Excursion to the Tatra Mountains, Central Western Carpathians: Tectonometamorphic Records of Variscan and Alpine Orogeny

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Introduction

The Tatra Mountains are located in the northernmost sector of the Western Carpathians. They are representative of the so-called core mountains within the Tatric unit, a major tectonic unit of the Western Carpathians (Andrusov 1968; Maheľ and Buday 1968; Maheľ 1986; Plašienka et al. 1998). The area of Tatras has been investigated since the 19th century by numerous French, German, Austrian, Polish, Hungarian, Czech and Slovak geologists who brought basic ideas about geology, tectonics and stratigraphy. New geological map in the scale of 1: 50,000 (Nemčok et al. 1993) is a synthesis of geological mapping on both Slovak and Polish territory.

Deformation and metamorphism in the Tatra Mts. are the vestige of a multi-stage evolution, during Variscan and Alpine orogeny. However, the Alpine overprint seems to be of a low grade, restricted to the local deformation. This allows to elucidate the pre-Alpine history of the basement and make some implications for the Variscan orogeny in the Western Carpathians. The aim of the excursion is to provide a general overview of main pre-Alpine tectonic units, exposed in the western part of the Tatra Mts.

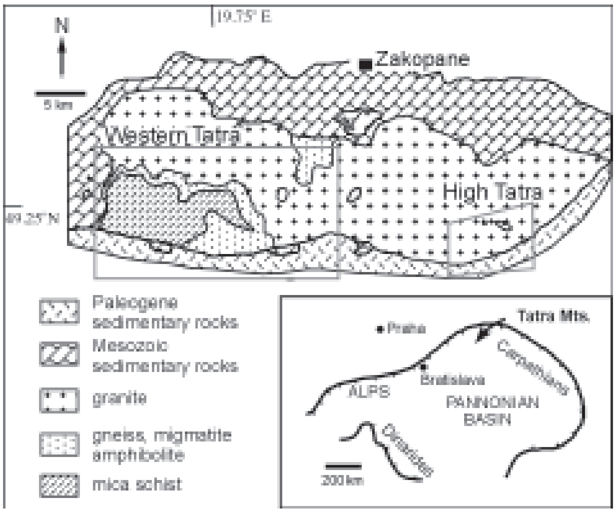

Fig. 1. Simplified geological map of the Tatra Mountains. The areas in boxes are enlarged in the Fig. 2.

Geological setting

The crystalline basement of the Tatra Mts. (Fig. 1) is composed of pre-Mesozoic metamorphic rocks and granites, overlain by Mesozoic and Cenozoic sedimentary cover sequences and nappes. Metamorphic rocks are abundant in the western part

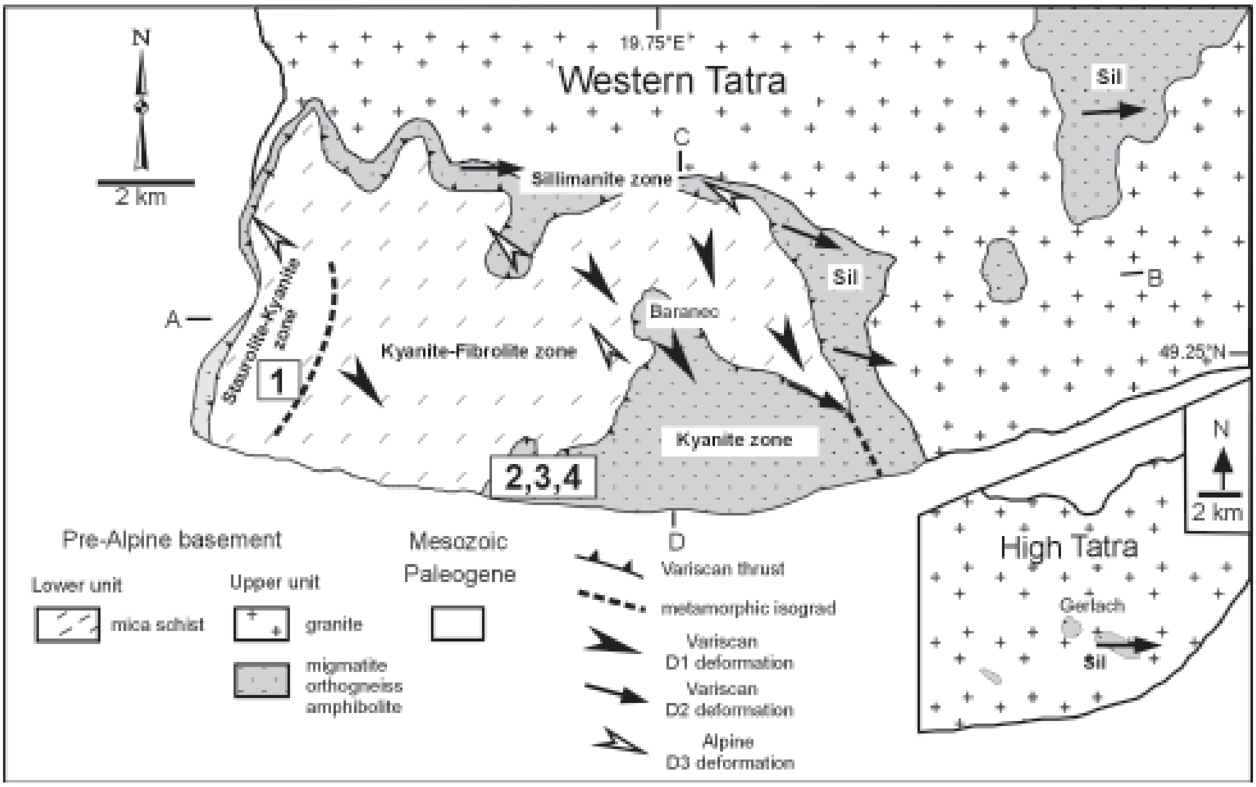

Fig. 2. Generalised tectono-metamorphic map of the Tatra Mountains with excursion stops.

(the Western Tatra Mts.), whereas in the eastern part (the High Tatra Mts.) they form only xenoliths in granites (Figs. 1 and 2).

Within the basement, two superimposed tectonic units – – lower and upper, differing in lithology and metamorphic grade, have been distinguished (Janák 1994). These units are separated by a thrust fault – a major tectonic discontinuity in the crystalline basement of the Tatra Mountains (Figs. 2 and 3).

The *lower unit* is exposed in the Western Tatra as a tectonic window of up to 1000-m thickness (Figs. 1 and 2); it is composed of micaschists. Kyanite-, staurolite-, fibrolitic sillimanite- and garnet-bearing metapelites alternate with quartz-rich metapsammites, indicating former flysch sediments (Kahan 1969). The staurolite-kyanite and kyanite-sillimanite (fibrolite) zones are separated by the staurolite-out isograd (Figs. 2 and 3).

The *upper unit* is composed of migmatites and granites. Relics of high-pressure metamorphism (eclogites) occur in amphibolites at the base of the upper unit (Fig. 3). The amphibolites are banded, with layers of mafic (amphibolite) and felsic (tonalitic to trondhjemitic) composition alternating on mm to dm scale. They enclose lenses (several dm to m) of eclogitic relics with garnet and clinopyroxene (Janák et al. 1996). Metapelites with kyanite show incipient migmatization and formation of granite leucosomes. Orthogneisses are mylonitic with augen-like porphyroclasts of K-feldspar. Higher levels of the upper unit (sillimanite zone) are intruded by a sheet-like granite pluton (Gorek 1959), whose composition ranges from leucogranite to biotite tonalite and amphibole diorite (Kohút and Janák 1994). In associated metapelites, migmatisation is ubiquitous and prismatic sillimanite together with garnet; K-feldspar and cordierite are diagnostic minerals. Amphibolites contain garnet, but eclogitic relics are not preserved. Similar assemblages were also reported from the northern part of the Western Tatra (Gawęda and Kozłowski 1996).

Deformation

Polyphase Variscan and Alpine deformation under distinct *P-T* conditions and kinematics (Figs. 2 and 3) are recognised (Kahan 1969; Fritz et al. 1992).

The absence of Mesozoic rocks in the contact between both tectonic units of the crystalline basement indicates a pre-Alpine thrusting (Kahan 1969). The earliest, Variscan deformation (D_1) is demonstrated by dynamically recrystallised feldspar porphyroclasts in the orthogneisses, and amphibole and biotite lineation, as well as quartz ribbons, in both metapelites and metabasites. A mineral and stretching lineation is formed within the diffusion-controlled deformation of quartz. Predominant kinematic indicators suggest top to the south-east shear, which is interpreted as the sense of the Variscan nappe displacement. Kinematic indicators suggest predominantly top-to-the-south, southeast thrusting of the upper unit onto the lower one. However, at higher levels of the upper unit, the lineation (defined mostly by biotite and sillimanite in the migmatites) is transposed into the west-east direction (Fig. 2). The same west-east orientation of fabrics can be observed in the marginal zones of the granite pluton, which has been affected by a solid-state deformation. The sense of shearing is generally dextral, or top-to--the-east, indicating that deformation (D_2) was related to orogen-parallel extension. However, the Variscan normal faults, accomplishing the extensional unroofing and denudation of the crystalline basement, are not preserved due to erosion of upper crustal levels in post-Variscan time, or they have been reactivated during Alpine tectonic events.

Alpine deformation (D_3) under brittle conditions is manifested by top-to-the-northwest shear, which is attributed to a Late Cretaceous contractional event. The last major deformation (D_4) is related to uplift of the Tatra Mountains due to Late Tertiary transpression along west-east trending wrench zones, accompa-

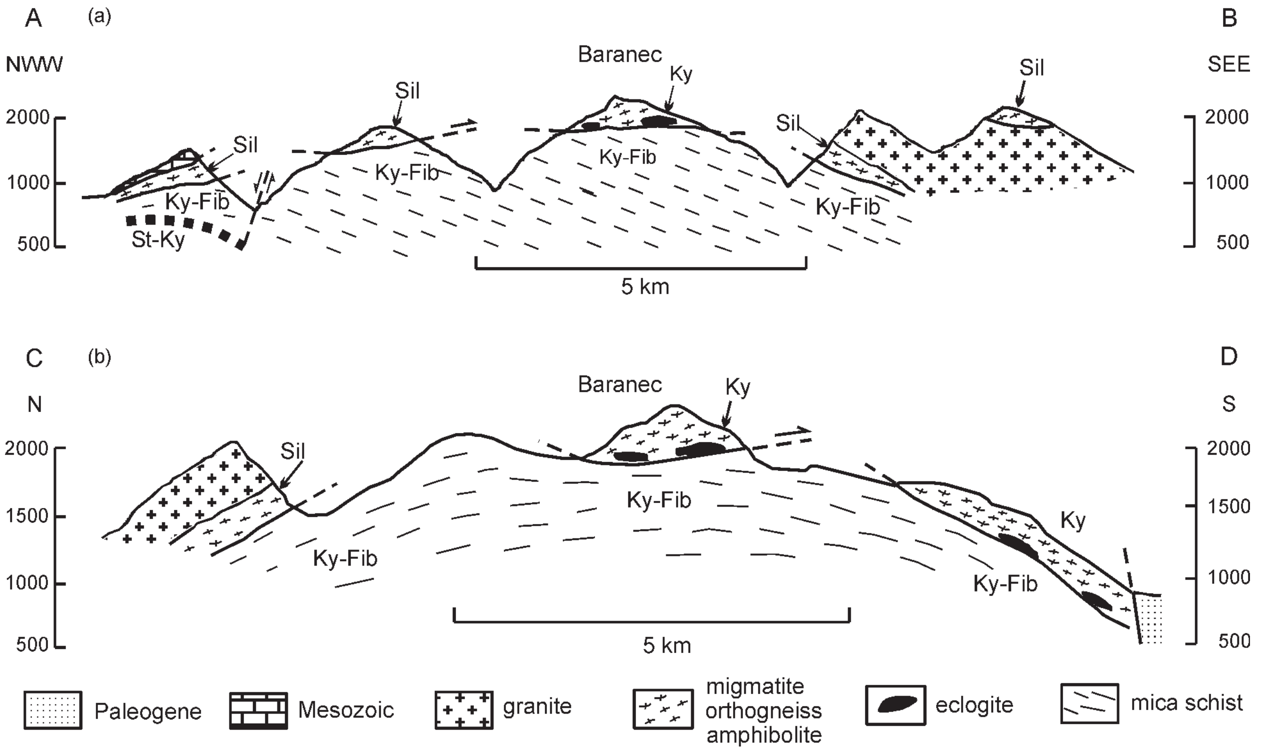

Fig. 3. Schematic profiles across the western part of the Tatra Mountains.

nied by normal faulting in a north-south to northwest-southeast direction. Alpine north to north-westward movement of the basement together with its sedimentary cover and Mesozoic nappes is also documented by magnetic fabric (Hrouda and Kahan 1991).

Geochronological data

The oldest tectono-metamorphic events in the Tatra Mountains seem to be Early Devonian, 406 Ma, according to the zircon single grain data from orthogneisses (Poller et al. 2000). Major granite magmatism took place in Late Devonian and Carboniferous time (c. 370–315 Ma), according to Rb-Sr (Burchart 1968; Gawęda 1995) and U-Pb single-zircon data (Poller et al. 1999, 2000). The ^{40}Ar-^{39}Ar ages of biotite and muscovite from granitoids and metamorphic rocks (330–300 Ma), obtained by both step-heating (Maluski et al. 1991, 1993) and laser ablation (Janák and Onstott 1993; Janák 1994) methods, record a cooling and uplift during late-Variscan time. As shown by argon spectra of muscovite from the mylonitic granite (Maluski et al. 1993) and orthogneiss (unpublished data of Dallmeyer), low temperature steps reveal a younger, Alpine tectono-thermal overprint. Apatite fission track data record the final uplift during the Tertiary, at 15–10 Ma (Burchart 1972; Kráľ 1977).

Metamorphism

Lower Unit

Metapelites in the lower unit contain the assemblages: kyanite ± ± staurolite + fibrolitic sillimanite + garnet + biotite + muscovite$_1$ ± chlorite$_1$ + plagioclase + quartz. Relics of rutile are sporadically present and ilmenite is more abundant. Staurolite is abundant in the staurolite-kyanite zone, exposed in the westernmost part of the Tatra Mts. (Fig. 2 and 3). Kyanite and fibrolitic sillimanite are diagnostic minerals of the kyanite-sillimanite (fibrolite) zone where staurolite relics appear only sporadically. As inferred from metamorphic textures, fibrolitic sillimanite is a relatively younger phase than staurolite and kyanite. Later retrograde overprint is demonstrated by the formation of chlorite$_2$, chloritoid, margarite and muscovite$_2$ in the microfractures and pseudomorphs after staurolite, kyanite and garnet. Metamorphic *P-T* conditions from about 550–620 °C and 5–6 kbar in the staurolite-kyanite zone to 620–660 °C and 6–8 kbars in the kyanite-sillimanite (fibrolite) zone have been calculated (Janák et al. 1988; Janák 1994; Ludhová 1999).

Upper Unit

Metapelites in the upper unit show the following mineral assemblages: garnet + kyanite ± sillimanite + biotite + plagioclase ± K-feldspar ± muscovite with staurolite relics, and garnet + + sillimanite + biotite + quartz + plagioclase ± K-feldspar ± ± muscovite; or biotite + sillimanite + cordierite ± garnet + + quartz + plagioclase ± K-feldspar ± muscovite in the sillimanite zone. Ilmenite, rutile and magnetite represent Fe-Ti oxides. Minor and accessory minerals include orthoamphibole (gedrite, anthophyllite), chlorite, epidote, carbonates (calcite, siderite), zircon, monazite and apatite. Retrogression led locally to the origin of chloritoid, muscovite, margarite and chlorite in late fractures. The leucosome formation in the metapelitic migmatites resulted from the dehydration-melting of muscovite and biotite (Janák et al. 1999). Decompression from a high-pressure stage (12–14 kbar) led to the transformation of kyanite to sillimanite. Locally (area of Ježová), cordierite have been formed at ca. 4–5 kbar (Ludhová and Janák 1999). The CO_2 – rich fluid was generated during the interaction of melt-derived water with metapelite graphite (Janák et al. 1999; Hurai et al. 2000). Consequently, peak metamorphism high-grade assemblages have been strongly obliterated by retrogression at subsolidus conditions.

Metabasites with garnet and clinopyroxene occur in the kyanite zone, showing symplectitic (diopside + plagioclase) and kelyphitic (amphibole + plagioclase) textures. Thermobarometric calculations from mineral inclusions in the garnet cores yield 670–700 °C and 10–15 kbar, recording the initial path from amphibolite to eclogite facies conditions (Janák et al. 1996). The symplectites have formed by breakdown of inferred omphacite (Jd36), suggesting extensive re-equilibration of eclogites in the amphibolite/granulite facies conditions (650–750 °C; 8–12 kbar) during their exhumation. Several generations of amphibole (pargasite, hornblende, cummingtonite, actinolite) are evidence of a transformation down to greenschist facies copnditions. The fluid inclusions (Janák et al. 1996; Hurai et al. 2000) contain nitrogen–dominated, water-absent fluid similar to that reported from typical high-pressure eclogites. Presence of tonalitic and trondhjemitic veins suggests partial melting in metabasites. In the sillimanite zone metabasites, high pressure relics are lacking.

As inferred from spatial distribution of metamorphic zones and mineral assemblages in the upper unit, the highest pressure conditions have been attained at the base of the unit, while the upper levels reveal metamorphic recrystallization at lower pressure conditions.

Uplift of the Tatra Mts. – testing the 2D geometrical models

The Tatra Mts. are one of the so-called “core mountains” of northern and western Slovakia, which are Late Tertiary asymmetrical horst to domal horst structures. The Tatra Mts. expose pre-Tertiary units in a lozenge-shaped, areally large basement high (50 × 15 km) surrounded by Paleogene basins. Depositional systems of the Central Carpathian Paleogene (Podhale) Basin do not respect this elevation and do not contain material from its basement complexes. Apatite fission-track measurements from the Tatra granitoids yielded ages between 10 and 20 Ma (Burchart 1972; Kráľ 1977). These data indicate the uplift started in the Early/Middle Miocene. Thickness (400 m) and distribution of Quaternary glaciofluvial sediments in foots of the Tatra Mts. reveals the uplift continued during the neotectonic (Plio-Quaternary) period.

Since the Tatra horst is asymmetrical one (Mesosoic cover and nappe units occur on the northern slopes, moderately to steeply N-dipping), the main role during uplift is ascribed to the southern W-E trending boundary fault, the so-called “sub-Tatra” fault. However, this is not a simple fault, it consists of several crosscutting and arching segments trending W-E to SW-NE (Choč-Prosečné-Krowiarky fault; West Tatra-Kôprová fault and East Tatra-Ružbachy fault). Sad to say, kinematics of these faults was and still is poorly known, which has resulted in several considerably differing models of the Tatra uplift. In the thirties to sixties of the previous century the sub-Tatra fault was intuitively interpreted as a north-dipping reverse fault, considering the enormous rise of the Tatra core relative to its foots. Later, some technical and geophysical works doubted the reverse fault concept, because of subvertical, or even steeply south-dipping character of the sub-Tatra fault was recognised (at least of its accompanying subsidiary faults). This led to the concept of its normal, down-throw character. Finally, the only kinematically consistent and theoretically balanced model by Sperner

(1996), which was based on microtectonic measurements (but not from the sub-Tatra fault itself!), assumes very complex tectonic history of the area with rotating both the stress field and the whole domain during the Neogene, resulting in changing kinematics of individual faults dominated by strike- and oblique-slip movements (see also Bac-Moszaszwili 1993). The main role in the Tatra Mts. uplift was again ascribed to a reverse southward movement along the sub-Tatra fault (Sperner 1996).

Not only the fault kinematics, but the overall geometry of the Tatra high is crucial for the evaluation of its genetic models as well. Simple scheme presented in Fig. 4a assumes vertical or steeply S-dipping dip-slip character of the sub-Tatra fault and continuous moderate N-dip of Mesozoic strata from the northern Tatra slopes into the eroded region. These boundary conditions were used also in previous models and indicate rather unreliable values of the amount of movement along the fault: throw in the order of 15 to 13 km (A–A' and B–B', respectively, in Fig. 4a). If a reverse dip-slip movement along a steeply N-dipping surface is considered, the throw would reach hardly acceptable figures up to 29 km (cf. Sperner 1996). This value may be reduced to a more reliable assessment by supposing a more shallow dip or subhorizontal attitude of Mesozoic strata above the fault. Testing various cross-sectional models of the Tatra Mts. uplift under these circumstances suggests that:

- Normal faulting, either planar or listric, of brittle upper crust during crustal extension or lithospheric stretching may be ruled out since, in addition to geometrical constraints (throws higher than a few km cannot be balanced), no lithospheric or crustal thinning is observed in the area (the crust is among the thickest in the Carpathians here), no Miocene extensional basins accompany this basement uplift and the broader surroundings of the Tatra Mts. show rising tendencies since the Early Miocene.
- The sub-Tatra fault belongs to a system of planar dip-slip faults produced by tilting and horizontal axis rotation of domino-type prismatic upper crustal blocks that formed due to horizontal top-to-the-north simple shearing of the Central Carpathian crust triggered by underthrusting of the North European plate. This space-saving explanation has been found as a viable mech-

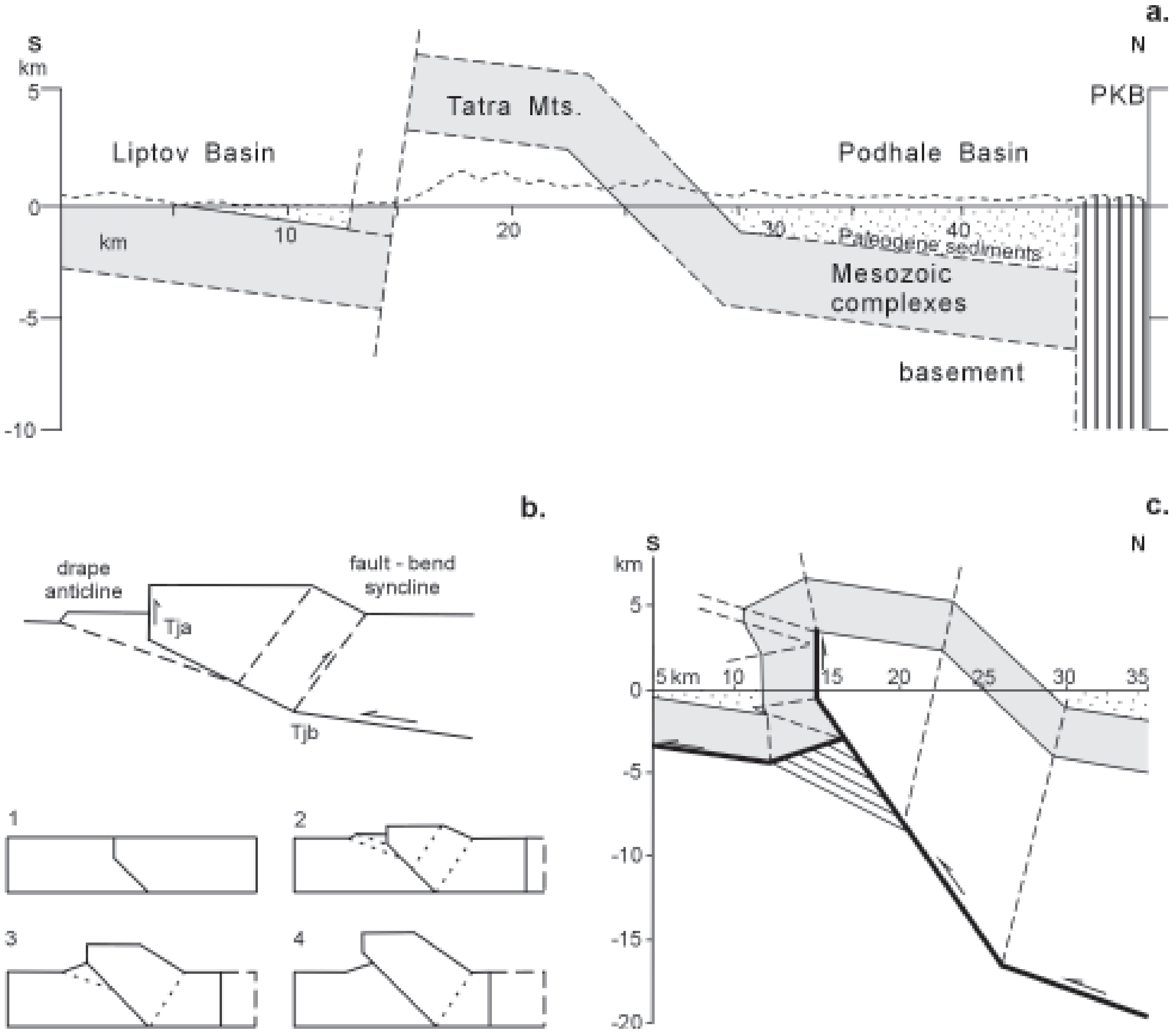

Fig. 5. a – generalised geometry of the Tatra basement uplift and its surroundings using more plausible parameters (PKB – Pieniny Klippen Belt); b – the favoured model of Narr and Suppe (1994) and its kinematic evolution (1–4, the Tatra Mts. correspond to the situation 3 in their western part and 4 in their eastern, the most uplifted part; c – the balanced cross-section of the Tatra Mts., corresponding to the surface boundary conditions as in Fig. 5a.

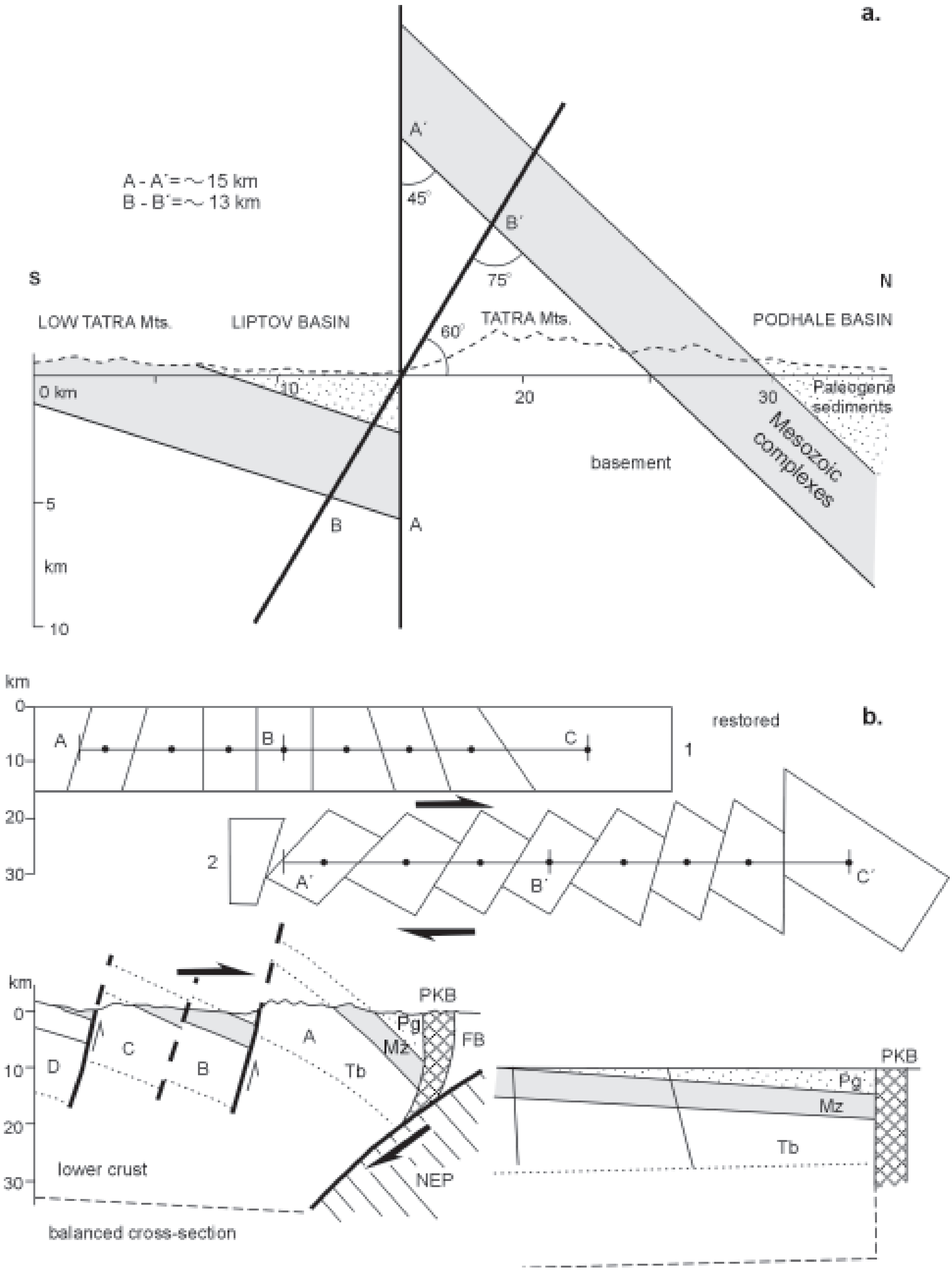

Fig. 4. a – traditionally interpreted geometrical constraints, based on a simple extrapolation of surface data, the fault-throw (A–A', B–B') estimates for the dip-slip sub-Tatra fault vertical (A) and steeply S-dipping (B), zero elevation on the vertical scale refers to the foot of the Tatra Mts.; b – balanced and restored crustal sections using the model of antithetic domino blocks rotating around horizontal axes: A – Tatra block, B – Poprad block, C – Low Tatra block, D – Vepor block. Tb – Tatric basement, Mz – Mesozoic complexes, Pg – Paleogene sediments, PKB – Pieniny Klippen Belt, FB – Flysch Belt, NEP – North European Platform.

anism during the last years (Marko unpublished) and partly resembles the model of "spindle-shaped semi-cylinders" rotating around horizontal axes presented by Grecula and Roth (1978). Nonetheless, the Marko's model requires a total decoupling of rectangular upper crustal blocks from the extremely ductile lower crust (Fig. 4b), cannot be properly balanced and therefore it seems to be improbable.

- Contractional model of Sperner (1996) also meets serious problems with crustal-scale balancing of the excessive Tatra uplift. She used a combined transpression-transtension kinematic model of Ramsay and Huber (1987, their Fig. 23.41), in which the uplift of the transpressional sector of a wrench zone is accommodated by subsidence within an adjacent transtensional basin. No such Miocene basin is present in the neighbourhood of the Tatra Mts., however. Thus, in spite this model is an attractive one, it is not supported by the regional geological structure and its geometrical characteristics are unreliable.

After all possible models were rejected, the geometrical constraints in Fig. 4a should be modified. Indeed, the regional situation corroborates quite different geometrical characteristics of especially the up-thrown Tatra block (Fig. 5a). Moderate to steep dips of Mesozoic and basal Paleogene strata from the northern slopes of the Tatra Mts. cannot be directly extrapolated neither further to the north to the vicinity of the Pieniny Klippen Belt (Paleogene strata do not exceed the thickness of several km there, so they are only gently N-dipping in the Podhale Basin), nor to the eroded region above the Tatra Mts. (they lie almost horizontally at the western termination of the Tatra high). Assuming the nearly vertical position of the sub-Tatra fault, the resulting gross geometry corresponds neither to an extensional setting with normal faulting, nor to a contractional structure produced by simple reverse faulting (Fig. 5a). On the other hand, it fits perfectly the geometry of low temperature, retrodeformable, "basement-involved compressive structures" modelled by Narr and Suppe (1994). The basic features of their model are (Fig. 5b):

- The basement uplift develops in a hanging wall of a non-planar, generally listric thrust fault that branches off the brittle/ductile transition within the crust, i.e. from depths of approximately 10–15 km;
- The presence of accompanying fault-bend folds as a response of stratified cover sequence to the fault slip and propagation, which are confined to two fault-fault-fold triple junctions (TJ): a frontal anticline – "drape fold", and the rear fault-bend syncline (TJa and TJb in Fig. 5b, respectively).

It is particularly the frontal subvertical dip-slip fault (sub-Tatra fault) and the presence of the fault-bend syncline (northern slopes of the Tatra Mts.), which makes this model so attractive for the Tatra case. Other similar compressive models (e.g., McConnell 1994) assume only inclined planar reverse faults and do not care about balancing of these structures in a crustal scale. The Fig. 5c presents one possible balanced solution of the situation in Fig. 5a. Based on this, the horizontal shortening associated with the uplift could be estimated to around 30%, and the maximum vertical elevation of the Tatra Mts. to some 8 km.

Propagation of a nonplanar thrust fault in the basement initiated intense shearing in a triangular zone in front of the steep fault segment (region with oblique ruling in Fig. 5c). Since the fault slip in the brittle upper crust must have been seismic, it is inferred that this is the domain where pseudotachylite veinlets occurring in basement granitoids in the vicinity of the sub-Tatra fault were generated.

Formation of a friction-generated melt – pseudotachylite is an extreme example of rupturing during a seismic event. This rock type was found within the NNE-striking fault zones on the southern slope of Mount Gerlach. The frictional melt injected a strongly cataclased granite to form variable vein types – from simple injection veins to complex anastomosing vein networks. Pseudotachylite consists of (1) a well crystallized matrix of K-feldspar, albite and hematite, and (2) plagioclase and quartz clasts. Primary matrix compositions indicate formation by disequilibrium, fluid-absent melting of biotite and minor feldspars. The high temperature dissociation of water followed by hydrogen escape increased f_{O2} to the stability field of hematite.

Description of stops

Stop No. 1

Topics: micaschists of the staurolite-kyanite zone in the lower unit
Location: Western Tatra Mts., Jalovecká valley. Outcrops along the path in the middle part of valley near Jalovčianka brook (Fig. 2)

The outcrops show the micaschists of the lower structural unit. These contain staurolite and kyanite porphyroblasts attaining the size of several mm, almandine garnet, fibrolitic sillimanite, muscovite, biotite and chlorite. Retrograde chloritoid, margarite and sericite are sometimes present. Staurolite is a diagnostic mineral of the apparent staurolite-kyanite zone exposed in this area. Peak metamorphic conditions reached about 550–580 °C and 5–7 kbars.

Stop No. 2

Topics: micaschists of the kyanite-sillimanite (fibrolite zone) in the lower tectonic unit, close to the contact with the upper unit.
Location: Western Tatra Mts., Žiarska valley – middle part, exposures ca 1500 m on the road towards the Žiarska challet (Fig. 2).

Outcrops in the Žiarska valley expose the micaschists of the kyanite-sillimanite (fibrolite) zone beneath the thrust contact. Mineral assemblage in metapelites contain kyanite, garnet, fibrolitic sillimanite, biotite, muscovite, plagioclase, rutile, ilmenite and quartz. P-T conditions of metamorphism reached 620–640 °C and 6–7 kbars.

Stop No. 3

Topics: banded amphibolites and orthogneisses, HP-HT metamorphism and deformation at the base of the upper unit.
Location: Western Tatra Mts., Žiarska valley – lower part, rock exposures ca 30–50 m above the road to Žiarska challet (Fig. 2).

Banded amphibolites are a characteristic lithology, marking the detachment plane of the upper (overthrust) unit. Mafic layers consist of amphibole (hornblende to pargasite) and plagioclase, with minor quartz, ilmenite, rutile and sphene. Leucocratic bands are composed predominantly of plagioclase (oligoclase) and quartz, almandine garnet is also present. by breakdown of garnets in coronal textures.

Orthogneisses are coarse-grained with augen-like K-feldspars of 1–2 cm size, or fine-grained, foliated, with distinctive mylonitic fabric. Quartz is platy and ribbon-textured, K-feldspar is perthitic, often with microcline twinning and signs of dynamic recrystallization. Plagioclase is albite to oligoclase, locally, myrmekite has developed. The micas form a "mica-fish" texture. Biotite is Fe-rich, often replaced by chlorite. Muscovite is slightly phengitic, some $^{40}Ar/^{39}Ar$ spectra are discordant due to an Alpine overprint. Garnet is almandine and spessartine-rich, partly replaced by biotite and chlorite. Accessory minerals are apatite, zircon and monazite. Cathodoluminescence study of zircons (Poller et al. 2000) revealed the cores overgrown by magmatic rims. U-Pb dating of these zircons (Poller et al., 2000) provided the lower intercept age of 406 ± 5 Ma, recording magmatic zircon crystallization, whereas the upper intercept of 1980 ± 37 Ma age indicates an inherited material in the zircons.

Stop No. 4 (alternative)

Topics: orthogneisses
Location: Western Tatra Mts., Žiarska valley – lowest part. Rock exposures ca 100 m above quarry (Fig. 2). Not always accessible, the bridge can be broken in spring !

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