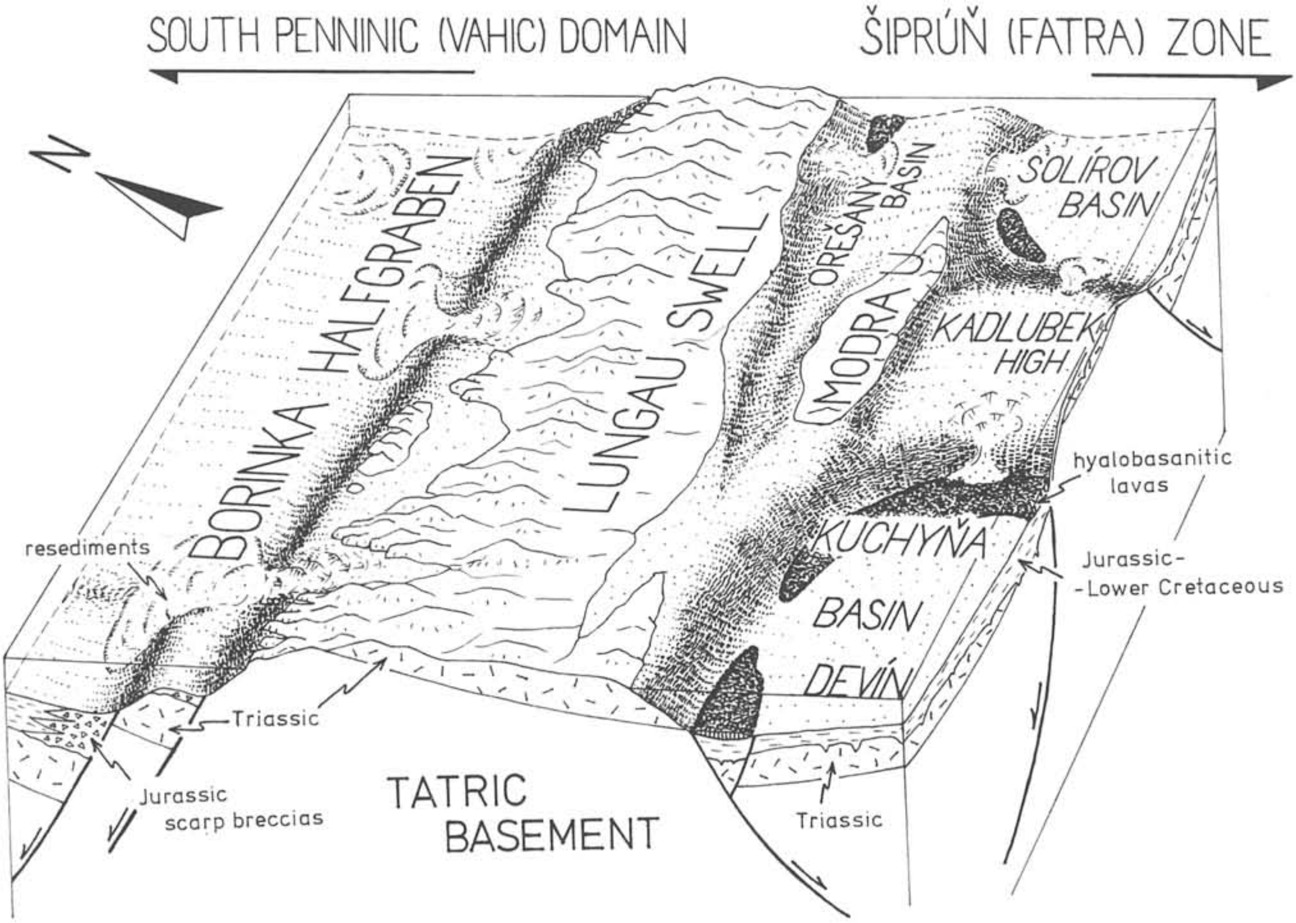

Fig. 3. Block-diagram showing inferred paleogeographical setting of the Mesozoic lithostratigraphic units of the Tatricum in the Malé Karpaty Mts. area (Original D. Plašienka).

reaching the thickness of 500–600 *m* are the most distinctive feature of this succession: Middle Jurassic marly calcarenitic **Slepý Formation,** Upper Jurassic –? Lower Cretaceous dark gray (unnamed) calciturbidites, and Barremian – Lower Aptian coarse-grained sandy limestone **Solírov Formation** (Jablonský et al. in print). Lower Jurassic sediments consist of shallow-marine biodetrital and sandy limestones. Strong tensional impulse (Toarcian?) with subsequent submergence of the sea bottom to bathyal depths is recorded by dark shales, greywackes and polymict conglomerates, similarly as in the Kuchyňa and Solírov Succession.

All remaining units, i.e. Devín, Kuchyňa, Kadlubek, and Solírov Successions belong to the same allochthonous tectonic body – the Bratislava Basement Nappe. Their present-day juxtaposition is inherited from the original sedimentary area, where they sedimented in more or less independent domains with partly different, but often parallel paleotectonic (and, subsequently, also lithostratigraphic) development (Fig. 3). The thickness of the mostly pelagic Jurassic–Lower Cretaceous sequences of these successions is rather low, never exceeding 400 metres.

The **Devín Succession** is characterized by Lower Jurassic extraclastic brecciated shallow-marine limestones, forming also fissure fillings and neptunic dykes in the underlying Triassic carbonates. Middle Jurassic to Lower Cretaceous sequence consists of pelagic facies (siliceous, cherty, nodular and micrite limestones).

Lower Jurassic limestone breccia in the **Kuchyňa Succession** penetrates by neptunic dykes into crystalline basement (Triassic sequence being almost completely eroded). Sea ingression and rapid sinking of the bottom happened at the Early/Middle Jurassic boundary. Middle Jurassic to Lower Cretaceous sediments are pelagic with some intervals rich in biodetrital limestones (Dogger, Hauterivian–Barremian).

The **Kadlubek Succession** is the most outstanding unit (only about 50 *m* thick), marked by condensed pelagic sedimentation on an intra-oceanic high (red nodular limestones, disintegrated hardgrounds, neptunic dykes, etc.) during the whole Jurassic–Early Cretaceous.

The **Solírov Succession** is similar to the Kuchyňa one, but with several specific features. One of them is the Solírov Formation – redeposited biodetrital sandy limestones, mostly Barremian in age.

Compressional tectonic regime, basement shortening and imbrication started probably during Turonian in the future area of the Malé Karpaty Mts. The geometry of the extensional fault structures in the basement was widely utilized during this period, hence the shape and pattern of thrust bodies were constrained by the pre-existing anisotropy (Fig. 4). Listric extensional normal faults facing to the SE limiting the Lungau Swell were inverted into overthrust faults, therefore the basement of basinal domains S of Lungau- and Orešany areas began to form extensive allochthonous sheets (the **Modra and Bratislava Nappes**), while less dissected basement and cover sediments of the Orešany, Lungau (not exposed nowadays) and Borinka domains remained in subautochthonous position (Fig. 5).

Compressional thrust movements are recorded structurally by the paragenesis of the first Alpine deformational stage AD_1, (Plašienka and Putiš 1987; Putiš 1987). The most prominent structures are ductile to brittle-ductile overthrust shear zones formed under low-grade P-T conditions and large recumbent folds. The overthrust plane of the Bratislava Basement Nappe cropping out in the Prepadlé Valley near

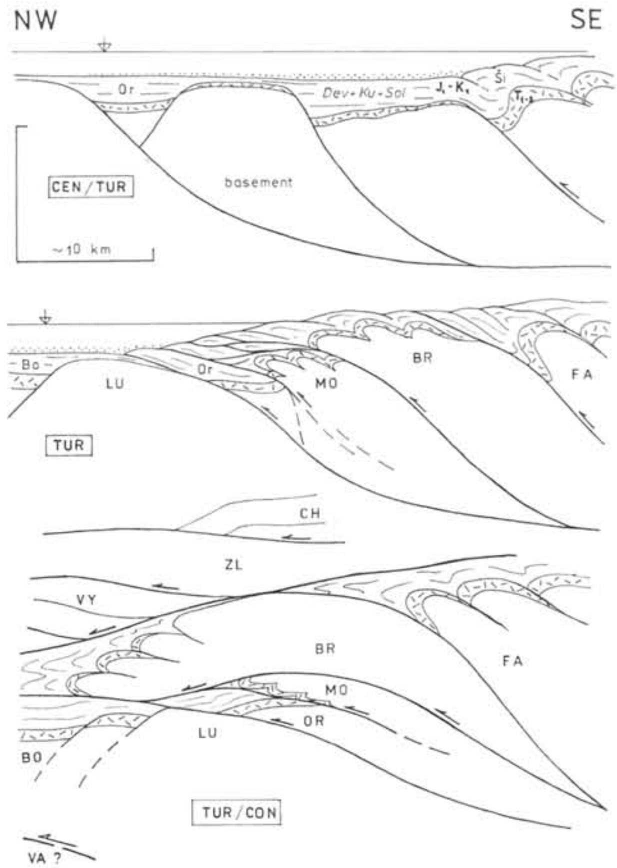

Fig. 4. Schematic paleotectonic model of the development of thrust faults from pre- existing listric normal faults and individualization of Tatric basement nappes in the Malé Karpaty Mts. area during the compressional deformational stage AD_1. Lithostratigraphical units: Or – Orešany, Dev – Devín, Ku – Kuchyňa, Sol – Solírov, Ši – Šiprúň, Bo – Borinka. Tectonic units: BO – Borinka, LU – Lungau, OR – Orešany, MO – Modra, BR – Bratislava, FA – Fatra, VY – Vysoká, ZL – Zliechov, CH – Choč Unit.

Borinka can serve as a typical example. The shear zone shows non-coaxial deformational regime with penetrative foliation S_1 (representing *xy* plane of the finite strain ellipsoid) and stretching lineation L_1 (*x* axis) in uniform NW–SE attitude. Small-scale asymmetric structures and F_1 folds point to the translation of the allochthonous body from the SE to the NW (Plašienka 1990). The result of compressional tectonic regime was not only shortening and thrusting inside the Tatric basement, but also overthrust of superficial cover nappes: the Vysoká Nappe and higher ones (Fig. 4). Nevertheless, their emplacement under brittle conditions had little influence on the basement structures.

Krížna Nappe system

Extensive system of superficial nappes, formed by detached Mesozoic cover of the pre-Apline basement which disappeared between the present-day Tatricum and Veporicum, has been named by Andrusov et al. (1973) "Fatricum". It consists of large Krížna (Zliechov) Nappe, lying on a complex system of small frontal scales (Vysoká, Belá, Ďurčiná, Havran, etc. nappes). Mahel' (1983) attributed also Manín

Unit to the last group: however, this opinion is not supported by many Carpathian geologists.

Vysoká Nappe

This unit (Fig. 1) consists of Mesozoic (Anisian–Albian) allochthonous sediment pile, accumulated in the northern part of the "Fatricum" domain, in close proximity of the southern Tatricum. This fact caused in the past many uncertainties in tectonic and paleogeographic attribution of this unit (Andrusov 1959).

The Anisian **Vysoká Formation** represents carbonate ramp sediments of the "Gutenstein type", 200–250 *m* thick. Micritic limestones contain tempestite horizons and biogene layers with marine benthic fossils. Upper member of this formation bears marks of hypersaline environment, such as strong dolomitization and pseudomorphs after crystals of evaporite minerals. The successive **Ramsau Dolomite** is about 40–60 *m* thick. Limestones in the uppermost part of this "basal carbonate complex" yielded rich Carnian bivalve fauna (Mahel' et al. 1967, 1986). They are comparable with the **Opponitz Limestone** of the higher units. Laterally, they pass into brecciated and cellular dolomites.

The **Carpathian Keuper** complex, although tectonically reduced, attains 200–300 *m* thickness in several places. Red and variegated shales contain intercalations of pale gray quartzose sandstones (in lower member) and grey dolomites (in the uppermost parts).

The Upper Rhaetian **Fatra Formation** is represented by the sequence of neritic fossiliferous limestones (Michalík 1974). They are overlain by thick (about 100 *m*) shaly **Kopieniec Formation,** Hettangian in age. Lower Jurassic sandy crinoidal limestones resemble **Trlenská Formation** (Bujnovský et al. 1979) of the Tatricum or Manín Unit. Upwards, they pass into siliceous limestones with nodular texture. The Dogger sequence of dark shales, silicites and siliceous limestones, is often reduced tectonically (Mahel' 1972; Borza and Michalík 1987).

The Upper Jurassic **Niedzica** and **Czorsztyn Formations** represent typical products of "Ammonitico Rosso" facies. They contain intercalations of slumping breccias and red silicite nodules. Inserted **Czajakowa** (Ruhpolding ?) **Formation** silicites yielded Oxfordian radiolarian microfauna (Michalík et al. 1988), the topmost part of the Czorsztyn Limestone is dated as Late Tithonian by a rich microplankton association (Borza and Michalík 1986).

Lower Cretaceous sequence consists of the massive **Padlá Voda Limestone Formation** with limestone breccia intercalations and of schistose marly limestones of the **Hlboč Formation** (Borza and Michalík 1987; Michalík et al. 1990). Pelagic formations are covered by the organogenic **Bohatá Formation** limestones of neritic origin. Above the carbonate complexes there are lying more or less preserved (frequently silicified) Albian **Poruba Formation** marls.

Choč-, Lunz- and " higher nappes" system

This section deals with the units which originated along the southern border of the Alpine-Carpathian Shelf (their recognition and exact correlation is problematic due to later tectonic deformations; Fig. 1). The sequences coming from this area are characterised by a thick pile of marine deposits.

The **Ipoltica Group** consists of Upper Carboniferous **Nižná Boca Formation** and of Permian clastic and volcanic rocks of **Malužiná Formation.** A rigid complex of basic volcanics (700–900 *m* thick) forms an important element controlling the tectonic style of the NW part of the Malé Karpaty Mts. (Vozár 1966; Mahel' 1972, 1982). Two eruption phases are represented by effusives, less by dykes of intermediate and basic volcanic rocks of TH-magmatic series, along with their tuffs, tuffites and "hyaloclastites" (Vozárová and Vozár 1979). Multicoloured coarse clastics are accompanied by tuffs and red shales with evaporites. Clastic material is polymict, poorly rounded and very poorly sorted. It has been deposited in grabens produced by systems of normal faults. The faulting was accompanied by volcanism and by periodic block movements.

Benkovský Potok and **Šuňava Formations** lie probably transgressively upon the Ipoltica Group (their mutual contact is not visible in outcrops). Both formations consist of a complex of shallow-marine fine-grained clastics, fining upwards. However, tectonic deformations, as well as the bad exposure prevent more exact observations. The thickness of the Lower Triassic sequence is about 200–250 meters.

Substantial part of the carbonates in northern part of the Malé Karpaty Mts. and in eastern part of the Vienna Basin basement consists of Triassic sequences equivalent to the Tirolic and Juvavic of the Northern Limestone Alps. Carbonate ramp evolution here has started on a flat siliciclastic shelf during the Early Pelsonian. The basal member of the **Gutenstein Formation** consists of bituminous, stromatolitic, oolitic and brecciated micrites and dolomicrites, representing extremely shallow, frequently also hypersaline conditions (Lintnerová et al. 1988; Michalík et al. 1989). The basal dolomites pass laterally into thin-bedded **Gutenstein Limestone** with gypsum pseudomorphs and crinoid ossicles. The successive **Annaberg Limestone Formation** is about 200–300 *m* thick. It consists of micrites and biomicrites, sometimes affected by late diagenetic recrystallization. The **Steinalm Formation** reaches 400–500 *m* in Havranica and Jablonica Nappes, 30–40 *m* in Veterlín Nappe, but only a few meters in the Choč Nappe (Dobrá Voda DV-1 Borehole, cf. Michalík et al. 1991). It represents the first products of an arising carbonate platform. The **Zámostie Formation** is the last (Late Pelsonian) representative of the shallow marine Anisian sequence in the subsiding intraplatform depressions (Choč and Veterlín Nappes).

The **Reifling Formation** contains cca 100 *m* thick basinal cherty micrites and microsparites with frequent Illyrian to Cordevolian microfossils (Masaryk et al. 1984). The upper part of this sequence contains intercalations of clastic limestones derived from neighbouring carbonate platforms. The 800 *m* thick **Wetterstein Formation** represents the same time interval in the Havranica and Jablonica Nappes. It consists of white dasycladacean and sphinctozoan limestones, or of huge slope breccias. White dolomites of Late Ladinian or Early Carnian age form its higher part.

Allodapic tongues of the **Raming Limestone** coming from the reef slope affected the basinal sedimentation at the end of the Ladinian in the Veterlín Nappe. Subsequently, huge slope breccias (up to 1000 *m* thick) filled the basin and enabled progressive growth of sphinctozoan and coral reefs (Lintnerová et al. 1990).

The overlying **Reingraben Formation** with intercalations of fine (Lunz) clastics is covered by **Opponitz Limestone Formation** and by thick **Hauptdolomit.** Triassic sequence in the Havranica Nappe is terminated by **Dachstein Limestone** and by Rhaetian **Norovica Formation** (Mahel' 1958). In other places, however, Upper Cretaceous erosion has removed considerable part of the top Triassic and Lower Jurassic sequence. Liassic dark crinoidal and organodetritic limestones contain rich marine fossils.

We suppose that both Veterlín and Havranica-Jablonica partial Nappes belonged during Paleo-Alpine deformation phase to a common nappe and their separation was coeval with differentiation of the nappes in Northern Calcareous Alps. Therefore, they are correlable more satisfactorily with the Alpine nappes, despite of several differences. Shortening through nappe stacking covered only a very short time span: several Ma mainly during the Late Turonian. Afterwards, this nappe pile underwent further shortening through reverse faulting and upright folding, changing gradually into transpressional movements when the shortened crust reached its maximum thickness capable to sustain body forces. General uplift and cooling accounts for features of ductility decrease and strain hardening.

Upper Cretaceous cover

The nappe structure in the northernmost parts of the mountains is covered by a sequence comparable with the Gosau sequence of the Northern Calcareous Alps (Salaj 1962; Mahel' 1987; Mahel' and Salaj 1987; Salaj et al. 1987). It started with transgressive Coniacian **Valchov Conglomerate Formation.** Beside pebbles of basement rocks, they contain also pebbles of fresh-water (?Turonian−? Coniacian) Schizophyta limestones. The conglomerates are overlain by **Baranec Sandstone Formation** (50−150 *m* thick) with actaeonellid gastropods. Upper Coniacian pelagic marls of **Štverník Formation** contain abundant foraminifers. The successive Santonian flysch (**Hurbanova Formation)** is about 3000 meters thick. The Lower Campanian sequence is characterized by variegated marls and marlstones **(Košariská Formation).** Upper Campanian to Maastrichtian flysch (**Podbradlo** and **Bradlo Formation**) is highly carbonatic and contain calcarenite sandstones, microconglomerates and marls with abundant inoceramid bivalves.

Deeper in the mountains, Campanian carbonate sandstones and microconglomerates with large forams are cropping out (Köhler and Borza 1984). They are overlain by fragmentarily preserved bioherm limestone bodies with actaeonellid gastropods (Santonian *Trochactaeon sanctaecrucis* (Futteren) has been determined here by Dr. H. Kollmann from the Vienna Museum).

In the Biele Vrchy Hills (NW part of the Malé Karpaty Mts.), nappe bodies are covered by breccias with red matrix (**Bartalová** and **Kržľa Formations,** Michalík 1984). They could represent terrigene equivalents of the "Gosau" sediments.

In the basement rocks, the transpressional tectonic regime is recorded by hybrid structural association of the deformational stage AD_2, developed preferentially at the bordering zone of uplifting Tatric basement block in the SE and incompetent pile of the mainly Mesozoic sediments of the cover nappes in the NW. The geometry of macroscopic structures, i.e. oblique slip duplexes, reverse and strike-slip faults as well as the arrangement of small-scale structures, such as asymmetric folds F_2, crenulation cleavage S_2, etc. suggest dextral movement in the transpressional zone (Plašienka 1990).

Savian/Styrian transpressive movements in the "higher nappes" caused complete reworking of older tectonic units and creation of a new Alpine-like structure. This system consists of an extensive slice of Permian−Lower Triassic clastic rocks (similar to the Čierny Váh partial nappe of the Choč Nappe in the Central Carpathians), followed by individualized carbonate bodies of Veterlín and Havranica-Jablonica Nappes (similar to the Silica Nappe of Central Carpathians). If correlated with the Northern Calcareous Alps, the Choč sequence is most similar to the Göller Unit, the Veterlín and Havranica-Jablonica sequences resemble Schneeberg and Mürzalpe Nappes.

Paleogene cover

Paleogene sediments fill the Buková Furrow in the NW part of the mountains. This structure represents a fragment of a former extensive marine basin (Gross and Köhler 1989). Late Paleocene and Early Eocene transgreding sea probably covered almost all the area of the present-day Malé Karpaty Mts.

The Borové Formation represents the basal part of the transgressive Paleogene sequence. It consists of carbonate breccias, conglomerates and carbonate sandstones, followed by organogenic and organodetrital limestones. Late Paleocene sea transgression attacked uneven, locally karstified surface of Triassic carbonates of the "higher nappes". This is why the boundaries of the lithofacies mentioned above are often diachronic. Bioherms and biostromes grew sometimes directly on limestone basement, too. Fine-grained breccias containing Lower Eocene large foraminifers fill also clastic dykes penetrating several meters deep the Triassic carbonate basement. The Borové Formation in the MKP-1 Borehole is 41 *m* thick, its maximum thickness attains 80−100 meters.

The **Huty Formation** is characterized by a dominance of claystones over sandstones and fine conglomerate layers. Silty admixture is locally concentrated into thin, often convolutely bended laminae. Intercalations of rough carbonate sandstones and fine conglomerates contain 80−85 % of carbonate grains and pebbles. Although sedimentary environment of this formation was evidently somewhat deeper than the former one, the character of clasts proves relative proximity of shore. The amount of redeposited rests of shallow marine benthos is much higher compared with coeval rocks of the same formation in the Liptov and Spiš area in northern Slovakia. The maximum thickness of the Huty Formation is several hundred meters (450−500 *m* ?). Identified microfauna, large foraminifers and nanoplankton prove Early to Middle Eocene age of the formation.

The **Hrabník Formation** is uncovered only NW of Vajarská Hill at the S border of the Buková Furrow. Its sequence consists of dark claystones and claey siltstones with several intercalations of graded sandstones. The boundaries and the position of this Oligocene sequence, which have never been found elsewhere in the Buková Furrow, remain rather enigmatic. Poor associations of Kiscelian pelagic calcareous nanoplankton contained in the turbidites are similar to associations in the Ždánice Unit, in contrast to those occurring in the Central Western Carpathians. Similarly, findings of redeposited calcareous nanoplankton of the NP 24-25 Zone in Lower Miocene sediments at Dobrá Voda (Kováč et al. in press) indicate that sedimentation in the Alpine–Carpathian junction area lasted at some locations till Oligocene, in spite of general uplift in the region connected with erosion of Cretaceous and Paleogene sequences.

The tectonic escape of the Western Carpathian segment from the Eastern Alpine Domain during the Oligocene and Early Miocene was accompanied in the SW part of the Carpathians by N–S (NE–SW) sinistral strike slips with large amplitude of the motion. Synchronal ENE–WSW dextral strike slips created, together with south-vergent reverse faults of NE–SW direction, a half-syncline filled up by Paleogene sediments in the area of the present-day Buková Furrow. Transpressive stage of development is documented e.g.by en echelon folding of the Hrabník Formation turbidites (Marko et al. 1990). This area forms a part of the SE limb of a broad positive flower structure embracing the suture zone between Outer and Central Western Carpathians (i.e. Klippen and Peri-Klippen Belt; Figs. 5–7).

Neogene cover

Neogene sediments occurring in the Malé Karpaty Mts. are characterized by their great facies variability, changing bed thicknesses, frequent gaps caused by tectonic control of the deposition and migration of sedimentary areas.

Lower Miocene sediments are known from the N part of the mountains (Fig. 1). They were deposited in a W–E trending basin in the northern part of the present-day Vienna Basin, in the area of the Dobrá Voda and Jablonica Depressions and the Váh River valley. The southern margin of the sedimentary area was formed by the uplifted basement of the present-day southern part of the Vienna Basin, Malé Karpaty Mountains and the basement of the Danube Lowlands. The major structures controlling the basin evolution were still dextral WSW–ENE trending strike slips with important reverse component of motion. Such fault is at present situated at the northern margin of the Dobrá Voda Depression – a wrench fault furrow filled by asymmetric sedimentary wedge formed in a basin under compressive conditions (Marko et al. in press).

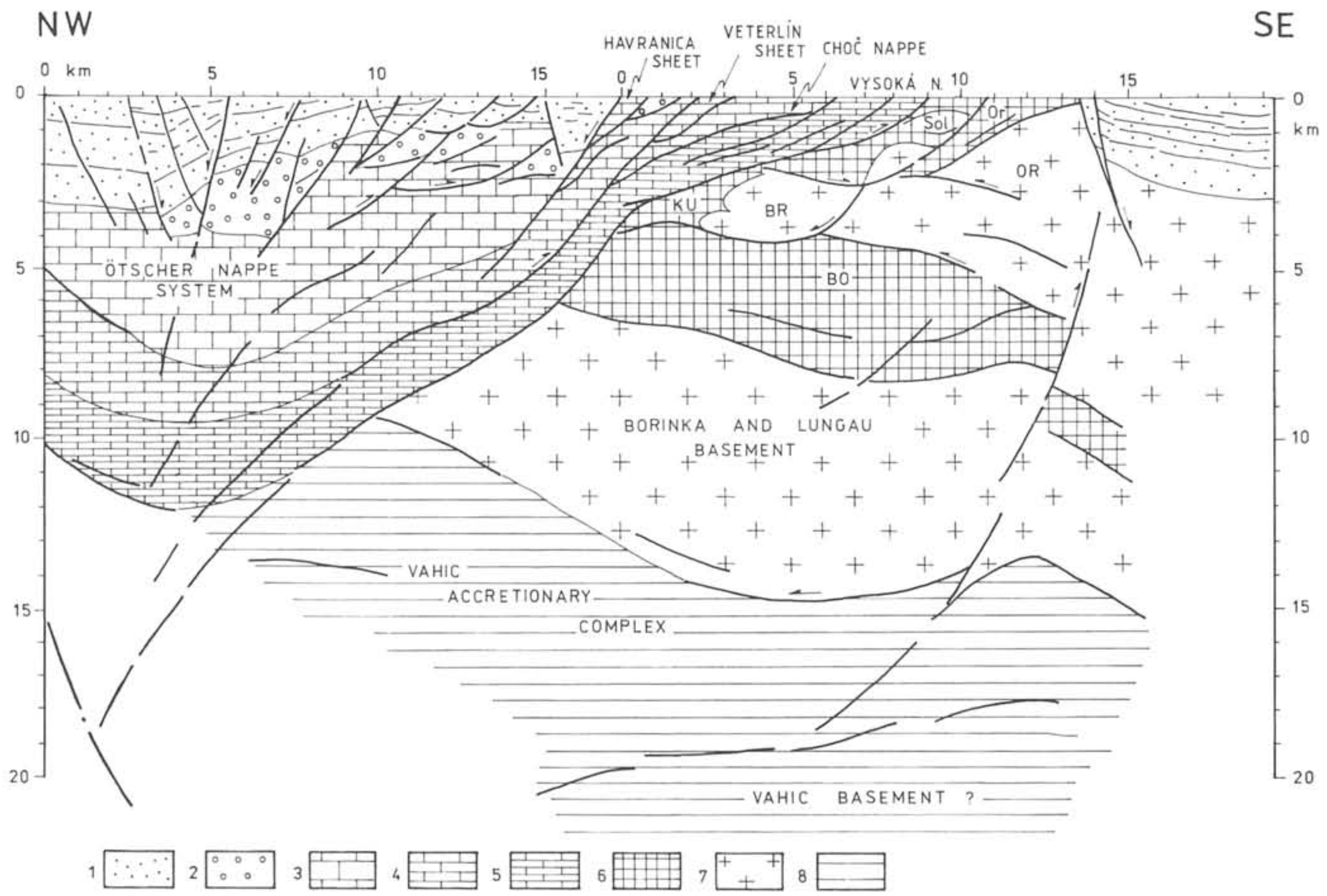

Fig. 5. Schematic cross-section through the middle part of the Malé Karpaty Mts., based on seismic sounding (geophysical interpretation by J. Honc, geological interpretation by J. Michalík and D. Plašienka).
Legend: 1 – Neogene cover; 2 – Paleogene and Upper Cretaceous cover; 3 – "higher" nappes; 4 – Choč Nappe; 5 – Križna Unit; 6 – Tatric Mesozoic cover (Bo – Borinka, Ku – Kuchyňa, Sol – Solírov and Or – Orešany successions); 7 – Tatric Basement (BR – Bratislava Nappe, OR – Orešany Unit); 8 – Vahic units.

The Eggenburgian transgressive clastic sediments were deposited in shallow archipelago sea environment (Kováč et al. 1989). **Dobrá Voda Conglomerate** from the Brezová Elevation attains the thicknesses of 20−50 *m*. The pebble material is composed of Triassic limestones and dolomites from local sources. However, the heavy-mineral association indicates sources north- and southward of the basin. Conglomerates and breccias forming talus cones bound to reverse faults can be found in a belt extending from Dobrá Voda to Čachtice.

The Ottnangian **Lužica Formation** represented by bioturbated dark aleuropelites with frequent fish scales is known from boreholes in the Dobrá Voda Depression. Intercalations of fine-grained conglomerates contain upwards increasing amount of quartz pebbles. The Ottnangian aleuropelites, folded at the Dobrá Voda fault, are interpreted as sediments of "wadden" (tidal flat − dominated) sea with anoxic regime. Clastic material came from souhern flat shores (Kováč et al. in press).

Tectonic control of the Lower Karpatian sedimentation is documented by turbidites and frequent slump bodies in pelitic "schlier" facies of the **Lakšár Formation.** The cyclic sedimentation on the basin margin is represented by conglomerates and sandstones with common plant remnants. The composition of pebbles is similar as of those from the Ottnangian conglomerates, the clastic supply was still derived from the south. Rapid subsidence and high accumulation rate resulted in good preservation of organic matter. (Kováč et al. in press).

The Upper Karpatian **Jablonica Conglomerate** reaches thicknesses of 300−500 *m*. Polymict pebble material is composed of Mesozoic carbonates, Cretaceous and Paleogene

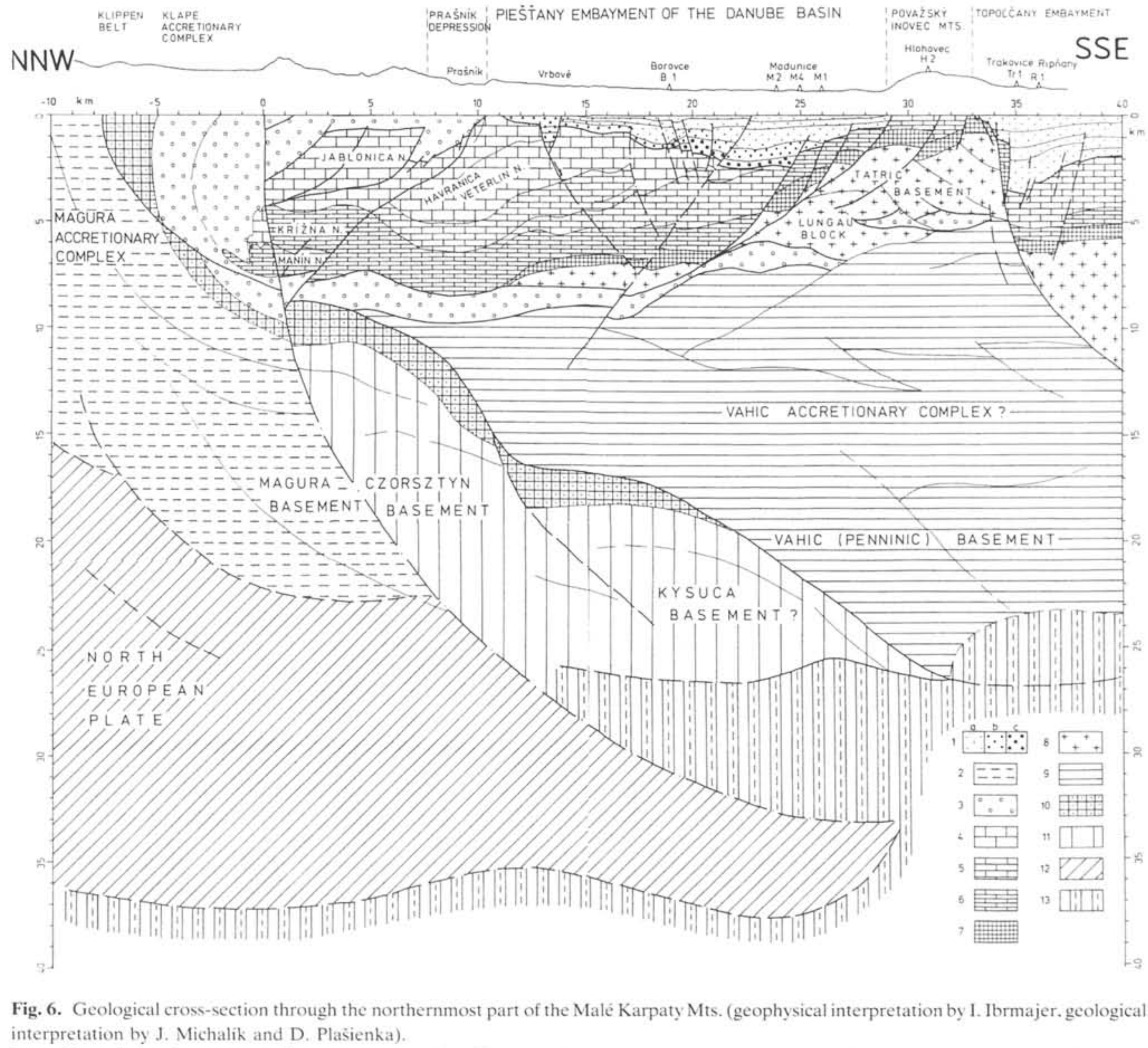

Fig. 6. Geological cross-section through the northernmost part of the Malé Karpaty Mts. (geophysical interpretation by I. Ibrmajer, geological interpretation by J. Michalík and D. Plašienka).

1a − Karpatian and younger sedimentary cover; 1b − Eggenburgian cover; 1c − Paleogene cover; 2 − Magura Accretionary Complex; 3 − Klape Accretionary Complex; 4 − "higher" nappes; 5 − Choč Nappe; 6 − Krížna Nappe; 7 − Tatric Mesozoic cover; 8 − Tatricum basement; 9 − Vahicum units; 10 − Klippen Belt units; 11 − Klippen Belt basement; 12 − North European Platform crust; 13 − mantle lithosphere.

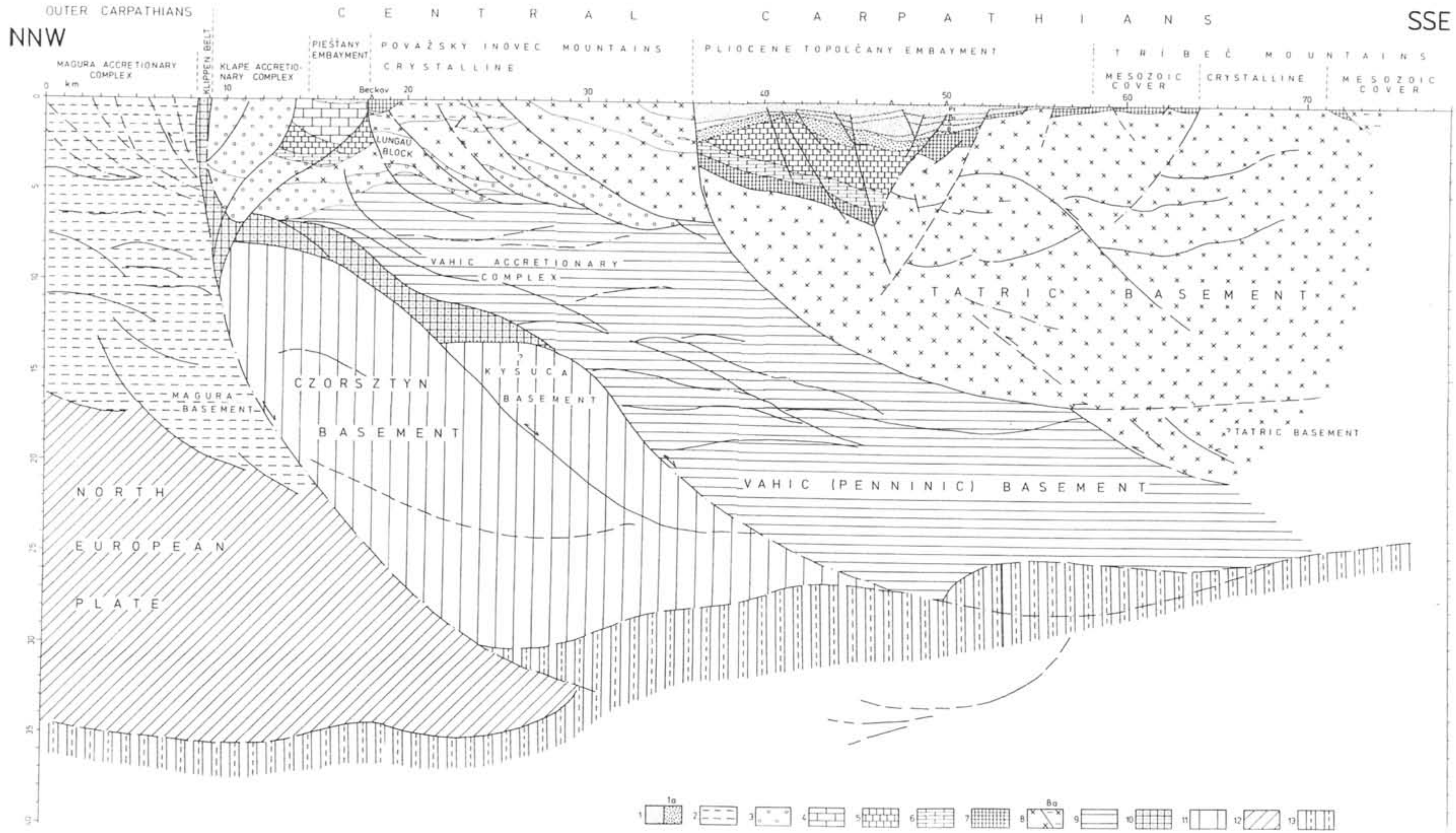

Fig. 7. Geological cross-section through the northern margin of the Malé Karpaty Mts. (geophysical interpretation according to I. Ibrmajer, geological interpretation by J. Michalík and D. Plašienka). Symbols: 1a – Upper Neogene cover, 1b – Lower Neogene cover; 2 – Paleogene flysch; 3 – Klape Accretionary Complex; 4 – "higher" nappes; 5 – Choč Nappe; 6 – Křížna Nappe; 7 – Tatric Mesozoic cover; 8 – Tatric crystalline basement, 8a – Upper Paleozoic sedimentary cover; 9 – Vahicum units; 10 – Klippen Belt units; 11 – Klippen Belt basement; 12 – North European Platform crust, 13 – mantle lithosphere.

sandstones, quartz, quartzites, granitoids, crystalline schists, acid and basic volcanics (Kováč 1986, Mišík 1986a). The diversity of pebble material and heavy-mineral associations in the alluvial delta fan transported in humid climatic conditions points to sources situated recently south and north of the Dobrá Voda Depression (Kováč et al. in press).

During Middle Miocene the SW part of the Carpathians underwent important paleogeographic changes due to paleostress field rotation from NNW to NE direction (Nemčok et al. 1989). Lower Miocene deposits of Jablonica and Dobrá Voda Depressions have been incorporated into the arising Malé Karpaty horst structure, separating Vienna and Danube Basins which started to open. Tectonic activity during the Badenian is well documented by sediments on the slopes of the Malé Karpaty Mts., as well as the structural pattern of their northern part.

Basin formation in SW part of the Western Carpathians during the Early Badenian was still controlled by sinistral NE–SW strike slips and N–S normal faults. The Lower Badenian transgression affected more intensively only the Vienna Basin. From the Middle Badenian, sedimentation in the Vienna Basin and the northern part of the Danube Basin was controlled above all by NNE–SSW and NE–SW normal faults. Steep morphology of the eastern Vienna Basin margin during the Middle Badenian is documented by conglomerates and breccias of the **Devínska Nová Ves Beds** (Vass et al. 1989). Granitoid boulders, some of them more than 2 *m* large, formed talus cones and debris aprons on the SW slopes of the Malé Karpaty Mts. Between Lamač and Pernek, they attain a thickness of 300–350 *m*.

Upper Badenian marine clastic shore sediments, in places with Litothamnium bioherms and patch reefs are known from a belt between Devínska Nová Ves and Rohožník. Besides conglomerates and sanstones of **Sandberg Beds,** marls of the **Studienka Formation** outcrop in this area as well. Such abrupt transition into basin facies indicates activity of NE–SW normal faults.

The sedimentation in the northwestern part of the Danube Basin started during the Middle Badenian. Upper Badenian transgressive clastics are known from NE margin of the Malé Karpaty Mts. Polymict **Doľany Conglomerate** with sand lenses originated from local sources. It contains limestone, quartz, less granitoid, phyllite, and amphibolite pebbles (Buday et al. 1962). Clays and sands rich in marine micro- and macrofauna of the **Madunice Formation** are known between Kráľová, Orešany and Smolenice. The foraminifer associations similarly as in the Vienna Basin indicate sea-water stratification into poorly aerated lower- and upper hyposaline layer (Molčíková 1961).

During the Badenian, ENE–WSW trending sinistral strike slips controlled the evolution of the northern part of the Malé Karpaty Mts. They formed the Dobrá Voda wrench fault furrow, the transpressional push-up dome of the Brezovské Mts. and caused block rotation between major strike slip faults. NW–SE dextral strike slips or dextral-normal faults and NE–SW normal faults compensated the deformation (Marko et al. in press). Counter-clockwise block rotation in the northern part of the Malé Karpaty Mts. is well documented by paleomagnetic data (Túnyi and Kováč 1990) and it resembles similar phenomena in the northern Pannonian Domain (Márton 1987).

Remnants of Upper Miocene and Pliocene sediments are preserved on both sides of the Malé Karpaty Horst. They were deposited during transtensional stage controlled by NE–SW normal faults (Nemčok et al. 1989). Marginal Sarmatian sandy deposits rich in $CaCO_3$, with mollusc shelly intercalations represent the marginal facies. Lenses of fine-grained well rounded gravels composed predominantly of quartz pebbles occur locally. The occurrence of the Nubecularia limestones, oolitic limestones and serpulid – bryozoan patch reefs near Dúbravka (Buday et al. 1962) is unique in this area.

The Pannonian clays, sands, more rarely fine gravels of coal seams (E Zone) occur in a belt from Bratislava to Pezinok (Holec et al. 1987). Deformation of Pannonian sands and clays near the village Sološnica indicates motion along NE–SW normal faults as well as along ENE–WSW trending strike slip faults (Marko et al. in press.).

Conclusions

1. Pre-Alpine basement consists of several Paleozoic volcano-sedimentary successions and of Variscan granitoids. It is composed of several superposed units comprising the basement along with its Mesozoic cover.

2. Mesozoic sedimentation in all the units could be divided into three sedimentary cycles (Triassic, Jurassic–Lower Cretaceous, Upper Cretaceous), affected by several abrupt changes (predominantly during early Carnian and during Toarcian).

3. Middle Cretaceous development has resulted in considerable space reduction during Paleoalpine compression, in nappe emplacement and complex folding. Upper Cretaceous basin has formed in eastern part (north in the present sense) of a newly established, partly emerged folded area. During the Paleogene, this sedimentary area widened westward (southern direction after Neogene rotation of whole block).

4. Compressional tectonic regime terminated in back-thrusting of the superficial nappes. Duplexes with horse-tail structures have arisen in this area. Fault bend folding has caused rotation of the individual segments along half-cylindric planes, and subsequent inclination of paleokarst plateaus on their surfaces.

5. Tertiary development can be divided into Oligocene and Early Miocene transpressional stage with dominating thrust reverse and strike slip fault tectonics, Middle Miocene transpressional stage with dominating strike slips and normal faults, opening the present-day Vienna and Danube Basins and Late Miocene–Pliocene transtensional stage with normal fault tectonics, stressing the Malé Karpaty Mts. horst structure.

Translated by K. Janáková

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