1. Geological Structure of Pre-Cenozoic Units – from the Edge of the Malé Karpaty Mts. to the Deep Basement of the Danubian Flat

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Abstract: Biotitic gneisses with sillimanite, amphibolites (s.s.), laminated metatuffites, calcium-silicate rocks with diopside and occasionally gabbro-dioritic rocks were found locally in the uncovered border of the mostly granitic crystalline area of the Malé Karpaty Mts. The periplutonic effect of the Hercynian Bratislava granitoid pluton caused metamorphic reworking of the pre-granite substrate. Relatively abundant pegmatites are characterized by dark K-feldspar, occasionally also with fan-shaped muscovite aggregates, typical of the investigated part of the Western Carpathians granite crystalline. Poly-deformation inventory of the crystalline rocks indicates Hercynian to Pliocene-Quaternary diapason of deformation structures.

Within the concept of the pre-Cenozoic basement of the Danubian Flat region, five basic tectonic (mega) units were suggested. The arrangement of these tectonic units is evaluated as Alpine (Cretaceous) with the fact that the higher structure, especially of the southern parts, was significantly modified by Tertiary tectonics. Discussions were devoted to their mutual tectonic relationship, Pannonian and Intra-Carpathian Palaeogene sediments, tectonic relationship with the neighbouring regions, etc. It can be assumed that the South-Veporicum unit forms the tectonic underlier of the Palaeozoic of the Komárno Block. The final part of the paper is devoted to discussion on Cenozoic tectonic events with an impact on the wider area of the area studied. The chronology of important fault lines is outlined, although it is often to be count on their repeated rejuvenilization.

Key words: Slovak part of Danubian Flat, pre-Cenozoic basement, Cenozoic tectonics, deformation phases, Malé Karpaty Mts., fault lines, Inner Western Carpathians

1.1 Introduction

The contribution deals with geological problems of the pre-Cenozoic units of the exposed south-west edge of the Malé Karpaty Mts. to the deep-covered basement in the SE part of the Danube Lowland – Danubian Flat region. The subject of the first part of the paper (1.2) is geological mapping, connected with the structural and petrographic studies of the narrow strip of emerging crystalline basement of the Malé Karpaty Mts., which form the NW border of the region under study (Maglay et al., 2018). The Crystalline, consisting mainly of granitoid rocks and metamorphites in part, crops out to the surface along the Malé Karpaty fault system between the towns of Bratislava and Svätý Jur. The second part of the paper (1.3) deals with considerably hypothetical issues of composition and tectonic development of the buried pre-Cenozoic basement of the Danubian Flat. Apart from several deep wells that have reached the crystalline basement at the edge of the Danube Flat, the area is filled with Cenozoic deposits reaching up to several kilometres in thickness. As to the variegated compilation sources, differing in topics and age of issuing, not directly dealing with the Cenozoic stratigraphy in this work, there are referred the original chronostratigraphic terms (mostly central Paratethys).

1.2 Malé Karpaty Mts. Crystalline rim

1.2.1 Overview of geological research

The Malé Karpaty Mts. form the Neo-Alpine horst of the SW-NE direction and together with the Hundsheim Hills (in Austria) represent the westernmost mountain range of the Western Carpathians, following the Eastern Alps units (Maheľ, 1986). The Crystalline core of the Malé Karpaty Mts. belongs to the northern domain of Tatricum megaunit situated in the overburden of the Borinka unit, affiliated to Infra-Tatricum (Plašienka et al., 1989). The Crystalline under investigation with its envelope successions (outside the region) is a part of the Alpine Bratislava nappe, namely the Bratislava sub-nappe s.s. (Plašienka et al., 1991). From the point of view of the primary Hercynian geological setting, the granitoid rocks in question build so-called Bratislava Granitoid Massif, differing in its composition and structural features from the more basic Modra Granitoid Massif (Adrian & Paul, 1864; Cambel & Valach, 1956). The residues of the metamorphic substrate conventionally belong to the so-called Pezinok-Pernek Crystalline (Cambel, 1958).

The geology of the south-eastern border of the Malé Karpaty Mts. is shown on three published regional geological maps (Koutek & Zoubek, 1936; 1936a; Maheľ & Cambel, 1972 and Polák et al., 2011; 2012). Basic information about the geological setting, lithology as well as supplementary bibliographic references can be obtained mainly from the explanatory notes to the above-mentioned geological maps. The first systematic work devoted mainly to the southern parts of the Malé Karpaty Mts. crystalline comes from Richarz (1908). Of the many published data on the geology of the crystalline and its composition, the important work was done by Cambel, who divided the Malé Karpaty Mts. metamorphic rocks into so-called Pezinok-Pernek crystalline Series and the Harmónia Series, locally admitting transitional relationships between these series (Cambel, 1958; Cambel in Buday et al., 1962). The granitoid rocks of the Malé Karpaty Mts. are divided into Bratislava and Modra granitoid massifs. The first consists of acidic and more coarse-grained granites-granodiorites, the substrate of which is formed by the Pezinok-Pernek Crystalline. The Modra Granitoid Massif is build of more basic granodiorites to tonalites and is bound to metasediments of the Harmónia Series. The basic work on the spatial distribution of the granitoid rocks, their petrography and petrochemical classification (Cambel & Valach, 1956) was later followed by a geochemical-petrological study on the typology and petrogenetic differentiation of the Malé Karpaty Mts. granitoids (Cambel & Vilinovič, 1987). Isotopic geochronological assays of the Malé Karpaty Mts. granites are summarized by Cambel et al. (1990) and report mostly the Early Carboniferous ages. The most recent dating specified the age of the Bratislava Granitoid Massif at approximately 355 ± 5 mil. years (Kohút et al., 2009).

The Harmónia Series was stratigraphically classified into the Devonian on the basis of the findings of sporadic remnants of tentaculites (Horný & Chlupáč in Buday et al., 1962). The Silurian-Devonian age range is judged on the basis of a palynological study of crystalline schist in the area of the Bratislava Massif (Čorná, 1968; Planderová & Pahr, 1983). This was later supported by the geochronological dating of synsedimentary basic magmatism situated in the upper parts of the Early Palaeozoic formation (in the Pernek area), set at 371 million years (Putiš et al., 2009a). Based on the geochemical study, Ivan et al. (2001) proposed to redefine the division of the Early Palaeozoic formations of the Malé Karpaty Mts. i.e. the Harmónia Series and the Pezinok-Pernek Crystalline (sensu Cambel, 1958) into Pernek (metabasalts of the N-MORB type) and Pezinok Groups (metabasalts of the E-MORB type, intra-continental or island arches), which should occupy a different spatial configuration.

The pre-granitoid Hercynian regional metamorphic fabrics of the Early Palaeozoic volcanic-sedimentary complexes reached only low-grade conditions, while the periplutonic metamorphosis left a fundamental metamorphic seal in the crystalline schists. The so-called regional periplutonic metamorphosis in the area of the Bratislava Granitoid Massif was characterized by the separation into four metamorphic zones – from the lowest biotite zone to the highest staurolite-sillimanite zone – based on a petrological study (Korikovskij et al., 1984). Alpine metamorphosis is manifested mainly in mylonite zones in the crystalline and reached anchimetamorphosis conditions (Putiš, 1987; Plašienka et al., 1993). The age of the Alpine deformation in the Bratislava Granitoid Massif is geochronologically determined at 77 mil. years, or 81 mil. years (Kantor et al., 1987; Putiš et al., 2009).

1.2.2 Results of geological mapping and petrography

The rim of the Malé Karpaty Mts. belonging to the Danubian Flat was geologically mapped in the width of 0.5 to 1 km, starting from the surroundings of Svätý Jur to the area opposite the island Sihoť in Karlova Ves (district of Bratislava). The geological mapping was mostly carried out in the environment of disappearing vineyards by means of mapping of eluvial debris, which, however, is often obscured by new as well as historical anthropogenic landfills and recultivations. Structural data were measured on the rocky outcrops (approx. 80 documentary points), of which a considerable part arose due to the current development construction activity in the area. On the other hand, some of the traditional rock exposures in Bratislava could not be re-assessed due to development activities, earthworks, or sites have been inaccessible because of new property rights.

Crystalline rocks are exposed at the foot of the mountain range – especially various types of granitoid and pegmatitoid rocks, which are largely covered by Quaternary deluvial, fluvial sediments and sporadically loess horizons. The following description of basic crystalline rocks proceeds from relatively oldest to younger rock types.

Biotite gneisses (massive gneisses, schistose mica gneisses, migmatitized gneisses)

The designation of biotite gneiss includes rock types ranging from fine-grained biotite phyllites to gneisses with black shiny biotite foliation planes to coarse-grained banded types with migmatitic textures (Fig. 1.1). The lower metamorphosed fine-grained gneisses as well as migmatitic gneisses cannot be strictly differentiated in the given map image for the rather small territorial extent as well as obscure interrelationships. The intensity of the grey coloration of metamorphites depends on the proportions of biotite and feldspar-silica mass (in local cases also on the presence of organic substance). In the scale of the map displayable occurrences of dark biotitic ores can be found e.g. in fresh excavations in the area of the Chapel of J. Nepomucký in the southern part of Svätý Jur (Fig. 1.1a). High-metamorphic "injection" migmatitic gneisses are best seen in the Svätý Jur area (Figs. 1.1b,c), but in fragments sporadically also in other places of the Rača district, in excavations above the railway depot in Bratislava).

Petrographically, the rocks have a lepido-granoblastic texture; with increasing metamorphosis the oriented but dispersed biotite is more segregated into continuous foliation planes. Small garnet is present in small quantities, reaching up to about 1 mm. The degree of metamorphosis is closely related to the injection manifestations of the granites, which is petrographically documented by blastesis of orders of magnitude larger biotite flakes against the biotite of the "matrix" in contact with the bands of penetrating coarse-grained granitic leucosome. The periplutonic/near-contact effect on the primary structure of the biotite gneiss also leads to the origination of transverse muscovite flakes, in which fibrolithic sillimanite is often formed.

Amphibolic rocks/basic tuffs, amphibolites, local gabbrodiorites

Rocks containing amphibole, starting from the north, begin to appear from the valley of the Vajnorský potok Brook. The amphibolic rocks usually have a dark green to grey-green colour and are mostly fine-grained. In the small natural exposures, they can be identified around the Bratislava – Rača district. From the spatial as well as from the lithological point of view it is probably a rock complex stretching from the area of the altitudinal

Fig. 1.1 Biotite gneisses: a) sub-vertically dipping biotite gneiss, loc. injected with leucocratic material (excavation of the family estate SW part of Svätý Jur); (b) demonstration of ptygmatitic folding in a migmatitized biotitic gneiss (a fragment in the vineyard between Grinava and Svätý Jur villages); c) stromatitic migmatite with two phases of leucocratic material (local rubble to the SW of the centre of Svätý Jur)

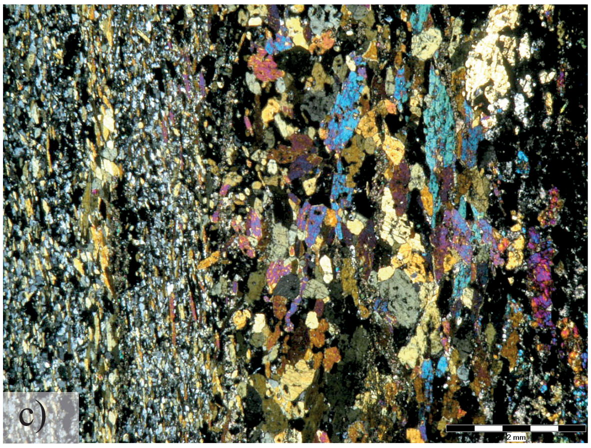

Fig. 1.2 Amphibolic rocks: a) chorismite texture composed of portions of amphibolite (dark) and calcium-silicate rock (light green) injected by aplitic vein in an advanced Hercynian -magmatic process (stone from the unpaved vineyard wall in Rača); b, c) different strips can be distinguished in the banded basic metatuffite (microscope image at II and X nicols, sample 194b): very fine-grained epidote in dark-shaded matrix; a minor epidote in association with amphibole; stripe composed of 1 – 2 mm olive-green amphibole and stripe of fine-grained amphibole and grains of quartz (locality: small exposure on a hill about 500 m NE of the terminal tram station in Rača)

points of Veľká and Malá baňa (north of Rača, beyond the investigated territory of the Danubian Flat, Maglay et al., 2018). Fragments of the amphibolic rocks are sporadically encountered at the foot of the slopes belonging to the Vinohrady district. Some fragments resemble the gabbrodioritic rocks of the type sporadically found in the wider area of the Horský park.

The predominant banded metamorphic texture first reflects the fine lamination of the primary pyroclastic rock. In contrasting amphibolic rocks, the pale veins of aplites and pegmatites penetrate into them (Fig. 1.2a). The alternation of light green and dark bands illustrates the composite lamination of basic tuff-tuffite (Fig. 1.2b,c. The basic mineral content – common amphibole, actinolite, plagioclase, epidote (clinozoisite), diopside or titanite and ilmenite was determined by petrography. The composition suggests that the carbonate component also built the primary composition, so the rocks studied can be genetically compared to the calcium-silicate rocks described from some sites of the Malé Karpaty Mts. metamorphic crystalline (Koutek & Zoubek, 1936; Cambel et al., 1989). The rocks underwent intense changes – plagioclase is practically replaced by dark clay minerals, sericite and fine clinozoisite; amphibole or clinopyroxene are mostly substituted by epidote and chlorite.

Granites-granodiorites

a) medium- to coarse-grained two-mica granites, locally fine-grained biotite granodiorite

Within the granitic rocks, the dominant position is occupied by medium to coarse-grained granites, usually of two-mica, sometimes biotitic types. We encounter them in practically the entire mapped zone, although in the southern half of the area, they are more abundantly leucocratic, muscovite types (see b). In the area of granites there are sporadically occurring small remnants of gneiss, sometimes only the oriented biotite relics in the granite mass. Basic ***two-mica granites*** have light grey to white shades, omnidirectional texture and used to be systematically dotted with black biotite. The granites are usually two-mica, but in places they contain only biotite (rarely just muscovite). In the exposures they are fractured by a complex network of fissures, often appearing in the form of irregular 0.5 – 1 m thick positions, separated by shallowly sloping plate jointing (Fig. 1.3a). From natural exposures or former quarries based in Bratislava granites we mention e.g. localities from Svätý Jur, northern edge of Rača and partly Roessler quarry in the Vinohrady district.

In the composition of these granites light components prevail – quartz, acid plagioclase and K-feldspar. The average mineral grain size of these granites is about 3 – 5 mm, while K-feldspar tends to form poikilitic phenocrysts, in places reaching up to 1 – 1.5 cm. In this way, the granite shows an indistinct porphyric character at places. Pertitization is frequently observed in K-feldspar phenocrysts, and often domains with a transition to a triclinic structure in the form of microcline lattice. Enclosures in K-feldspar are plagioclase and biotite, to a lesser extent quartz, muscovite and, in the case of acid members, the remnants of the older K-feldspar. Enclosed plagioclase is usually rimmed by albite, which, like albite grains with myrmekite, originated in the final stages of magmatic rock evolution.

A relatively rare, spatially limited, but at the same time characteristic granitoid member is represented by fine to medium-grained ***biotite granodiorites*** or granites. They have usually free igneous contacts with predominant granites, from which they differ macroscopically, apart from the granularity, in deeper grey shades and higher content of biotite and plagioclase. In fine-grained, equigranular textures, biotite phenocryst, sometimes also feldspar, in size up to 1 cm, can be observed at places (Fig. 1.3b). The microscopic structure of these rocks is clearly hypidiomorphic ("granitic"), which is documented by regularly limited crystal shapes of plagioclase. In a mineral composition with a grain size of about 1 mm, strongly sericitized plagioclase predominates over quartz. Rock can also be referred to as microgranodiorite, in places we do not exclude primary tonalite composition. In some cases, the finer-grained varieties with sporadic phenocrysts resemble granodiorite porphyrite. Dark-shaded, directly constrained fine-grained clinozoisite aggregates, usually bounded by a clear albite rim, suggest higher plagioclase basicity than commonly occurring granites. The mineral composition is sometimes enriched by muscovite and/or a K-feldspar phenocryst; in such a case the rock approaches the above mentioned granite.

The Bratislava granites often underwent *secondary fabric and deformation changes* of different intensity. Sericitization of plagioclase and chloritization of biotite in common types of granites imparts a green colour to the rocks; we can observe this phenomenon e.g. in fragments NE of the Svätý Jur's proluvial cone. Saussuritized more basic types of granitoids or mylonitization in general, change the colour of the rocks to dark grey shades. Cataclastic deformation of the granitic rocks is usually manifested in the form of so-called kakiritization. The local increase in deformation leads to the formation of mylonites and quartz blastomylonites, where it is difficult to determine the original character of the rock. Mineral changes are reflected in the formation of epidote-zoisite group minerals (especially at the expense of biotite and plagioclase), albitization, sericitization up to the origination of small muscovite crystals (at the expense of plagioclase), baueritization with simultaneous formation of Fe-oxides or chloritization (biotite alteration) and generally formation of clay minerals, as well as secondary enrichment in quartz.

b) leucocratic (pegmatitoid) granites

Field and petrographic observations of leucocratic granites point to gradual progression from the basic granites of the Bratislava Massif (Figs. 1.3c,e). They often pass into coarse-grained pegmatitoid nests. In general, they are poorer in micas, but in many cases contain conspicuous muscovite, and sometimes biotite also appears. By comparison with the slopes of the wider area of Svätý Jur, the leucocratic types occur more abundantly from the surroundings of Rača to the south. In the SE part of the territory, the pegmatitoid rocks occurring along with leucocratic granites indicate that both rocks are interrelated and represent the final stages of granitoid pluton evolution. In many places, the leucocratic granites also bear distinct signs of dynamic magmatic flow (Figs. 1.3c,f) or Late-Hercynian semiductile deformation (Fig. 1.4a), prior to the youngest stage of pegmatite formation. In the wider area of Bratislava, where these rocks are more widespread, there is a typical occurrence of fan-like muscovite aggregates (Fig. 1.4b), which are rare in other parts of the Western Carpathians granite crystalline.

Light coarse-grained granitic derivatives predominate both in surface debris and in the form of resistant natural exposures. However, it is obvious from the excavation material in the wider area of Koliba, the Bratislava Castle Hill or from the rare natural exposures that common types

Fig. 1.3 a) characteristic disintegration of granites of the Bratislava Massif (excavation of the northern edge of the Svätý Jur Town); (b) fine-grained biotite granodiorite with biotite phenocryst (ditto); c) penetration of the leucocratic melt into the "basic" granites (Račí potok Brook); d) accumulation of coarse-grained K-feldspars in a leucocratic granite (a fragment at the church in Neštich); e) contact of the three most widespread granite rocks: leucocratic granite (upper left corner), darker two-mica granite (in the middle) in direct contact with pegmatite (rubble dumps SE of altitudinal point Vtáčnik, Bratislava-Vinohrady); (f) diatextite rich in pegmatitoid leucosome (blocks on the ridge between the Fanglovský and Račí potok streams)

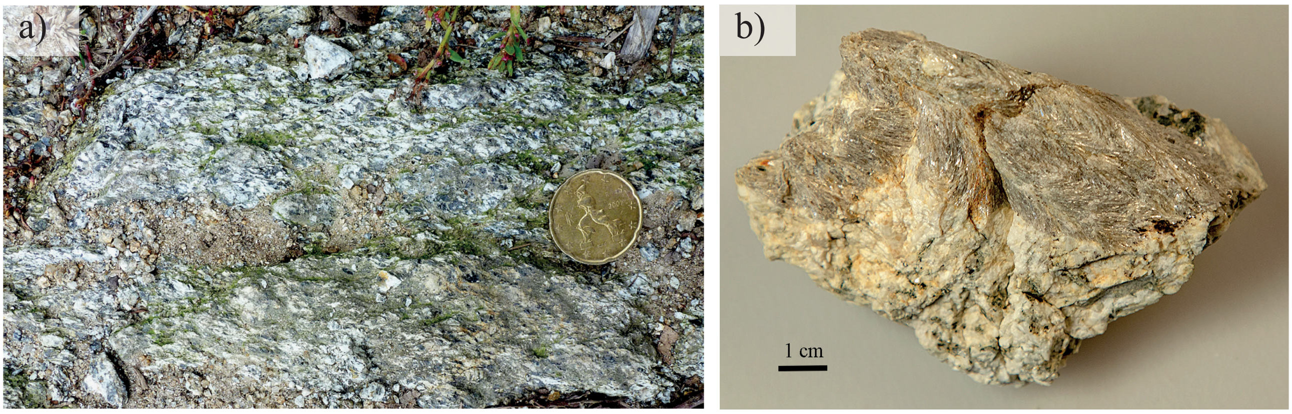

Fig. 1.4 a) leucocratic granite with pre-Alpine s-c structure (outcrop of the vineyard road bottom SW of Grinava); (b) fan-shaped muscovite aggregate in light pegmatitoid granite

of granites, biotite gneisses, and local amphibolites are also to be found. We assume that the neoid alpinotype deformation, which has more pronounced manifestations on the south-eastern tip of the Malé Karpaty Mts. contributed to this picture. Deformation rather affects regionally extended granites-granodiorites, which are then more liable to weathering than the coarse-grained quartzose pegmatitoids.

Coarse-grained muscovite pegmatites and massive aplites

Coarse-grained pegmatites appear in the form of veins penetrating along brittle joints in the apical parts of the Bratislava Granitoid Massif. Pegmatites most often range in thickness from x-dm to first m. Macroscopically, they are characterized by an increased proportion of quartz, albite, K-feldspar (up to 6 – 8 cm) and often 3 – 4 cm flakes of muscovite, which is sometimes alternated by biotite (Fig. 1.5). Characteristic is the grey-coloured microcline, the product of primary crystallization of residual granitic solutions. We separate pegmatites from the above-mentioned leucocratic ("pegmatitoid") granites on the basis of a direct venous course, characterized by a coarse-grained, sometimes partially graphitic or zonal pegmatite texture (zone of clear quartz crystals concentrated in the middle vein). They were formed after solidification of the basic granites, although we admit that in the case of weakly crystallized pegmatite, the structural or mineralogical difference is not always strict in comparison with the leucocratic granite.

Fine-grained white aplites with an average grain size of approximately 1 mm occur commonly along with pegmatites. In a light, "sugary" homogeneous mass of aplites, almost mica-free, a reddish garnet sometimes appears, occasionally we can observe a 2 – 3 mm K- feldspar phenocryst, too.

1.2.3 Summarized geological development and deformations on the SE edge of the Malé Karpaty Mts. Crystalline

The oldest geological unit is formed by Lower Palaeozoic crystalline schists, representing the metamorphic mantle of the Malé Karpaty Mts. granitoids. These rock sequences underwent a low-degree metamorphosis at the boundary of the Devonian-Carboniferous period ("Hercynian regional

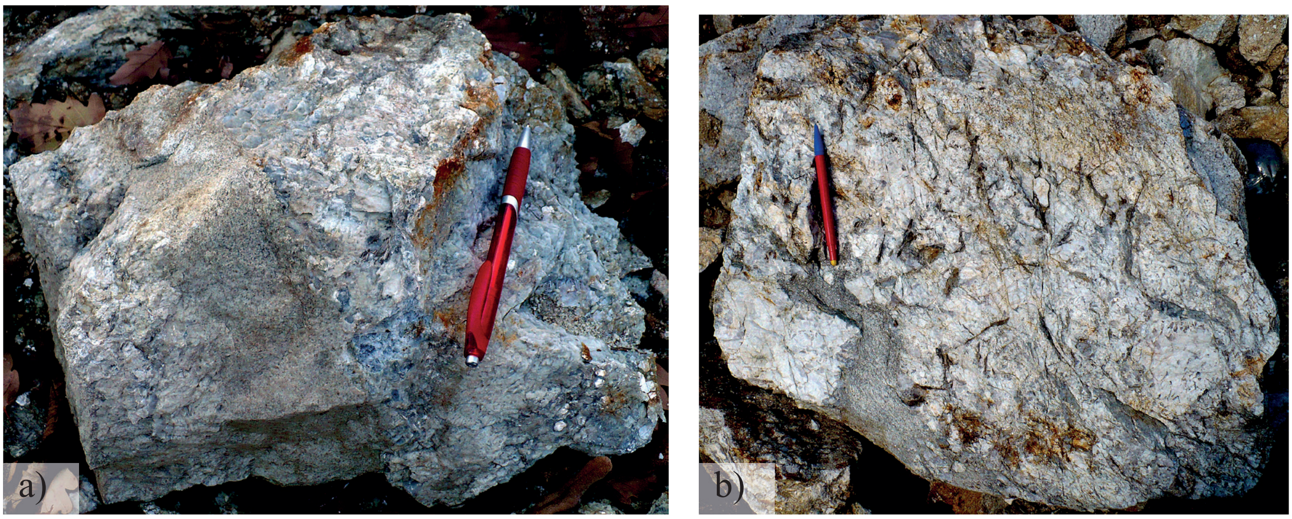

Fig. 1.5 a) coarse-grained muscovite-rich pegmatite in a sharp contact with granite (a construction pit of a family house, Pekná cesta Street); b) feldspar pegmatite melt with biotite phenocrysts enclosing high-temperature mixed residue of grey granite (construction work NE of the railway depot in Bratislava)

metamorphosis") by forming various types of phyllites. This event was followed by a dominant metamorphic recrystallization, caused by the penetration of the Hercynian granitoid rocks (approx. 350 million years ago). High temperatures as well as fluid contribution from the granitoid rocks of the Bratislava Massif fundamentally reworked the Lower Palaeozoic rock complexes ("periplutonic regional metamorphosis").

In the vicinity of the intruding granitoids and the phyllites of a clayey-sandy protolith, garnet-biotite gneisses formed. In the gneisses with a temperature increase, the phenocrysts of biotite grew in size, the muscovite flakes formed and in the mica the formation of fibrous sillimanite took place. This metamorphosis of the medium to higher grade of the low-pressure type amphibolite facies was accompanied by the formation of biotite foliation planes. Due to the penetrating leucocratic melt and the ductile folding, various textural forms of migmatite developed in localized zones.

Syndepositional basic volcanism, often mixed with the sedimentary component, was metamorphosed into varied textural and mineral types of amphibolic rocks. Sometimes even primary characters can be identified – e.g. light phenocrysts of the original plagioclase, magmatic minerals or the original banding of basic tuff to tuffite. Common amphiboles along with plagioclase, titanite, etc., represent a metamorphic transformation of the basic magmatic protolith. Clastic, pelitic and calcareous sedimentary components took part in the formation of strips composed of quartz, muscovite or diopside, clinozoisite, etc. Near the border of the investigated region, bodies of amphibolic diorites (even gabbrodiorites) are known enclosed in the granitoid massif, which have in our view a primary connection with the basic magmatites of the metamorphic mantle.

From a broader geological view, the metamorphic mantle rock composition of the Malé Karpaty Mts. Crystalline has even more peculiarities – there are no products of acidic magmatism ("orthogneisses"), which could occur prior to the Hercynian granitization, or high-metamorphic banded volcanogenic complexes ("leptinite-amphibolite complex"), which are common in the other areas of the Western Carpathians Crystalline. It is likely that the material derived from this "older" crystalline is the major sedimentary source of the crystalline schists of the Malé Karpaty Mts., which has been varied with by concurrent underwater volcanic activity. The composition, age and type of metamorphosis make it possible to consider these crystalline schists as representative of the "young" (upper) crystalline within the Western Carpathians crystalline units (Kováčik, 2005).

The basic granitoid mass is built of two-mica to biotite granite, and local granodiorite. Local occurrence of fine-grained biotitic granodiorites (formerly tonalites?) is understood in terms of penetrating of more basic melt into the crustal substratum, from which granites of the Bratislava Massif are melted by partial anatexis (however, the primary character of these rocks is mostly obscured by the mixing of granite magmas). Following from Rača to the centre of Bratislava, the presence of pegmatitoid material, in the form of leucocratic pegmatitoid granites, quartz-enriched granites or coarse-muscovite pegmatites themselves, becomes increasingly striking. Sometimes they have free relationship – one type slowly transits into the other, sometimes they are marked by sharp contact. For instance, notable is sharply bounded leucocratic granitic melt on contact with another type of granite or migmatite, indicating its penetration into a cooled, brittle-deformed environment. The described phenomena document the complex polyphase tectonic and magmatic Late-Hercynian evolution, which apparently relates to differential uplift processes.

The crystalline mass of the Bratislava Massif is greatly disturbed by the *"young" tectonics*, and the failure intensity appears to be increasing southwards. In the rock exposures, we often observe an opaque network of irregular brittle failures that mask older structural elements. The bearer of the oldest structural record is the gneiss (locally the amphibolite) substrate. Its deformation structures are expressed by basic metamorphic foliation, or fold-shear reworking, which can be identified with textural features of migmatitization. The dominant metamorphic structures have approximately E-W directions (ranging from 70 – 250° to 120 – 300°), usually dipping in moderate to steep angles to the south. This Hercynian metamorphic structure was in many cases injected with granitoid rocks, usually leucocratic granites. Mostly they conform to the structural pattern of the metamorphic substrate, which is copied by the basic separation of granite slabs, rarely biotite relics fabrics, or the ductile deformation texture of granitoids. Pre-Alpine rock succession ceased by the veins of pegmatites and aplites intersecting the already solidified basic granitoids of the Bratislava Massif. The course of these veins also ranges roughly in the direction E-W and NE-SW.

As a relatively widespread subsequent deformation process we consider Alpine (Cretaceous) secondary schistosity, which is more readable in granites and pegmatites than in the gneiss material. In particular, it manifests itself in the form of irregular, shallowly inclined cataclastic to mylonitic (partly blastomylonitic) schistosity. These deformations follow in particular the aforementioned older directions, but only with slight southern dips. Often, they also dip to the east or north-west directions. This deformation process can first be identified with the structural manifestations associated with the overthrust of the so-called Bratislava nappe.

We assume the tangle of various fracture failures as gradual manifestations of Neo-Alpine (Cenozoic) tectonics. For example, they can be studied in excavation works at the Bratislava Castle Hill (Figs. 1.6a,b; see also Madarás et al., 2014). In a microscale, the deformation of granites along such failures can usually be referred to as so-called kakiritization and occasionally even narrow mylonitic bands appear. The variously-oriented fissures are predominantly steep to subvertical. Informatively examined main failures are usually oriented in NW-SE and N-S directions, but one can also observe NE-SW and E-W course.

Fig. 1.6 The excavation works in the area of the Bratislava Castle testify to a multiphase neoid tectonic failures of the Castle Cliff; a) brittle deformation, prevailing failure directions dipping to the east; (b) young failure accompanied by the development of a light tectonic clay (scale – geological hammer)

The orientation of the first three mentioned failure directions in the marginal part of the Malé Karpaty Mts. is significantly reflected in the dominant tectonic lines of the pre-Neogene basement of the investigated region. In the structural plan of fault failures of the Neogene age, the inheritance of the E-W directions no longer occurs in such a frequency as in the previous deformation processes. A mylonite failure zone of irregular sub-horizontal course (Fig. 1.6) intersecting steep failures was recorded in the fresh excavation for multi-storey garages below the Bratislava Castle. This points to relatively young fault-controlled movements of the crystalline mass blocks.

Late manifestations of the Malé Karpaty Mts. uplift fault tectonics are also signalized by a slight inclination (about 10°) of sporadic loess sediments, irregularly preserved on the sunken granitic blocks (e.g. the western part of the Castle Hill above Lafranconi). The other geological argumentation of the relatively young tectonic activity provides the presence of grey calcareous clays in the direct basement of the Quaternary slopes in the lower part of the vineyards in Rača and Krasňany suburbs (ascertained from a shallow borehole and excavation of a residential house at Jurajov dvor tram station area). It is a Vráble formation of the Sarmatian age (oral information by K. Fordinál), which proves for the significant Late Miocene to younger uplift movements of this part of the mountain range, probably along the *Malé Karpaty Mts. fault*.

1.3 Covered pre-Cenozoic basement of the Danubian Flat

The Danube Basin represents a tectonically inhomogeneous unit – a superposed Neogene basin with genetically and tectonically diverse crystalline and Mesozoic basement (Buday et al., 1967). The eastern part of the region in question forms a depression with the greatest depth in the area of the Gabčíkovo Depression, estimated on the basis of geophysical data to be about 5,500 m (Fusán et al, 1987) or up to 8,500 – 9,000 m (Hrušecký, 1999). It is obvious that imaging of the pre-Cenozoic basement of the Danube Basin is burdened by a high degree of uncertainty due to the lack of necessary data. The construction of the basement structure depends not only on the quality of geophysical data, but also on the development of regional geological knowledge on a wider scale. Indirect and incomplete information on the nature of the pre-Cenozoic substrate often leads to diverse, often contradictory interpretations, which are mostly influenced by the ideas of tectogenesis of the Western Carpathians of a particular researcher. Similarly, the present study, together with the basement scheme (Fig. 1.7), bears a seal of subjective view. We are aware that the outline of the Cenozoic tectonics in the demarcated area is just one of the attempts to schematicize the continuous geodynamic events in a regional scale. In the following text we rely mainly on supporting geological publications dealing with the fundament of the central part of the Danube Basin and from other works we select data that we consider to be the most relevant.

1.3.1 Overview of pre-Cenozoic basement research and maps

Substantial progress in the knowledge of the geological structure of the Danube Basin basement was brought by deep drillings, which were largely realized in the 50 – 60s of the 20th century. They were focused on the prospecting for hydrocarbon sources, later also for geothermal purposes. In our territory, such boreholes extending into the pre-Mesozoic basement are summarized above all in the work of Biela (1978). Any further information can be found in the references cited here, mostly manuscripts. The first significant works, based primarily on the gravimetric image of the Danubian Lowland as well as the initial seismic, magnetometric data and knowledge from deep wells were published by Adam & Dlabač (1961), Pagáč (1964) and Buday & Špička (1967). The then tectonic interpretations were connected with the current knowledge gained during the compilation of the first edition of the general geological maps at a scale of 1: 200,000. The latter work presented a comprehensive view of the geological setting of the basement, in rough terms in the sense of today's regional geological understanding of the Inner Western Carpathians, and pointed out the importance of NW-SE and S-N tectonic lines.

From a comprehensive study of the SE part of the Danubian Plain (Gaža & Beinhauerová, 1977) it follows that the normal-slip movements of the faults do not have a significant effect on the Early Badenian deposits, since the faults are generally considered to be younger. Near the village of Zelený Háj (borehole ZH-1 in Biela, 1978) north of Komárno, various facies types of fossiliferous limestones were found below the Pannonian deposits at the depth of 1,608 m, whose age was determined on stratigraphy of tentaculites to be Devonian, most likely the Middle Devonian (Biely & Kullmanová, 1979). In the discussion about the tectonic affiliation of these, almost non-metamorphosed sediments, this work considered them to be part of the basement of the Transdanubian Mountains, which has an affinity to the Northern Greywacke Zone or the Spiš-Gemer Ore Mountains (SGR). The results of the Danube Basin basement research together with other Cenozoic basins in the Inner Carpathian Cenozoic basins were summarized and tectonically evaluated in the comprehensive work by Fusán et al. (1987).

Hrušecký (1999) provides an integrated study from the central part of the Danube Basin, emphasizing the importance of the Čertovica-Mojmírovce fault system and the Hurbanovo line, particularly on the basis of the results of reflective seismic profiles. He also draws attention to the Kolárovo, Ripňany, Medveďov and Cífer faults, but he does not consider the NW-SE fault lines to be well-documented, such as the Pezinok, Dobrá Voda or Danube faults. On the other hand, the *Dobrá Voda (Ludince) line* is regarded as a major fault line forming the Danube Basin (Fusán et al., 1987), which is conjoined by the parallel Pezinok and Danube faults, along which the basin gradually sinks in the southwest direction. Recent work in the Danube Basin (Hók et al., 2016) also attributes considerable importance to the faults in this direction, and along the Ludince line, which the authors refer to as the transverse fault in the Danube Basin; they suggest the Late Oligocene shift of the Malé Karpaty Mts. to the northwest.

Available geological and geophysical data from the basement also include a 3D geological model of the Danube Basin created within the TRANSENERGY project (Kronome et al., 2014), which was preceded by the tripartite project DANREG (Matura et al., 2000). The DANREG basement map shows the greater part of the Danubian Flat as the Greywacke Zone and in particular it is correlated with the Graz Palaeozoic. The contact with the south-eastern unit of *Pelsö* (see below) and its relationship with other Western Carpathian units are expressed along the Rába and Hurbanovo fault zones with white zones depicting an unknown basement (Matura et al., l.c.), which, despite cross-border cooperation, underlines the inconsistency in regional geological conceptions.

The southern part of Slovak Danube Basin area was also a part of the paper on Hungary's pre-Neogene basement (Wein, 1973). In the enclosed schemes the NE-SW fault lines separate the main tectonic units, which apparently pass further into the Slovak territory. Towards the Hungarian-Austrian border, it is the Lower-Austroalpine Sopron Crystalline, which is replaced by the Koeszeg-Rechnitz Palaeozoic east of Mosonmagyarovár (the author was aware that many Austrian geologists consider the Rechnitz phyllites as a Jurassic unit of the of Penninic; which is now a reliable fact – note). Approximately east of the connection between Györ and Nové Zámky, the basement is defined within the vast zone of the Transdanubian Mountains, which is approximately delimited in the area between the Rába and Balaton (sometimes also the Mid-Hungarian) lines. This geological structure is built of epicontinental Oligocene-Eocene sediments with Mesozoic islands, which point to slice tectonics along fault lines.

A more or less similar picture provides the Hungary's pre-Cenozoic basement scheme (Fülöp, 1989), where the "Rába low-graded metamorphites" are depicted also north of the Danube in the section from Šamorín till the inflow of Rába into the Danube – it means approximately in the deepest depression of the investigated part of the Danube Basin. Geophysical-geological characteristics of the Danube Basin, together with a relatively detailed elaboration of its Slovak part, are provided by Balla (1994). The inventive elements of this work include an unconventional conception of phyllite rocks in the wider area of the Mihalyi Elevation as a possible continuation of the Penninic Mesozoic. The Penninic zone also includes calcareous-shale rocks of unclear lithostratigraphic affiliation from deep wells in the Sereď area. The tectonic conception of Leško & Varga (1980) supposes the presence of *Penninic* in the Central Depression of the Danube Basin and Fusán et. al. (1987) do not exclude such a solution in the discussion, too.

In the new geological map of the pre-Cenozoic units of Hungary (Haas et al., 2010), till the Mosonmagyarovár, the Lower Austro-Alpine Crystalline is depicted. Furthermore, in the area of the largest deepening of the Danube Basin (up to 7,000 m approx. in the polygon of Mosonmagyarovár – Csorna – Györ), an unknown basement is marked and so-called *Transdanubic*, consisting mainly of Mesozoic rocks, is present east of Györ. From the west, the *Transdanubic* creates a narrow strip of the low-metamorphosed Variscan lithological complex, followed by Permian continental deposits, probably in the envelope position. The Jurassic-Cretaceous Penninic unit – the Rechnitz Tectonic Outlier – emerges between the towns of Szombathely and Község beneath this rock complex. East of the confluence of the Danube and the Mosoni Danube, the Mesozoic rocks are present in the Transdanubic zone, divided into different age and facies categories, such as the indicated alternations of deep-water and shallow-water facies even within adjacent chronostratigraphically identical units (Haas et al., l.c.).

A mega-block north of the Mid-Hungarian (Transdanubian) line is defined in most recent Alpine-Carpathian-Pannonian syntheses as a Pelsö composite unit (named after the Latin name of Lake Balaton, sensu Fülöp et al., 1987), or the Transdanubic (Haas et al., 2010). The presence of Cretaceous deposits, similar facies development of many Mesozoic members, and very low metamorphic imprint of both the Palaeozoic and Mesozoic rocks, led to a correlation of the area south of the Diosjenö-Hurbanovo line with the Dinarides, or Southern Alpine tectonic units (e.g. Haas & Kovács in Haas, 2013). However, the tectonic-province affiliation of the Mesozoic unit of the Transdanubian Mountains, Tari et al. (2010) traditionally incorporate into the Upper Austroalpine Unit.

1.3.2 Construction of the basement scheme – basic principles

In the submitted sketch-scheme of the pre-Mesozoic basement of the Danubian Flat (Fig. 1.7) we start from the conventional conception of the geological structure of the Inner Western Carpathians (e. g. Maheľ, 1986; Fusán et al., 1987). Based on geophysical, spatial and drilling data the fundamental tectonic units (designated as numbers 3 to 5 in Fig. 1.7) consist from the Crystalline, although the presence of Mesozoic relics may be considered in the area north of the Ludince fault (Dobrá Voda line) towards Nitra. To the aforementioned usual basement schemes of the Danube Basin we associate the *South-Veporicum Crystalline* and, in terms of the ubiquitous Neo-Alpine deformation west of the Cífer faults (sensu Hrušecký, 1999) we suggest *the external domain of Tatricum*. From an indicative study of available thin-sections material as well as geophysical information this part of the Tatricum Crystalline seems to be affected by intense cataclastic deformation, often healed by calcite veins. This is likely to be associated with a more intensive activity of younger N-S fault system in this segment, as well as with manifestations of NNE-SSW failures at the edge of the Malé Karpaty Horst. The course of these failures, including the Cífer faults, can be perceived as being approximately parallel to the direction of the "Mur-Mürz-Leitha" lineament (e.g. Bada et al., 1999, Hók et al., 2000). From the Crystalline itself, it is difficult to deduce its affiliation to the basic Central Carpathian tectonic units – the interaction of the crystalline units was primarily derived from the extrapolation of the basic tectonic lines found at the surface north of the Danube Basin.

In the southern part of the territory in question depicted unit of the Southern Veporicum belongs to the basement composition not only for its tectonic position, but also for its peculiarities in the Crystalline rock composition, in the intensity of Alpine metamorphosis and because of its difference in the Triassic lithology of the Mesozoic cover compared to the Northern Veporicum (it is an overall regional concept that does not directly follow from the data from the pre-Cenozoic basement). We believe that the basic superposition relations of the Palaeoalpine (Cretaceous) structure are also preserved towards the covered basement in the south. The Southern Veporicum rests below the low-metamorphosed older Palaeozoic – Gemericum fundament or Greywacke Series with its Upper-Palaeozoic cover (indicated by information from the borehole Modrany 2, outside the region, Biela, 1978), which is further covered by the Mesozoic of the Transdanubian (Mid-Hungarian) Mountains (s.l.). These relationships of Palaeoalpine nappe tectonics are camouflaged by younger fault-tectonics, which also formed a Cenozoic basinal filling.

In Fig. 1.7 there are depicted only the basic fault lines that are assumed to be related to the basement and to a greater or lesser extent illustrate the separation of the underlying tectonic basement units. The faults under the Danube Basin can be pinnate, they can change direction, slope, or interfere with each other and their appearance at the surface may not fully reflect the situation in the pre-Neogene basement. For the repetition of structurally similarly oriented tectonic movements during geological evolution, we can speak of the age of fault only within a certain time limit. Thus, e.g. the connection of the Rába line to the relatively younger(?) system of Šurany faults cannot be excluded.

The basic intra-Carpathian (Palaeoalpine) NE-SW tectonic lines appear to represent the Mojmírovce faults (a certain analogy of the Čertovica Line) as well as the assumed continuation of the Pohorelá fault system. Possible continuation of the Cretaceous tectonic lines of the 1st order in the basement of the Danube Basin is difficult to discern due to Palaeogene to Early Miocene collision processes and younger failure disturbances, but in the pre-Alpine basement their juvenile record can be assumed. The tectonic arrangement of the basement of the northern parts of the Vienna Basin, as well as the Transdanubic, shows that the Tertiary collision structure did not include the crystalline ("Lower Austroalpine" units), suggesting certain preservation of older, albeit partially remobilized deep-seated lines in the pre-Cenozoic basement.

The crystalline basement under the Cenozoic fill of the Danubian Flat defines roughly the Ludince fault from the north, and the Hurbanovo and Rába(?) faults in the south. The faults of the NW-SE ("Sudeten") direction have a transverse course to the basic intra-Carpathian lines. They also pass through the Malé Karpaty mountain range and are relatively younger than its basic structural pattern. The Danubian Flat region from the south delimits a young system of the Danube faults of the same direction. In the middle part, we can assume the Pezinok fault, which could has been primarily established in the Palaeozoic (it follows the synclinorium of the Pezinok-Pernek productive zone) and, last but not least, it was reactivated in the Late Miocene period.

1.3.3 Interpretation and discussion notes

1.3.3.1 Sketch of pre-Cenozoic basement

Concerning the affiliation of the Palaeozoic rocks (No. 2 in the legend, Fig. 1.7) in the SE part of the Danubian Flat we are in favour of interpretation, that it is a higher tectonic unit of the Inner Western Carpathians, which can be compared to the Upper Austro-Alpine nappes, namely the Greywacke Zone unit or Spiš-Gemer Ore Mountains (Biely & Kullmanová, l.c.). Due to the lithostratigraphic nature of rocks from the ZH-1 deep well, correlation relations could be sought in the area of the Graz Palaeozoic rather than in the uncovered parts of the Spiš-Gemer Ore Mountains. There is a varied suite of carbonate and lydite horizons with biostratigraphically documented Devonian age in the units of the Graz Palaeozoic (Flügel & Neubauer, 1984). To the south of the western edge of the Danubian Flat region, phyllites, traditionally regarded as the Palaeozoic of the (Northern) Greywacke Zone are found in the Mihályi Elevation (near Csorna). The appearance of low-metamorphic rocks, starting from the Gemericum fundament in the east, through the Devonian limestone from the ZH-1 well, the Mihályi, St. Gotthard or Ikervár occurrences to the Graz Palaeozoic in the west,

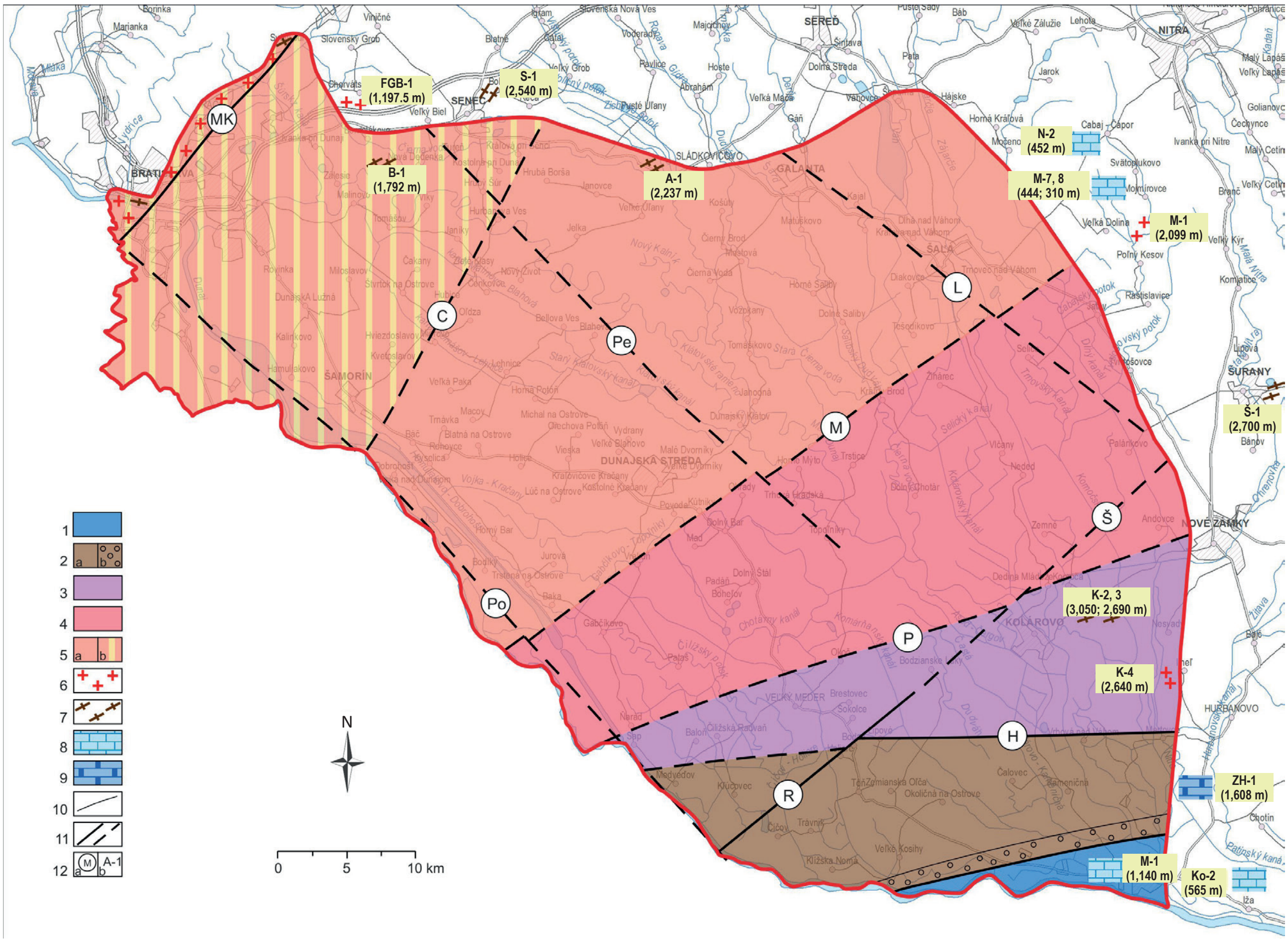

Fig. 1.7 Scheme of covered geological units of pre-Cenozoic basement of the investigated part of the Danube Basin

Legend to the scheme of covered geological units of the pre-Cenozoic basement of the Danubian Flat (Fig. 1.7)

Tectonic units:

1. *Mesozoic of the Mid-Hungarian Mountains: upper nappes of the Western Carpathians (?Silicicum, s.l.) – Upper Austroalpine*

2a. *Devonian (Lower Palaeozoic) (meta)sediments (Northern Greywacke Zone – Gemericum?)*

2b. *Permian sediments (envelope of Lower Palaeozoic)*

3. *Southern Veporicum – metamorphites, less granitoids, relics of Mesozoic?*

4. *Northern Veporicum – granitoid and metamorphic crystalline, Mesozoic*

5a. *Tatricum – granitoid and metamorphic crystalline, Mesozoic (“inner zone”)*

5b. *Tatricum – granitoid and metamorphic crystalline, Mesozoic? (“outer zone”, cataclasites)*

Exposed crystalline (Malé Karpaty Mts.) and in deep boreholes (the number corresponds to the depth of the reached basement):

6. *granitoids*

7. *metamorphites*

Labelling of rocks in deep boreholes (the number corresponds to the depth of the reached basement):

8. *Mesozoic carbonates*

9. *Devonian limestones*

General:

10. *geological boundaries*

11. *deep-seated fault lines: highly probable; assumed*

12a. *designation of main fault lines:*
R – Rába line, L – Ludince (Dobrá Voda) line, H – Hurbanovo line, MK – Malé Karpaty Mts. marginal fault, Po – Danube faults, Š – Šurany faults, M – Mojmírovce line, P – Pohorelá line, Pe – Pezinok fault, C – Cífer faults

12 b. *deep boreholes reaching into basement*

can be imagined as part of the later tectonically disrupted SW-NE zone of the Lower Palaeozoic rock suites, located tectonically on Central-Alpine or Inner Carpathian units. In the case of Devonian rocks from the borehole ZH-1, however, the idea of the presence of higher parts of the Gemericum – e.g. Drnava Fm. (sensu Snopko, 1967) cannot be excluded, although the Gelnica Group is slightly higher metamorphosed.

In the vicinity of Komárno at the SE border of the Danubian Flat and further towards Štúrovo (outside the region) the presence of the Mesozoic carbonates is evidenced by the drilling works, which apparently overlie the Palaeozoic complex. They build up so-called Komárno Block and behind the Danube they follow the Mesozoic complex of the Transdanubian Mountains, as shown in the wider area of Komárom in the pre-Cenozoic basement maps (most recently Haas et al., 2010). The inconsistency in the tectonic classification of this Mesozoic unit, outlined above, is difficult to elucidate at the current level of knowledge. In spite of the South-Alpine facies affinity or significant presentation of the Lower Cretaceous members, we tend to favour the system of the highest Eastern – or highest Inner Carpathian nappes with respect to the configuration of the regional geological structure.

The crystalline units located northwest of the Komárno Block are considered (even in the absence of other data) in the sense of the Palaeoalpine (Cretaceous) tectonic arrangement, which has roughly features of NE-SW belt-structure. To the north of the Hurbanovo fault, the crystalline, composed predominantly of metamorphic rocks, is perceived as the Southern Veporicum. It is likely that the Southern Veporicum Crystalline, with any relics of the Upper Palaeozoic or Mesozoic envelope, is the tectonic underlay of the Palaeozoic of the Komárno Block. This could create some analogy to the surface contact of the Southern Veporicum (especially the Kohút zone) and the Gemericum.

In the basement sketch (Fig. 1.7), behind the Southern Veporicum unit, the Northern Veporicum unit continues in the north-west direction, characterized by a considerable extent of granitoid rocks. The Northern Veporicum domain is characterized by better preserved Mesozoic succession and is also signalled by a massive outlier of the Hronicum Mesozoic in the area of the Levice tectonic block. Beyond the Čertovica-Mojmírovce line the Tatricum basement followed conventionally the Veporicum zone, but with the fact that the Northern Veporicum and Tatricum crystalline basement are considered as practically identical. In this context, there is another issue raised – where in the uncovered crystalline basement a tectonic scar of Fatricum Unit, if, of course, we respect its existence is placed.

Within the Tatricum, a more deformed domain of the "Tatricum Outer Zone" is indicated in its western part. The above-mentioned conspicuous and almost ubiquitous cataclastic deformation can be observed not only in the lower parts of the drill cores (e.g. deep boreholes in the wider area of Senec, Sereď), but also in the southern parts of the Malé Karpaty Mts. Crystalline. A complex spectrum of young failures in the crystalline may be related to tectonic processes of a wide age range – from the fold deformations recorded in the Lower Miocene sediments at the northern edge of the Dobrá Voda Depression in the Karpatian (Kováč et al., 1991) till the Pliocene – (Quaternary) movements of the southern parts of the Malé Karpaty Mts.

1.3.3.2 Pre-Cenozoic basement and Tertiary tectonics

The Tertiary tectonic events are difficult to assess in the central part of the investigated area because of the fact that (except for the so-called Komárno Block) on the pre-Cenozoic basement only Middle-, but mainly Late Miocene deposits were identified. The quasi-western continuation of the Hurbanovo line (dashed in Fig. 1.7) may hypothetically divide the crystalline in the north and the Upper-Austroalpine units in the form of the Palaeozoic Greywacke Zone and/or the Mesozoic in the south. The north-situated, dominantly Variscan crystalline in the East Alpine terminology corresponds to the Lower or Middle Austroalpine. In this case, the contact of the low- to non-metamorphosed Palaeozoic – Mesozoic tectonic overburden compared to the lower mega-units of the internal Western Carpathians would be independent of their Palaeoalpine arrangement. Through an imaginary western extension of the Hurbanovo line, which is likely to be of a Late-Oligocene – Early-Miocene age (Kováč et al., 2016; Kľučiar et al., 2016), could be transferred to the north-eastern sector of the Tertiary contact zone of the Eastern Alps. From this point of view, it is possible to admit in the southern zone of the Danube Basin (even north of the Hurbanovo line) the structural manifestations, that formed the Northern Limestone Alps.

The Palaeogene of the southern facies, also known as Buda or Pannonian facies, plays the role in the reflections on the pre-Cenozoic basement of the Danube Basin, which is best examined by the drilling works in the Komárno Block (Seneš et al., 1962, Brestenská & Lehotayová, 1960, Zlinská, 2016). To the oldest member of the discordantly deposited Buda Palaeogene the Kiscelian age is attributed and the sediments are well correlated with the Palaeogene of the Esztergom region (Brestenská & Lehotayová, 1960; Zlinská, 2017; Kľučiar et al., 2016). The highest stratigraphic horizons of the "Štúrovo Palaeogene" are of the Egerian Age (Seneš in Andrusov, 1965, Vass, 2002). The Komárno tectonic block is constrained by the Hurbanovo fault from the north and from the west probably by a failure of the Rába system. Data on the nature of the fauna in the Bánovská kotlina Basin, in the "Bojnice Palaeogene" (Maheľ & Gross, 1975 in Gross, 1978), in the Handlovská kotlina Basin (Zlinská & Gross, 2013), evidence for some biofacies kinship with the Buda Palaeogene, even north of the Hurbanovo fault or west of the northern continuation of the Rába fault system. This suggests the interconnection of the Buda, Central Carpathian and Magura Oceans, which is affiliated to the Middle Eocene period (Kováč et al., 2016; Soták et al., 2016). The Hurbanovo fault shows a considerable vertical amplitude, because to the north of it there were not found neither Mesozoic nor Palaeozoic units of the Transdanubian (Mid-Hungarian) Mountains. However, it can be assumed that the Danube Basin was covered with Palaeogene deposits of the Buda facies even to the north of the Hurbanovo fault, which were later denuded.

The tectonic events in the Danubian Flat region are difficult to perceive without any connection with the sedimentary and structural record in the area of the Malé Karpaty Mts. and data from the adjacent part of the Vienna Basin. The Tertiary development of the basement of the Vienna Basin is indicated by the deformation of the Late Cretaceous to Early Palaeocene sediments, which are an integral part of the Eastern Alpine nappes. The classical question of where the boundary between the Eastern Alps type of structure and the Inner Carpathian (Cretaceous) tectonic units runs is far from being concluded (based on drilling and geophysical work in the Záhorská nížina Lowland, a certain status quo between the Alps and the Western Carpathians creates at least the Senica – Lakšárska Nová Ves – Láb line, Kysela, 1988). From the configuration and content of the higher Mesozoic nappes, the idea that the Palaeoalpine primary structure of the Malé Karpaty Mts. could later be partially covered by the Northern Limestone Alps units could not be rejected with certainty. In this part of the Danube Basin, the overburden composition was eroded down to the crystalline, but in the case of the Malé Karpaty Mts. the relics of such a structure could be preserved in the form of the highest nappe relics of the Mesozoic. These have long complicated their tectonic affiliation, since they can be correlated well with the Eastern Alps nappe units (Vetters, 1904; Biely et al., 1980; Michalík, 1991). Neither from the basement of the northern part of the Vienna Basin nor from the northern edge of the Transdanubian Mountains, there is any evidence to support the Tertiary movements of the crystalline basement. Provided, the Tertiary thrust tectonics had taken place in the discussed area, it was probably only within the higher tectonic units.

In the following lines we will try to outline the structural-tectonic evolution in the Tertiary period, which concluded the formation of the pre-Cenozoic basement of the Danubian Flat and its surroundings. There are assumed four basic, in some cases differential uplift events that do not contradict the generalized succession of deformation events during Tertiary collision. Such deformations are indicated in our territory, in the north-eastern part of the Eastern Alps, or in the southern basins with the Buda evolution of Palaeogene. A look at these events suggests the complexity of Cenozoic fault tectonics and, overall, we can assume that the rejuvenation of faults is more a rule than an exception.

From the geological position, biostratigraphic and facies data it follows that in the Tertiary period the *first* uplift of the "Malé Karpaty Mts. block" (s.l.) occurred after the deposition of the Late Cretaceous strata, in the period prior to the late Palaeocene transgression (Gross & Köhler, 1989). The *second* uplift event can be attributed to the elevation structures created in the Late Eocene period, when the southern part of the contemporary "Malé Karpaty Mts. Block" was uplifted. The development of the given elevation structure probably took place along with the uplifting of the north-eastern East-Alpine domains (e.g. Sopron Crystalline, maybe even Penninic in the Rechnitz outlier?). On a wider palaeographic scale, the supposed uplifted threshold rampart in this domain inhibited to link the Eastern Alps and Buda sedimentation areas (as opposed to the communication between the Buda and the "Central Carpathian" Palaeogene deposition in that period). The elevation movements of the second stage are supported by the Late Palaeocene – Middle Eocene age range of the Malé Karpaty Mts. Palaeogene sedimentation, which also shows a strong affinity for the "peri-Klippen Palaeogene" (Gross & Köhler, l.c.). Late-Eocene kinematic events could be activated in response to the emplacement of the Northern Limestone Alps on the Flysch zone, dated since the Eocene period (Tollmann, 1978).

Tectonic or latent discordance between Eocene and Oligocene sediments is often noted in the Buda Palaeogene sedimentation areas (Vass, 2002, Nagymarosi, 1990). The Oligocene sediments of the Buda development, deposited directly on the pre-Cenozoic basement, are also indicative of the Eocene uplift of the area of the Komárno High Block area and its subsequent subsidence. The tectonic events at the Eocene-Oligocene interface may be documented in the western domain of the Buda Palaeogene areal by the Early Oligocene uplift accompanied by denudation of the Eocene basement (e.g. Nagymarosy in Haas, 2013). In the Buková Furrow, in the north-western part of the Malé Karpaty Mts., Hrabník Formation of the Kiscelian age is present (Marko et al., 1990), which also does not follow the Eocene basement.

The Oligocene Hrabník Formation was folded in the Early Miocene period, as indicated by the non-folded top-horizon of the Karpatian (Early Badenian) age (Marko et al., 1990). It is remarkable that the Eocene sediments of the so-called Buková Palaeogene are deformed only insignificantly compared to the Hrabník Formation. From the biostratigraphic and superposition data, the period around the border of the Oligocene – Lower Miocene (e.g. Kováč, 2000) can be considered as the fundamental Cenozoic uplift of the "previous" Malé Karpaty Mts. In the sequence of the tectonic events outlined, this is the *third* uplift phase. The south-western edge of the Malé Karpaty Mts. adjacent part of the Vienna Basin does not contain Eggenburgian sediments (Jiříček & Seifert, 1990), unlike its western part, which could also suggest the Early Miocene uplift of the area. Predominantly on the basis of indirect indications, it can be assumed that in an area situated roughly between the fault lines bounded by the northern Ludince and the southerly elongated Hurbanovo line, a west-declining east-west ridge elevation formed in the Egerian (Early Miocene) period. The continental Egerian sedimentation in the north-western area of the Buda Palaeogene (Tari et al., 1993) may also support such an uplift structure. It was probably created as a result of the post-collision (late-collision) strike-slip shear kinematics advancing in the direction of the Northern Limestone Alps, through the then overburden of the Malé Karpaty Mts., up to the southern domains of the Danube Basin. It is possible that the failures close to the Hurbanovo line represented a structure in that period, restricting the central part of the

Danube Basin from the south. On the northern edge of the Eastern Alps, especially north of the Danube, deformation processes in the age diapason Egerian to Karpatian were documented (Brix et al., 1977; Wachtel & Wessely, 1981). The supposed elevation zone in rough features is surrounded by Eggenburgian transgressive sedimentation, documented on the north-western edge of the Vienna Basin, in the Blatné Depression, the Ipelská kotlina Basin, or in the Upper Nitra Basin or at the southern foothills of the Sopron Mountains.

Polymict Jablonica Conglomerate of the (Late) Karpatian (Mišík, 1986; Fordinál et al., 2012), as well as its deep-water equivalents, represent the link between the Vienna and northern parts of the Danube Basin (Kováč & Baráth, 1995). A study of the source material of the shallow-water facies, including the Jablonica Conglomerate from the NW part of the Danube Basin (Pagáč, 1964a; Csibri et al., 2018), suggests that it originates from the Malé Karpaty Mts. rock inventory, partly also from the Alpine units, whereas the transport of the pebble material is expected from south to north (Mišík, 1986). From the given circumstances it can be assumed that the material of the Early Miocene units originated from the elevation (elevations), which can be temporally joined with the uplifted Danube ridge elevation (approximately the central part of the Danube Basin today).

The supposed east-west elevation structure, to which the Malé Karpaty Mts. probably also belonged, was eroded during significant tectonic events in the Karpatian – Early Badenian period (traditionally the "Styrian Phase"). The tectonic processes of this period Kováč (2000) associates with the process of extrusion of the Central Western Carpathians in the Karpatian phase of rifting. In the deep morphostructures along the faults, the (Early)-Badenian units were subsequently deposited – represented by the Bajtava Formation from the east, Špačince and Devínska Nová Ves Fms. in the west (Fordinál et al. in Polák et al., 2012).

The Hurbanovo line ceased its major kinematic activity before or during the deposition of the Bajtava and Špačince Fms., which are spread, according to available data (Vaškovský & Halouzka, 1976; Biela, 1978; Vass, 2002; Zlinská, 2016), south as well as north of this line, which proves for its (Early) Badenian termination. Subsequently, the Hurbanovo line became inverse, as evidenced by the subsidence of the Crystalline and the uplift of the Komárno Block. However, it is a relative movement – probably both blocks were subsiding, as indicated by virtually the same Middle- to Late-Miocene overburden on both sides of the line.

This debate naturally raises the question of the existence of the Malé Karpaty Mts. between the Vienna and Danube Basins. The Malé Karpaty Mts. elevation morphological structure in its then form had developed in parallel with the rapid subsidence of the Danubian Flat territory since the Early Badenian period. The character of its pre-Neogene rock inventory (crystalline with the relics of autochthonous and allochthonous Mesozoic units), from the point of view of the after-Karpatian tectonics, ranks it to the interface with the Vienna Basin, which is characterized by a considerable thickness of folded Mesozoic sequences, and the Danubian Flat with exposed pre-Badenian crystalline. The Karpatian-Early Badenian processes, in the form of "basin and range tectonics", caused due to the deep-seated normal faults the extension collapse till the crystalline-eroded Danubian ridge, with the "Palaeo-Malé Karpaty Mts." segment not subsiding but creating a new horst structure. We associate this with the *fourth*, last major Tertiary uplift event in the surveyed area. The basic features of the Malé Karpaty Mts. horst of today's form developed along the NE-SW shear system, which was probably related to the parallel Malé Karpaty Mts. marginal faults, separating the mountains from the Danube Basin. In elucidating the composition and evolution of the pre-Cenozoic basement, the post-Badenian tectonic events have no longer played an essential role.

1.4 Conclusions

The Malé Karpaty Mts. crystalline complex situated on the western edge of the investigated area is built of mainly biotite granites to granodiorites with local bodies of biotite gneisses and amphibolitic rocks. In addition to amphibolites (s.s.), laminated metatuffites, calcium-silicate rocks with diopside and occasionally gabbrodioritic rocks were identified in the fragments. The periplutonic effect of the Bratislava Granitoid Pluton caused a metamorphic reworking (maximum in the amphibolite facies) of the pre-granite substrate, which represents the second regional Hercynian metamorphic phase. In the south, there are more-and-more abundant pegmatitoid varieties with striking dark K-feldspar or fan-shaped muscovite aggregates, which are typical for this region. In the polydeformation inventory of the Lower Palaeozoic to Carboniferous crystalline rocks, it is possible to distinguish Hercynian, Alpine (Cretaceous) and Cenozoic deformation structures. In an artificial excavation at the Bratislava Castle, a complex tangle of brittle failures was observed, which is likely to indicate "young" tectonics reaching up the Pliocene-Quaternary period.

The following tectonic units (from north-west to south-east) have been suggested within the composition of the pre-Cenozoic basement of the Danubian Flat region: Tatricum (external and internal zone), northern Veporicum, southern Veporicum, Palaeozoic nappe of the Northern Greywacke Zone (Graz Palaeozoic) – Lower Gemericum ("Drnava Fm.") and overlying Oberostalpin – Silicicum (s.l.). The first three units are apparently built of crystalline, while the Southern Veporicum is considered to be more distinctive against the Northern Veporicum than the Northern Veporicum to Tatricum. It is likely that the Southern Veporicum crystalline, with possible relics of the Upper Palaeozoic-Mesozoic envelope, forms the tectonic basement of the Upper Palaeozoic nappe of the Komárno Block.

Discussions were devoted to the deposits of the Pannonian and Central Carpathian Palaeogene as well as to the comparison with the tectonic pattern in the north-eastern part of the Vienna Basin. It is likely that before the

Early Badenian inversion there had existed in the central part of the Danube Basin an E-W elevation zone, when the crystalline basement was exposed along with the (then) domain of the Malé Karpaty Mts.

The arrangement of basic tectonic units is understand as Alpine (Cretaceous) with the fact that the higher structure, especially the southern parts, was significantly modified by Tertiary tectonics. However, in overall there is no indication in favour of crystalline basement overthrusting during this period.

The final part of the article is devoted to the discussion of the tectonic events with an impact on the wider area of the territory under study. Based on inter-regional compilation data, four tectonic phases associated with uplift movements were earmarked in the Tertiary period.

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