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Ductile deformation and recrystallization of the Variscan magmatic complex in the hanging wall of Cretaceous thrust (Veporic unit, Central Western Carpathians)

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Abstract: The metamagmatic Veľký Zelený Potok (VZP) Complex of the Veporic basement shows Meso/Late Variscan postcollisional collapse of the collided Pre-Alpine supracrustal Čierny Balog and Hron Complexes. The collapse was followed by the emplacement of the VZP magmatic complex into an extensional detachment fault zone (346 Ma ago). This zone was also active during the Early Alpine continental rifting phase.

The VZP Complex is mostly represented by layered diorites, often porphyric Qz-diorites to diorites, which are internally differentiated into dark Pyrx-Amph or Amph-rich layers of meladioritic (gabbrodioritic) composition, or into pale tonalitic-trondhjemitic layers. The whole VZP complex is, after ductile deformation, about 250 m thick. Some serpentinite bodies accompany the base of the VZP Complex, but these are tectonically incorporated into micaschist-gneisses of the Pre-Alpine supracrustal Hron Complex.

Layered diorites and gabbrodiorites were emplaced into Pre-Alpine supracrustal gneiss-migmatitic rocks of the Čierny Balog (CB) Complex which now have the character of the Alpine Gt micaschists. The VZP and CB Complexes are cut by leucocratic granitic to pegmatitic veins (233±10 Ma).

The mylonitic layering was superimposed on magmatic layering due to ductile behaviour of Plg and Qz in dioritic orthogneisses. Newly formed Gt (Gross-rich) is in equilibrium with the mylonitic mineral assemblage: recrystallized Plg and migration recrystallization Qz ribbons, as well as with the newly formed blue-green tiny (Tsch-rich)$Amph_2$, Bt, WhM(Phn), Chl, Rut, Ep-Zoi, ±Chtd. Thus the Alpine metamorphism and deformation occurred at the temperatures 530-600 °C and medium pressures of 8-10 kbar (using geothermobarometry).

Compressional uplift along the Pohorelá detachment fault was accompanied by hanging-wall extensional unroofing. The VZP Complex represents the hanging wall complex of the Alpine South Veporic Kráľova hoľa Nappe detached along the mid-Cretaceous (Pohorelá) shear/fault zone and thrust over the North Veporic (Supratatric) Krakľová Nappe.

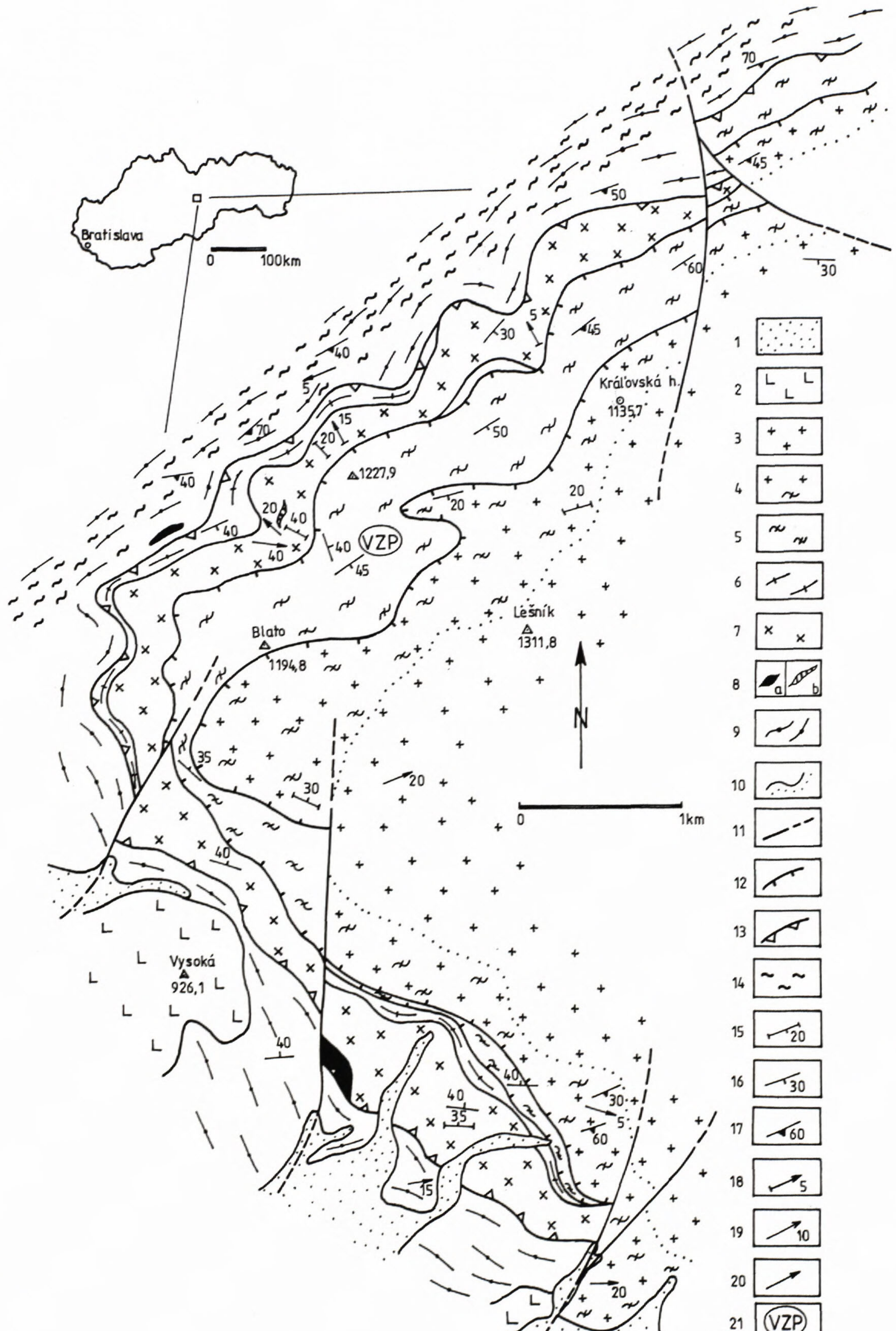
Key words: Western Carpathians, Veporic Zone, layered magmatites, detachment fault, collapse, Early Cretaceous, collision, ductile deformation - recrystallization.

Introduction and geological setting

The Veľký Zelený Potok (VZP) Complex belongs to the Veporic basement of the Central Western Carpathians (Fig. 1). It is composed of Meso/Late Variscan basic, mafic, intermediate to acidic magmatic members. The time of emplacement of the magmatic complex was estimated according to radiometric dating of porphyric metadiorites (346 Ma, U-Pb on Zr, KOTOV et al., pers. comm.).

The VZP metamagmatic complex of the Veporic basement indicates Meso/Late Variscan postcollisional collapse of the collided Pre-Alpine supracrustal Čierny Balog and Hron Complexes. The collapse was accompanied by the emplacement of the VZP magmatic complex into an extensional detachment fault zone, which formed along the former Variscan collisional tectonic boundary between the collided Pre-Alpine supracrustal Čierny Balog and Hron Complexes. Cooling ages of Amph: 357,9±0,7 (40Ar-39Ar method, DALLMEYER et al., 1993, 1996) from amphibolites of the Hron Complex indicate that the collisional (barrovian) stage of the regional Variscan metamorphism in the Veporic Pre-Alpine supracrustal complexes took place at least 370-380 Ma ago.

The extensional detachment fault zone was also active during the Late Paleozoic, when emplacement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VZP

of the Vepor granitoid pluton (303-288 Ma, U-Pb, BIBIKOVA et al., 1990), Hrončok granitoid body (265 Ma, Rb-Sr, CAMBEL et al., 1990, PETRÍK et al., 1995), as well as subvolcanic and volcanic rocks (due to Early Alpine continental rifting phase, 276-213 Ma, U-Pb, KOTOV et al., 1996) occurred there at higher structural levels.

In the Alpine tectonic structure the VZP Complex represents the hanging wall complex of the Alpine South Veporic Kráľova Hoľa Nappe detached along the mid-Cretaceous Pohorelá shear/fault zone and thrust over the North Veporic (Supratatric) Krakľová Nappe. Thus the VZP Complex represents a Meso/Late Variscan magmatic sequence incorporated into the Early Cretaceous collisional structure of the Veporic unit (PUTIŠ, 1989, 1991a, b, 1992, 1994, 1995, PLAŠIENKA, 1991, 1993, MADARÁS et al., 1994).

Lower/middle crustal boundary rheology of the mylonitic rocks close to Pohorelá thrust reveals perhaps the highest Alpine metamorphic conditions which have been found to date (VRÁNA 1964, 1966, 1980, PLAŠIENKA et al. 1989, MÉRES & HOVORKA 1991, KORIKOVSKY et al. 1992, MAZZOLI et al. 1992, PUTIŠ 1989, 1994, KOVÁČIK et al. 1996, KOTOV et al. 1996) in the Veporic region: temperatures of 530-600 °C at the pressures 8-10 kb (PUTIŠ et al., 1995, 1996).

The aim of this paper is to define the geological position and lithological sequence of the VZP layered magmatic complex at the type locality (the upper part of the Veľký Zelený Potok valley in the NW Veporské vrchy Mts.), and also to show its tectonic relationship to the deep crustal Alpine detachment (Pohorelá) fault.

The paper gives an overview of the new data concerning ductile mesostructures (foliations, lineations, folds), microstructures (kinematical and deformation mechanisms indicators), rheological behaviour of rock-forming minerals (Qz, Plg, Amph), CPO fabrics of Qz and Plg, as well as the estimation of P-T conditions of ductile strain according to the newly formed mylonitic/ metamorphic mineral assemblage and thermobarometric calculations. Existing, so far unpublished radiometric, geochemical and petrological (electron microanalyses of minerals) data are to be published separately.

Views on rocks and tectonic position of the VZP Complex

The rocks of the proposed Veľký Zelený Potok (VZP) Complex were classified as amphibolites, paragneisses, phyllites and micaschists and their phyllonites (MAHEĽ et al., 1964, KLINEC, 1966, 1976, IVANIČKA & KOVÁČIK, 1989).

A new period of investigation of this complex started with the re-interpretation (MIKO et al., 1987) of the rock sequence in the 500 m deep borehole KV-1 (KLINEC, 1968) near Pohronská Polhora village. PUTIŠ & MIKO (in MIKO et al., 1987) distinguished there two different rock sequences, or complexes, one above another, separated by a distinct phyllonite zone (at the depth 220-260 m) of supposedly Alpine age: the upper complex, which is dominated by para- and orthogneisses, and the lower complex, dominated by amphibolites, layered amphibolites, gabbroic intercalations and gneisses. Detailed petrographical and structural data are available in unpublished manuscripts (MIKO et al., 1987, PUTIŠ, 1995). The upper complex appears to be analogous with the Čierny Balog Complex (KRIST, 1976, KRIST et al., 1992, PUTIŠ, 1995), and the lower part of the borehole profile is now proposed as the Veľký Zelený Potok (VZP) Complex.

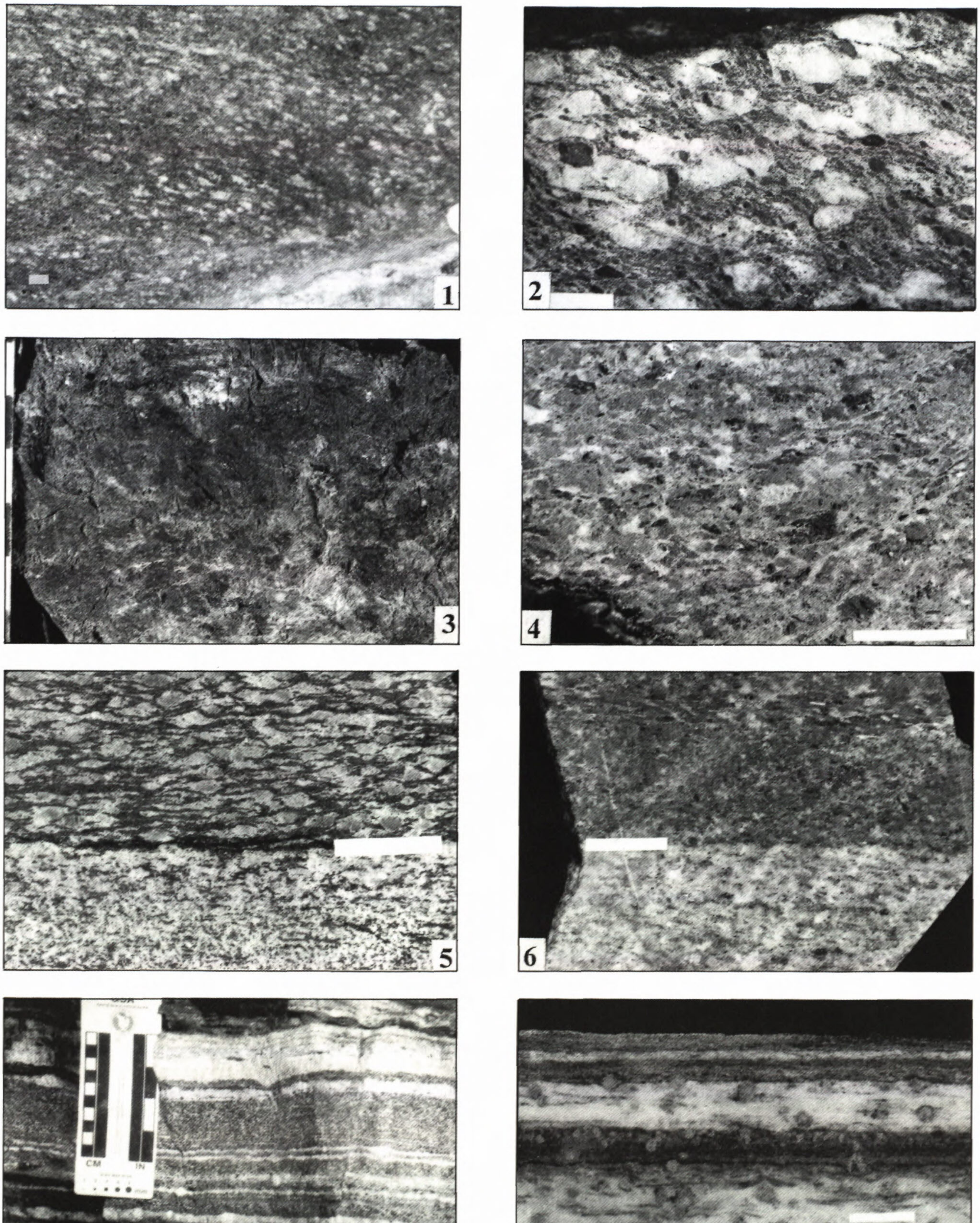
The VZP Complex resembles the gabbro-peridotite-basalt formation with intermediary to acidic members (MIKO & PUTIŠ, 1989 in KRIST et al., 1992, Fig. 74) overlying the micaschist-gneisses of the Hron Complex in the eastern part of the Nízke Tatry (Low Tatra) Mts. (PUTIŠ, 1989, MIKO & PUTIŠ in BIELY et al., 1992).

Layered amphibolites, as a part of high-grade metamorphic crystalline complexes, have been studied in the Nízke Tatry Mts. (SPIŠIAK & PITOŇÁK, 1990, 1992), the High Tatra Mts. (JANÁK, 1991, 1992, 1994, JANÁK et al., 1995) and in the Malá Fatra Mts. (JANÁK & LUPTÁK, in press).

The VZP Complex was included into the high-grade Leptyno-Amphibolite Complex (HOVORKA et al., 1992, HOVORKA & MÉRES, 1993, MÉRES et al., 1996).

The detailed study of the proposed Veľký Zelený Potok Complex has been carried out at the type locality (the Veľký Zelený Potok valley, Fig. 1) and other characteristic occurrences between Pohronská Polhora and Polomka villages, as well as on the northern slopes of the eastern part of the Nízke Tatry Mts. (PUTIŠ, 1992, 1994).

Fig. 1 Geological-structural sketch of the Veľký Zelený Potok Complex in the Veporic unit of the Central Western Carpathians.
1 - Quaternary sediments, 2 - Late Tertiary volcanites - andesite and tuff, 3 - mylonitized granite to tonalite of the Variscan Vepor pluton, 4 - granitoid with xenoliths of gneisseous mantle, 5 - gneiss to migmatite (Čierny Balog Complex, Early Paleozoic), with leucocratic granitic to pegmatitic veins, 6 - Alpine Gt micaschist (after gneiss and migmatite of the Čierny Balog Complex), 7 - dioritic orthogneiss with layers of meladiorite (gabbrodiorite), tonalite, to pale trondhjemite layers, 8a - serpentinite, 8b - (pre-Alpine) amphibolite, 9 - micaschist to gneiss with thin bodies of fine-grained and garnet amphibolite (pre-Alpine supracrustal Hron Complex, Early Paleozoic), 10 - geological boundary, 11 - fault, supposed fault, 12 - thrust, 13 - Cretaceous overthrust (detachment) plane of the Kráľová hoľa Nappe ovber the Krakľová Nappe (Hron Complex), 14 - main mylonite zone of the Pohorelá "line", 15- magmatic/subsolidus foliation S_0, 16 - mylonitic/metamorphic foliation S_1, 17 - mylonitic foliation S_2, 18 - lineation of magmatic flow L_0, 19 - mineral and stretching lineation L_1, 20 - intersection lineation L_2, 21 - VZP - Veľký Zelený Potok Valley.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Lithological composition and succession of magmatic phases of the Veľký Zelený Potok (VZP) layered magmatic Complex

The VZP Complex comprises the following meta-magmatic members:

Serpentinites (with the newly-formed Atg and Trem, Pl. III/1) accompany the base of the VZP Complex. They usually occur as protrusive lense-shaped bodies detached(?) from the VZP Complex and attached to the deeper (mid-Cretaceous) Krakľová Nappe (to the Pre-Alpine Hron Complex) that is mostly built of medium temperature micaschists and small bodies of amphibolites.

Layered amphibolites (Pl. I/7, 8) mainly represent the lower and upper part of a large differentiated metadioritic body, now (after ductile deformation) about 250 m thick. Undifferentiated dioritic parts have a composition which is the average of the dark (Amph, Plg, Tit, ±Qz) and pale (Plg, Qz, Mgt, ±Amph) bands. Intermediate tonalitic to pale trondhjemitic bands (Pl. I/5, 6) complete the magmatic sequence of the VZP Complex. A part of dioritic orthogneisses (Pl. I/1, 2) formed from porphyric diorites ($Amph_1$ with rims of $Amph_2$, partially recrystallized often hypidiomorphic Plg, Tit, newly-formed Bt, Qz) and these are dominant in the middle and upper part of the VZP Complex in the Veľký Zelený potok valley area S of Beňuš village.

A part of relatively homogeneous dioritic orthogneisses exposed in both Veľký Zelený Potok and Zavarguľa valleys is characterized by mafic layers of variable thickness of centimetre, decimetre, and less metre order (Pl. I/3-6). These mafic layers are rich in $Amph_1$ (Pl. 1/3) and indicate a metahornblenditic composition. A gradual transition from almost massive types with relic magmatic/subsolidus foliation, through layered orthogneiss up to banded mylonitic types (with distict ductile behaviour of Plg and Qz) may be seen in outcrops (Pl. I, IV).

Small metamafic (metagabbroic: Pyrx, Amph, ±Plg, ±Qz) boudinaged a few dm thick lense-shaped bodies (Pl. IV/1-3) have been found within dioritic orthogneisses in the Veľký Zelený potok Valley. They have scarcely preserved low-Ti monoclinic pyroxenes (with exsolution lamellae) diablastically overgrown by (hyp)idiomorphic low-Ti Amph. The large pale brown-green edenitic hornblende ($Amph_1$) crystals enclose Pyrx- diopside with a characteristic metamorphic reaction rim composed of colourless fine grained aggregates of actinolitic $Amph_2$ (Pl. II/1,2). Lower Ti-content in Amph1 and Pyrx can be explained by the newly-formed Tit or Rut.

Some pale to white leucotonalitic (trondhjemitic) layers (Plg, low content of Qz, Amph, Tit, sometimes higher content of Mgt) a few dm thick are usually situated next to tonalitic layers, often with a gradual transition contact. On the other hand, other occurrences with sharp boundaries could indicate sill-like veins. A few cm thick layers are commonly present in metadiorites. In some places they fill discordant tension cracks cutting the relic subsolidus foliation and they appear to be the youngest member of the VZP Complex.

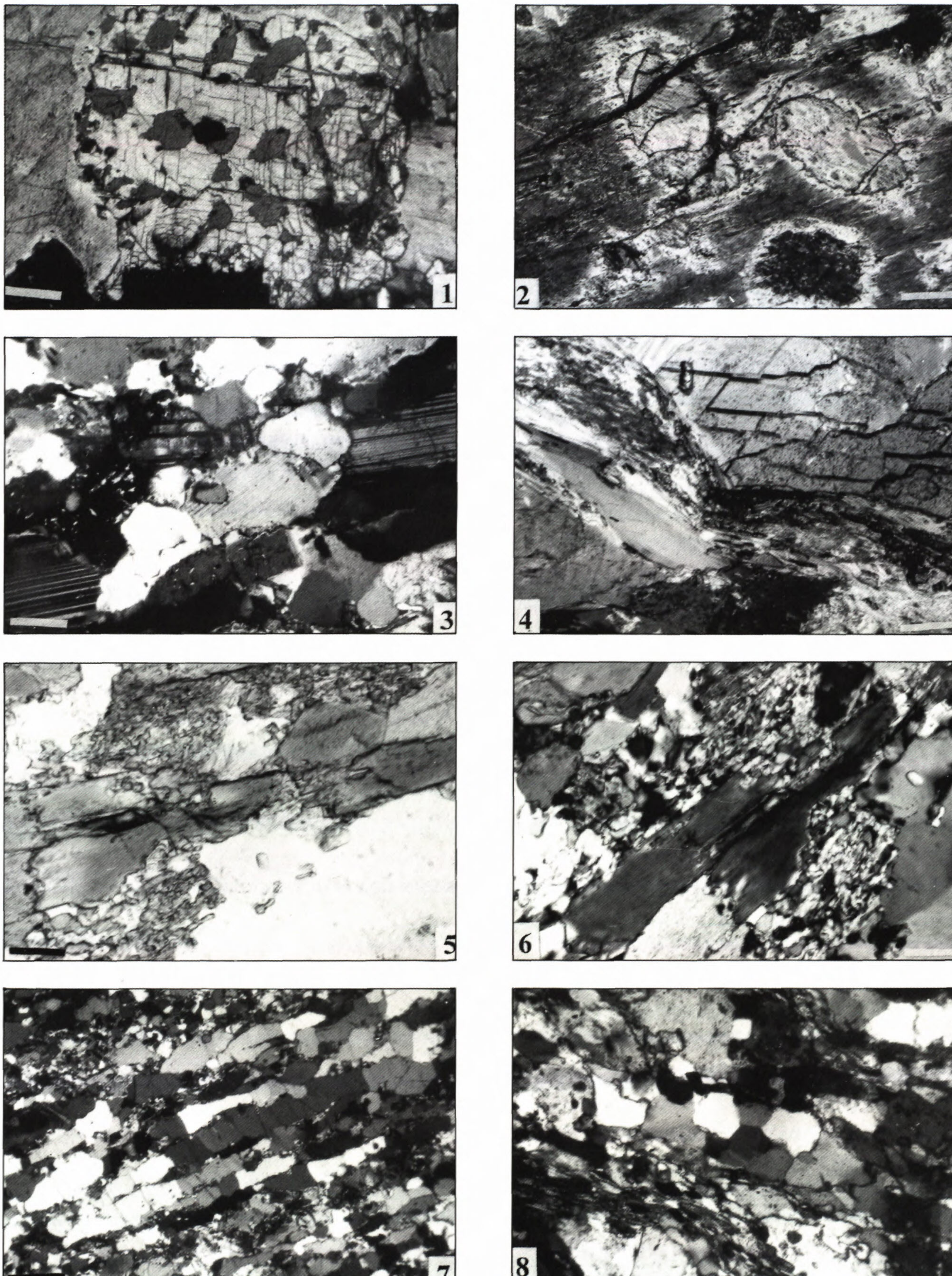
Different in composition and much younger (233 Ma±10, U-Pb on Zr, Kotov et. al., pers. comm.) appear to be leucocratic granitic to pegmatitic veins (Qz, Plg, Ms, ±Kf) filling extensional mesofaults and cutting the higher-temperature magmatic/subsolidus foliation of the VZP layered magmatic complex, including trondhjemitic veins.

Layered diorites were emplaced into older supracrustal rocks - migmatitic gneisses (with rare thin bodies of normal or Gt amphibolites) having now the character of Gt micaschists (Pl. III/7, 8, Pl. IV/7). It is possible to see transitions from migmatitic augen/stromatitic protomylonites (Qz, Plg, Bt, Ms, Gt-Alm rich cores), through augengneisses, to micaschists or blastomylonites (Qz, Ms replaced by WhM-Phn/Pgn aggregates, Chl, Clz, Gt-Gross-rich rims, Ky?, ±Bt, ±Plg) in large outcrops in the Veľký Zelený Potok Valley. This part of the VZP rock sequence resembles the supracrustal Čierny Balog Complex.

Succession of deformation - recrystallization events

The VZP Complex represents a Meso/Late Variscan magmatic sequence incorporated into the Early Cretaceous collisional structure of the Veporic unit.

Pl. I. Macrostructures of the magmatic, subsolidus and solid stage of the layered VZP Complex (scale-bar=1cm): 1 - subhorizontal magmatic foliation (S_0) cut by trondhjemite vein of the subsolidus stage of the porphyric (meta)diorite. 2 - magmatic hypidiomorphic Plg (with recrystallized rims) and $Amph_1$ in porphyric dioritic orthogneiss, and superimposed Alpine S-C fabric (Berthé et al., 1979). 3 - Pyrx-Amph slightly recrystallized gabbroic intercalation in diorite. 4 - Pyrx-Amph-Plg gabbroic intercalation in diorite. 5 - contact of (meta)dioritic and (meta)tonalitic layers, 6 - contact of (meta)dioritic and (meta)leucotonalitic (metatrondhjemitic) layers. 7 - layered dioritic orthogneiss (amphibolite) with superimposed ductile deformation (ductile thinning of pale layers with newly formed large Plg porphyroblasts). 8 - the strongest stage of ductile deformation of layered amphibolites (subhorizontal S_1 foliation) with newly formed Gross-rich Gt with dark rims of newly formed Tsch-rich fine-grained $Amph_2$.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In general, Alpine metamorphic event is dominated in the VZP Complex (with the exception of the less extensive gneiss-migmatitic Čierny Balog Complex within the VZP Complex, with some relics of Pre-Alpine metamorphism). Previous Early Variscan Gt(Alm) - Amph facies metamorphism which occurred in the Čierny Balog and Hron (Early Paleozoic ?) Complexes (e.g. KRIST et al., 1992) was not identified within the VZP metamagmatic Complex. But still Hb1, Pyrx and Plg could preserve their composition since the emplacement P-T conditions of the VZP Complex.

The age of the metamorphic recrystallization of the VZP Complex is constrained by the age of leucocratic granitic/pegmatitic veins (233±10 Ma, U-Pb on Zr, KOTOV et al., pers. comm.) which were concordantly or discordantly emplaced into the (gabbro)dioritic (346±0.7 Ma, U-Pb, KOTOV et al., l.c.) -tonalitic-trondhjemitic magmatic sequence. Similarly, e.g. Late Paleozoic subvolcanic/ volcanic veins (278-216 Ma, U-Pb on Zr, KOTOV et al., 1996) cut the magmatic/subsolid foliation of granitic orthogneisses in the Čierny Balog Complex (near Čierny Balog village). Thus the metamorphism and solid-state ductile deformation of the VZP Complex appear to be Alpine in age.

Mylonitic metamorphism and rheology of rock-forming minerals constrain the low/mid-crustal boundary conditions during the uplift of the VZP metamagmatic Complex. The mylonitic layering in dioritic orthogneisses has (in some places) its origin in magmatic layering, and the ductile behaviour of Plg and Qz clearly reflects superimposed mid-crustal mylonitic rheology in layers (bands) with higher ductile strain localization. Newly formed Gt (Gross-rich, PUTIŠ, 1989, 1994, PUTIŠ & KORIKOVSKY in KOTOV et al., 1996) is in equilibrium with the mylonitic mineral assemblage: recrystallized Plg and migration recrystallization Qz ribbons, as well as with newly formed blue-green tiny $Amph_2$, Rut (Ilm, Tit), Bt, WhM (Phn), Chl, Tit, Clz, Ab and ±Chtd.

Alpine grossularite-rich Gt usually grew within Plg or in some ranges along S_1 planes of layered amphibolites. Relics of albitized Plg are often preserved in the core of the Gt (Pl. III/3, 4). The growth started by irregular skeletal nuclei (Pl. III/2) or in the form of a large amount of tiny garnets in Plg gradually joined into a usually idiomorphic Gt rim. The breakdown of Plg indicates higher pressures. These were proved by higher Si^{4+} content (3,46-3,52 f.u.) in Phn of the neighbouring orthogneisses and calculated pressures 8 - 10 kbar (MASSONE & SCHREYER, 1987). Atoll-like forms of Gt (Pl. III/8) were found in granitic orthogneisses.

Alpine blue-green (tschermakite-rich, see also KOVÁČIK et al., 1996) $Amph_2$ substitutes brown-green $Amph_1$ (Mg-Hbl) (Pl. II/5, 6, Pl. III/5, 6). Other newly-formed minerals like Bt, Chl, WhM-Phn, Clz, Tit are concentrated in mylonitic foliation of gabbrodioritic, dioritic and tonalitic orthogneisses (Pl. II/4).

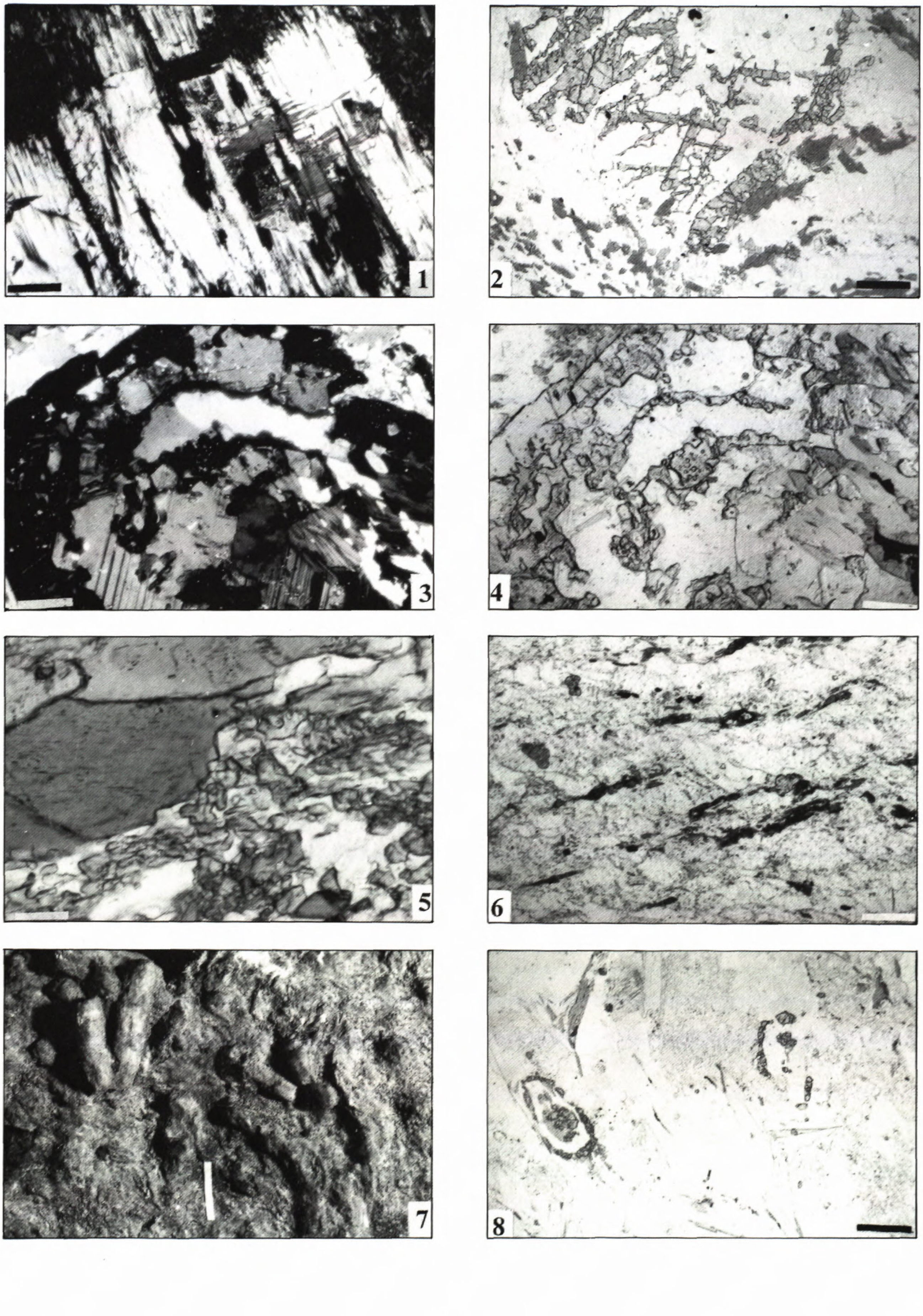
Gneiss-migmatic micaschists of the Pre-Alpine Čierny Balog Complex) also exhibit newly-formed Gross-rich Gt rims (Pl. IV/7) and the relic large-flaked Ms is replaced by fine-grained aggregate of the newly formed WhM of Phn/Pgn composition. Large prismatic crystals of Ky(?) are entirely replaced by WhM (Pl. III/7).

Early Alpine Gt(Gross) - $Amph_{(2)}$ facies metamorphism was reached near the base of the hanging wall VZP Complex within the Pohorelá detachment fault zone. Alpine metamorphism of the VZP Complex indicates the deepest part of the Early Cretaceous Pohorelá detachment fault. Nearly the same Alpine structural and metamorphic level is represented by the Čierny Balog Complex overlying the VZP Complex, or by a part of the underlying Hron Complex (compare with PUTIŠ, 1994, KORIKOVSKY & PUTIŠ in KOTOV et al., 1996).

The Vepor granitoid pluton and the accompanying cover (Foederata, or Struženík) complex already represent the upper crustal structural level. It is proved by the perfect ductility of Qz and semiductility of Fsp in dominant Bt zone metamorphic conditions (PUTIŠ, 1991 a, b, 1994, 1995). The granitic mylonites (84-86 Ma, 40Ar-39Ar on WhM, DALLMEYER et al., 1993, 1996) of the Vepor pluton, inclusive the Permian - Mesozoic cover rocks, are overlying the Čierny Balog Complex.

The whole hanging wall structural sequence of the Pohorelá detachment fault (bottom to top: reduced Hron Complex VZP Complex, Čierny Balog Complex and Vepor pluton granitoids, incl. the Permian - Mesozoic cover rocks) was incorporated into the Early Cretaceous (South Veporic) Kráľova Hoľa Nappe thrust over the (North Veporic, or Supratatric) Krakľová Nappe (with dominated Pre-Alpine Hron Complex) along the Pohorelá "line".

Pl. II. Microstructures of the magmatic, subsolidus and solid stage. 1 - Pyrx overgrown and enclosed by Amph, with a reaction rim between Pyrx and Amph, in (meta)gabbro; scale-bar=1mm. 2 - Pyrx (with exsolutions) and reaction (pale) rims in contact with later crystallized magmatic $Amph_{(1)}$, in (meta)gabbro; sc.b.=1,5mm. 3 - magmatic-subsolidus foliation (S_0) defined by Plg and some larger Qz grains in trondhjemite layer; sc.b.=1mm. 4 - solid-stage foliation (S_1) defined by newly formed (Alpine) Bt, WhM, Tit, Chl, Ep-Clz, $Amph_2$, which cut $Amph_1$ aggregate in (meta)diorite; sc.b.=1mm. 5 and 6 - Alpine dynamometamorphic "breakdown" of magmatic Amph1 to newly formed tiny $Amph_2$ grains in dioritic orthogneiss; sc.b.=0,5mm. 7 - higher-temperature Qz ribbon fabric in layered (metadioritic) amphibolite; sc.b.=1mm. 8 - lower-temperature internal dynamic recrystallization of Qz ribbons into polygonal aggregate of subgrains in layered amphibolite; sc.b.=0,5mm.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Meso- and microstructures of magmatic/ subsolidus and solid-state deformation/ recrystallization

Magmatic/subsolidus foliation (S_0) is macroscopically visible especially in porphyric dioritic orthogneisses (Pl. I/1,2-S-planes) due to subparallel orientation of hypiiomorphic Plg and some Amph. Oriented structure is also seen in dark gabbrodioritic layers (Pl. I/6). Magmatic layering into pale and more or less dark layers is the most distinct macroscopic feature of the VZP Complex (Pl. I/5-7). Even in the relatively homogeneous dioritic orthogneiss, there is characteristic alternation of coarse-grained and fine-grained layers of comparable composition.

The most probable mechanism of the layering appears to be magmatic laminar flow, accompanying the differentiation and alignment of Plg and Amph mega- and microcrysts parallel to the direction of flow. It is quite characteristic of intermediate magmatic complexes (e.g. PARSONS, 1987, FOUNTAIN et al., eds., 1992, PERCIVAL et al., 1992, SHELLEY, 1992, HALL, 1996), where a viscosity contrast between the mafic and felsic mineral aggregates is supposed during laminar flow and cooling in dynamic conditions of the shear zones. A continuous evolution of the magmatic to subsolidus foliation is characteristic for magmatic complexes emplaced into shear zones (e.g. PATTERSON et al., 1989, 1990). The presence of some sill-like veins can not be excluded.

Mesoscopic magmatic foliation is also recognizable due to leucotonalitic/trondhjemitic veins concordant or discordant with S_0 planes (Pl. I/1). The composition of these leucocratic veins (Plg, Qz, ±Amph, Tit, Mgt) strictly depends on composition of the host rocks and they could form by differentiation of primary dioritic rocks .

Other leucocratic granitic to pegmatitic veins contain a great amount Qz, Ms, and much less Kf than Plg. These veins (233±10 Ma, U-Pb, Kotov, pers. comm.) are cutting the subsolidus foliation of the VZP Complex. In some places such veins represent filled conjugate systems of tension fractures.

The position of subhorizontal magmatic/subsolidus foliation (e.g. 30/30, 330/20, 280/20, Pl. V/1.) is influenced by the Alpine collisional structure and kink-type macrofolds with NW-SE directed fold axes.

Mylonitic/metamorphic foliation (S_1) of the VZP magmatic complex either follows or obliquelly (at an acute angle) cuts the magmatic/subsolid foliation. S_1 planes are subhorizontal, or slightly inclined to the N or S (Pl. V/1.). They are usually superimposed on S_0 planes. S_1 planes are defined by the newly formed mylonitic/ metamorphic minerals like Bt, WhM (Phn/Pgn), Chl, $Amph_2$ (Tsch-rich), Gt(Gross-rich), Ep-Clz and recrystallized ggregates of Qz (Qz ribbons - Pl. II/7, or Qz polygonal aggregates - Pl. II/8) and Plg (Pl. II/7).

Concordant (// to S_0) or discordant leucotonalitic, or younger leucogranitic/pegmatitic veins also exhibit mylonitic S_1 foliation.

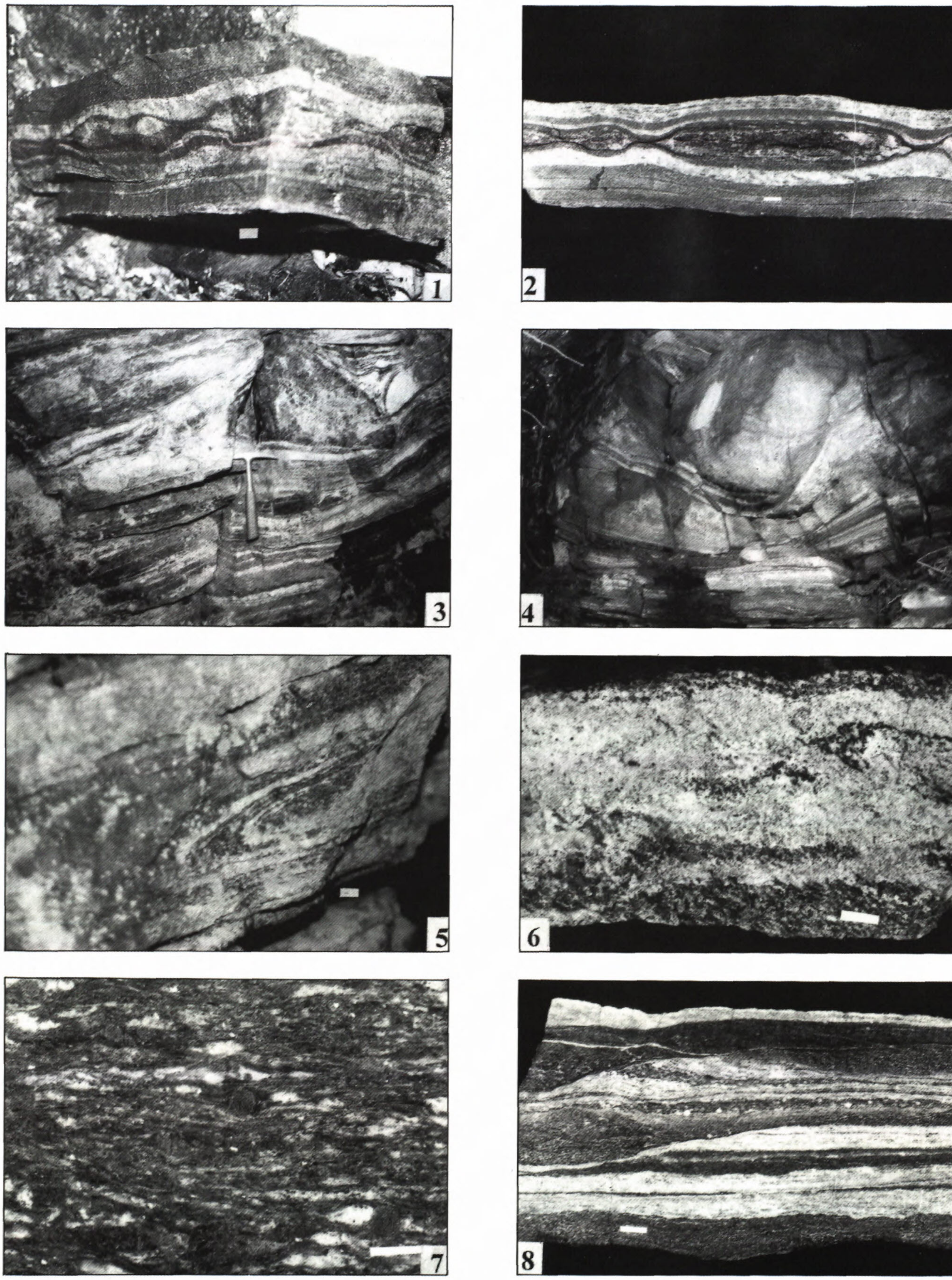
Metamafics and metaultramafics do not have a penetrative foliation S_1, because the mafic minerals (Amph±Pyrx) prevail over Plg. Subparallel to irregular systems of ductile-brittle fractures are filled with recrystallization products: Bt, Chl, Tit, WhM(Phn), Clz, $Amph_2$ (Pl. I/4, Pl. II/4).

Lineation of magmatic flow (L_0) has a dominated NW-SE direction (Pl. V/3.). It also varies from 330° or 150° (direction of dip) to 295° or 115°. It is defined by the alignment of (partially recrystallized) magmatic forms of Plg and Amph (Pl. I/1, 2, 5, 6) in magmatic foliation *(S_0)*.

Mylonitic/metamorphic lineation (L_1) is defined by recrystallized fine-grained aggregates of $Amph_2$ in layered dioritic orthogneisses to amphibolites, or by Bt and WhM in gneiss-migmatitic micaschists (visible on S_1 planes of rocks). Brown-green (pre-Alpine) $Amph_1$ was passively rotated into a direction parallel with WNW-ESE mineral and stretching L_1 lineation. It is partially (to totally) replaced by (Alpine) blue-green $Amph_2$ (Pl. II/5, 6, Pl. III/5) which also grew parallel to mylonitic foliation *(S_1)* and lineation *(L_1)*, or even in C-planes (Pl. III/6). Mylonitized mafic rocks have well visible lineation due to oriented growth of newly formed Bt, together with Chl, WhM(Phn) and $Amph_2$(Act). In general, this type of lineation is oriented in NW-SE to WNW-ESE direction (Pl. V/3.) and it resembles partially the direction of magmatic/subsolidus lineation *(L_0)*.

Intersection lineation (L_2) with the 280°-270° (or 100°-90°) (Pl.V/4) direction of dip formed due to development of a dense (E-W) *ductile cleavage (S_2)* (Pl.V/2) followed by rotation of Plg and less $Amph_1$ (Pl. IV/6).

Pl. III. Microstructures of Alpine recrystallization and solid stage fabrics. 1 - newly formed tremolite aggregate in antigoritic serpentinite, usually parallel to S_1 foliation; scale-bar=0,25mm. 2 - newly formed (Alpine) skeletal Gros-rich Gt in equilibrium with newly formed Tsch-rich tiny $Amph_2$ in layered amphibolite; sc.b.=0,5mm. 3 and 4 - zonal Gross-rich Gt encloses the relics of albitized Plg; all Gt zones appear to be in equilibrium with $Amph_2$, Bt, Chl, Clz; sc.b.=0,5mm. 5 - Alpine dynamometamorphic replacement of $Amph_1$ by tiny $Amph_2$ aggregate; sc.b.=0,25mm. 6 - Alpine S-C fabric in pale layers of amphibolite; C-planes are defined by newly formed $Amph_2$; sc.b.=1mm. 7 - Gt-Ky(?) migmatitic-granitic micaschist (the surface of S_1 foliation); sc.b.=1cm. 8 - Atoll-like newly formed Gross-rich Gt in granitic orthogneiss; sc.b.=1mm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Intrafolial folds (F_1) (Pl. IV/5) with the B-axes parallel to mylonitic mineral and stretching lineation *(L_1)* formed due to layer-parallel shortening connected with thickening or thinning of layers. Accompanying compressional ductile mesothrusts with NW vergency are scarcely preserved too.

Among the most characteristic mesostructures are symmetrically *boudinaged layered structures* in both XZ and YZ planes (Pl. IV/1, 2), which indicate a pure shear regime of mylonitic deformation. The development of superimposed extensional lineation, circular cores of mesofolds and intersection lineation (Pl. IV/6), on the other hand, indicate a transition to constriction.

The cores of lense-shaped boudins elongated in the direction of L_1 lineation are represented by relatively more rigid massive coarse-grained Pyrx-Amph meladiorites or gabbrodiorites (Pl. IV/3), which are not mylonitized (Pl. II/1, 2) and were avoided by the ductile flow.

Similar structures are observable even in homogeneous dioritic orthogneisses due to high ductile strain localization into some layers surrounding 1-2 m thick only slightly deformed orthogneisses (Pl. IV/4). Internal structures of such metadioritic boudins have at least partially preserved magmatic/subsolidus structures. On the other hand, the surrounding, both dark and pale layers exhibit strong ductile deformation and recrystallization in the form of fine-grained distincly oriented aggregates. The originally magmatic layering can be stressed by a more intensive (dense) ductile layering due to localized ductile flow (Passchier & Trouw, 1996). Ductile flow can be accompanied with the diffusional migration of Ca, Na, Si to pale layers and Fe, Mg to dark ones (e.g. Kretz, 1994), thus supporting the formation of ductile (mylonitic) layering.

Sigma and/or delta structures of Plg mostly indicate top-to-SE-ESE extensional sliding connected with porphyroclast rotation (Pl. I/2, 7, Pl. IV/7, 8).

Younger appear to be *ductile or ductile-brittle extensional mesofaults S_3* (320-345/60-75). Some of them are filled with Qz or Ep.

Approximately the same age is assigned to *brittle-ductile to brittle extensional mesofaults S_4* of the NW-SE direction, inclined to the SW-SSW (230-190/20-35) (Pl. IV/8).

The deeper foot wall unit - pre-Alpine Hron Complex of the mid-Cretaceous Krakľová Nappe, exhibits NE-SW directed mylonitic foliation (dipping to the SE: 135-150/45-70) and lineation (dipping to the ENE: 70/5-10, or to the WSW: 240/5-10) - (Pl. V/2, 4) which are closely related to the Pohorelá detachment fault system.

Rheological behaviour and crystallographic preferred orientation (CPO) fabrics of rock-forming minerals

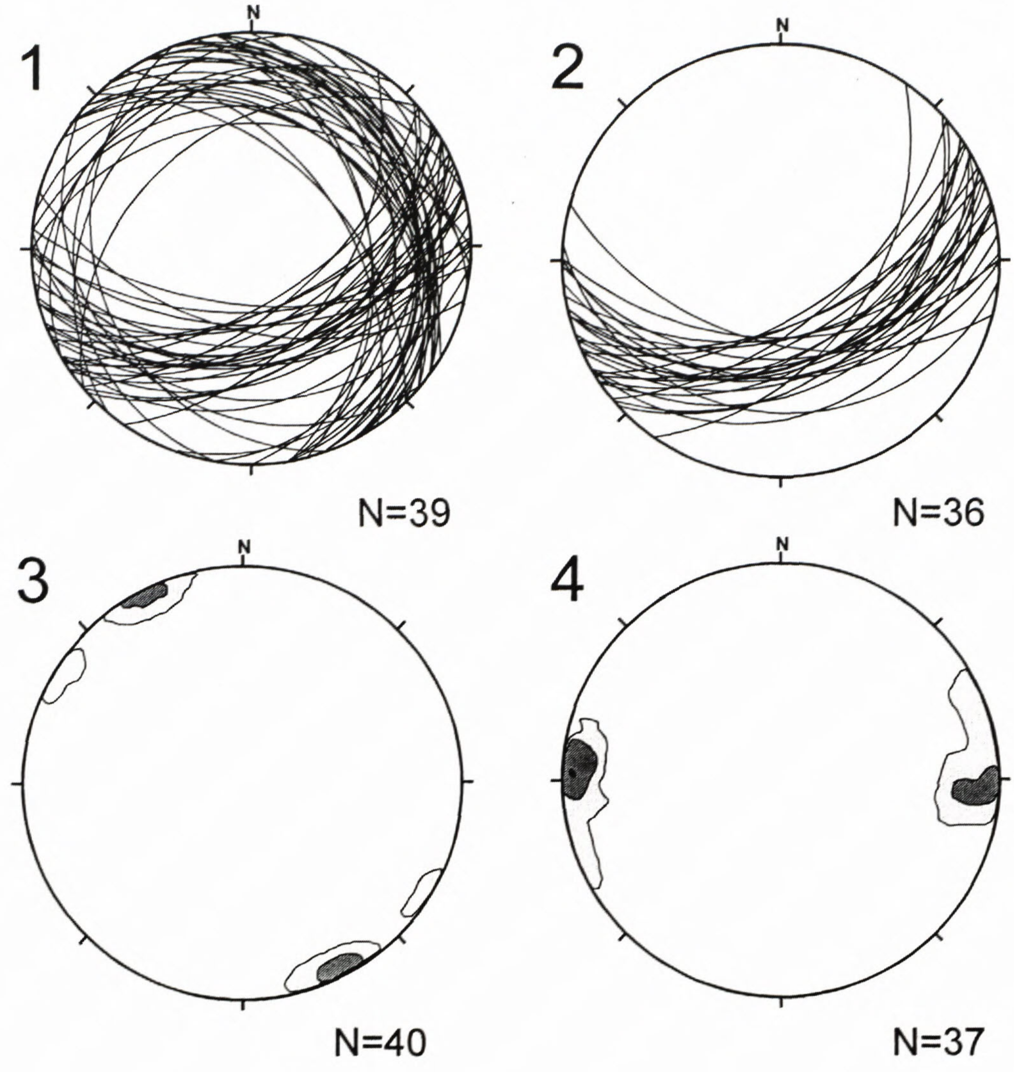
Ductile behaviour of Qz. Well preserved magmatic structures of some pale layers of trondhjemitic composition reveal intersticial position of Qz grains within Plg (±Amph, Tit) aggregates (Pl. II/3). Superimposed deformation at higher temperatures caused migration recrystallization of Qz to microscopic ribbons (Pl. II/7) separated from Plg-rich microlayers. The Qz ribbons exhibit two stages of recrystallization. The higher-T stage is represented by subgrains with boundaries perpendicular to ribbons. Their c-axes patterns represent higher-T (over 500 °C) rhomb and/or prism <c> glide systems (Pl. VI/1-3) in subgrains.

The superimposed dynamic recrystallization of large Qz ribbons into a polygonal aggregate of Qz (Pl. II/8) already belongs to the lower-T stage of deformation. A combination of basal <a> and prism <a> glide systems is evident from Qz c-axes preferred orientation patterns (Pl. VI/4-7) indicating temperatures of power law (dislocation) creep between 500 and 300 °C (e.g. Lister & Hobbs, 1980, Schmid & Casey, 1986). The asymmetry of diagrams reflects top-to-ESE direction of extension (Pl. VI/4-7).

Ductile behaviour of Plg (and Qz) indicates a typical mid-crustal rheology (at the temperatures over 500°C at medium pressures) of the layered metamagmatic complex during the initial stage of hanging wall exhumation on the Pohorelá detachment fault.

Porphyric hypidiomorphic Plg of Qz diorites to diorites exhibit recrystallization along crystal rims and formation of dynamically recrystallized aggregates in tails of porphyroclasts (Pl. I/2). Ductile mylonitic microlayering

Pl. IV. Alpine solid-stage mesostructures of the metamagmatic VZP complex (scale-bar=1cm). 1, 2 and 3 - boudinaged dark metamafic (Pyrx-Amph ±Plg, metagabbroic) layers within ductilely thinned layered amphibolites due to viscosity contrast during Alpine extensional uplift. 4 - boudinaged dioritic orthogneiss within layered amphibolites with high strain localization. 5 - intrafolial mesofolds due to layer parallel shortening. 6 - circular cores of mesofolds in YZ cut indicating constriction in direction of stretching (L_1) and intersection (L_2) lineations parallel to XZ plane. 7 - Alpine migmatitic/granitic Gt micaschist with flattened and stretched Plg and Plg+Qz aggregates, respectively. 8 - ductile-brittle extensional cleavage (S_3 and S_4 planes) in layered amphibolite



Pl. V. Great Circle (Equal area, lower hemisphere projection) and Contour orientation diagrams of mesostructures of the VZP Complex. 1 - Magmatic S_0 and mylonitic/metamorphic foliation planes S_1. 2 - Alpine extensional cleavage planes S_2. 3 - Lineations of magmatic flow L_0, and mylonitic/metamorphic lineations L_1. 4 - intersection lineations L_2.

of Qz and Plg aggregates causes formation of distinct macroscopic banded structures.

Flattened individual Plg grains of metamagmatic rocks are usually covered by recrystallization products: Clz, $Amph_2$, Chl, Gt, Bt.

Some pale low strained layers have quite well preserved (pre-solid) oriented textures of Plg aggregates (Pl. II/3) separated by intersticial Qz grains. Plg layers (due to migration recrystallization of Qz and dynamic recrystallization of Plg) exhibit higher-T mylonitic fabrics characterized by (001) planes (// with Nγ) subparallel to S_0.

Behaviour of Amph. Less deformed and recrystallized gabbro-dioritic to tonalitic rocks have often still randomly distributed $Amph_1$(Mg-Hbl) with brown-green to green pleochroism. These Amph-s appear to be of magmatic origin, but they already have metamorphic composition. Pre-Alpine brown-green $Amph_1$ is replaced by Alpine blue-green $Amph_2$ at least along the rims, or it is replaced by an aggregate of tiny newly formed blue-green $Amph_2$ during dynamic recrystallization (Pl.II/5,6, Pl.III/5). "Symplectitic" forms of the newly formed $Amph_2$ with Ep-Clz are characteristic too. $Amph_2$ is also present within recrystallized Plg_1 grains together with Ep-Clz and Gt(Gross-rich).

The most intensive deformation and recrystallization of Amph (either brown-green or blue-green) is recognizable in fine-grained banded amphibolites (Pl. I/8) with the maximum strain localization in both Plg-Qz-rich and Amph-rich layers. We can find there only some relics of larger brown-green, but mainly blue-green Amph, which are almost totally replaced by fine grained $Amph_2$ aggregates oriented in L_1 lineation.

Oriented $Amph_1$ (in *S-planes*) of mafic meladioritic to metagabbrodioritic rocks are cut by microshears (*C-planes*) filled with the newly formed Bt, Chl, WhM-Phn, Clz, Tit, $Amph_2$.

Conclusions

The VZP Complex of the Veporic basement indicates Meso/Late Variscan postcollisional crustal collapse and emplacement of a magmatic complex into the extensional Variscan detachment fault zone (since appr. 346 Ma, U-Pb, Kotov et al., pers. comm.). It probably occurred due to melting and differentiation processes in the collapsing lower crust. The VZP Complex seems to be a precursor of Early Alpine continental rifting magmatism (Kotov et al., 1996) in the former continental margin of the Meliata-Hallstatt Ocean (Kozur, 1991, Putiš, 1991a, Plašienka, 1991) which included the Veporic unit.

The Veľký Zelený potok (VZP) Complex is mostly represented by layered and porphyric Qz-diorites to diorites, which are internally differentiated into some mafic (Pyrx-Amph or Amph-rich) meladiorites (gabbrodiorites), or pale tonalitic to (plagiogranitic) trondhjemitic layers.

The layers are usually a few dm or cm (scarcely a few m) thick. The whole VZP complex is about 250 m thick (after the ductile deformation). Some serpentinite bodies accompany the base of the VZP Complex.

Layered diorites are emplaced within gneiss-migmatitic rocks (Pre-Alpine Čierny Balog Complex) which have after the Alpine recrystallization the character of Gt micaschists. The youngest magmatic rocks that do not belong to the VZP Complex, appear to be leucocratic granitic-pegmatitic veins (233±10 Ma, U-Pb, Kotov et al., l.c.) parallel to or cutting the magmatic/subsolidus layering of dioritic orthogneisses.

The superimposed solid state mylonitization-recrystallization is Alpine in age. The mylonitic layering in dioritic orthogneisses has locally its origin in magmatic layering. The ductile behaviour of Plg and Qz in high-strained layers (bands) reflects superimposed mid-crustal mylonitic rheology and the formation of some layers due to localization of high ductile flow. The newly formed Gt (Gross-rich) is in equilibrium with mylonitic mineral assemblage: recrystallized Plg and recrystallized Qz ribbons, as well as with other newly formed minerals such as blue-green tiny $Amph_2$ (tschermakite-rich), Bt, Tit, WhM, Chl, Rut (partially replaced by Ilm and Tit), Clz, ±Chtd.

The VZP Complex represents the deepest part of the hanging wall complex of the Pohorelá detachment fault. The VZP Complex belongs to the Alpine South Veporic Kráľova Hoľa Nappe detached along the mid-Cretaceous Pohorelá shear/fault zone and thrust over the North Veporic (Supratatric) Krakľová Nappe. Thus the VZP Complex represents Meso/Late Variscan dioritic-tonalitic-trondhjemitic complex cut by Early Alpine leucogranitic-pegmatitic veins and both were incorporated into the Early Cretaceous collisional structure of the Veporic unit.

Qz and Plg CPO patterns indicate power-law (dislocation) creep as the main micromechanism of ductile (plastic) deformation during the exhumation. Pure shear regime of deformation passed into simple shear dominated regime near the base of the VZP Complex, close to the detachment fault. The simple shear regime dominated in the upper part of the complex with the top-to-ESE direction of extension. It means that compressional (Pohorelá) thrust was accompanied by the hanging wall extensional unroofing (Putiš, 1994).

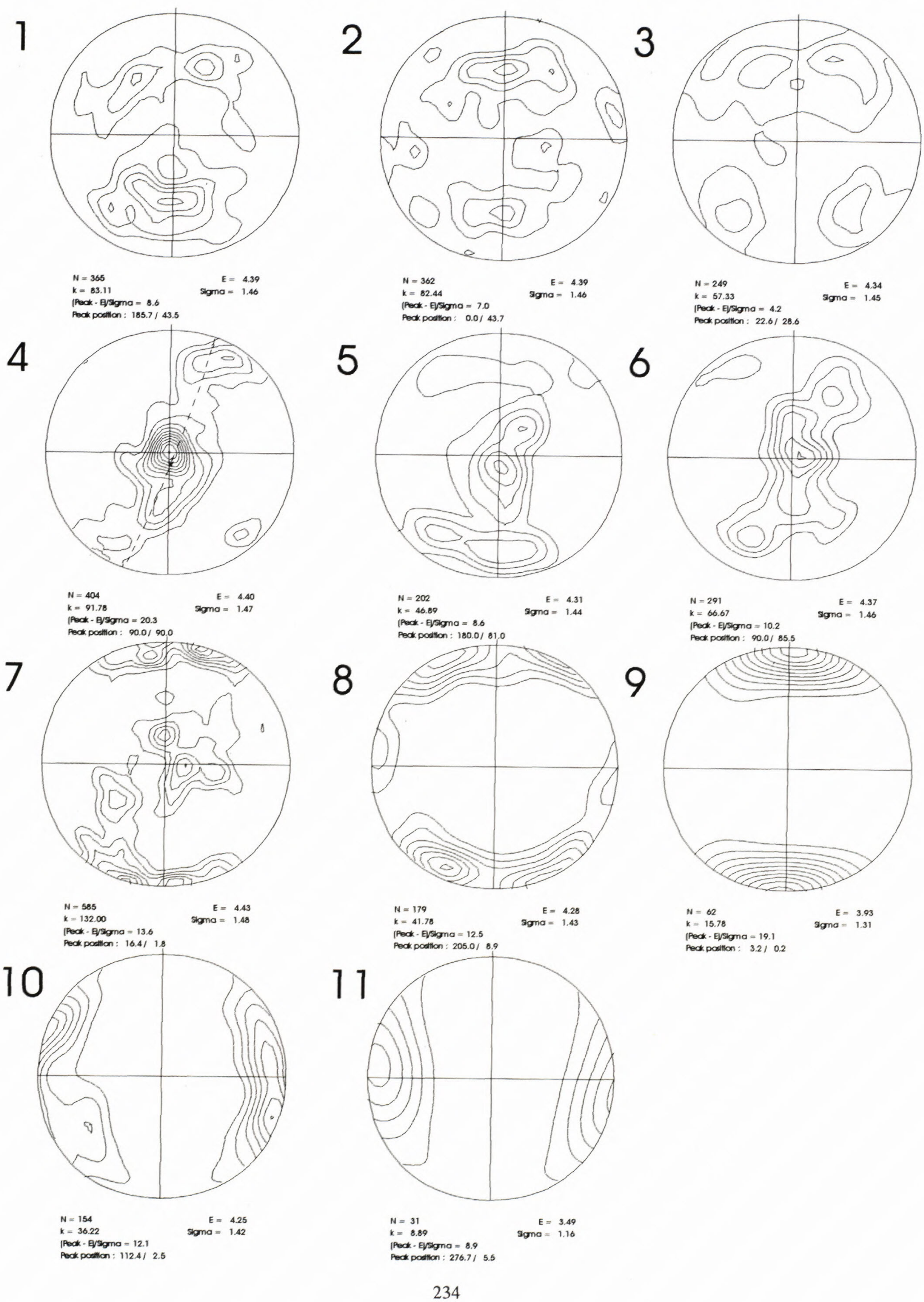
Discussion

The age and the evolution of the VZP Complex are not compatible with the Leptyno-amphibolite Complex (LAC). The LAC (Hovorka et al., 1992, Hovorka & Méres, 1993) was defined as a Pre-Alpine lower-crustal cumulate complex metamorphosed at higher amphibolite to granulite facies conditions. The representative rocks of the LAC are layered amphibolites with inclusions of Rut-Gt-Cpx (HP/HT) metabasites, as well as high-grade Ky-Gt gneisses. Partial melting of the amphibolite complex has been mentioned either.

The VZP Complex formed after the main (regional) Variscan metamorphism and is represented by a Meso/Late Variscan magmatic complex (since 346 Ma) that is cut by the Early Alpine (233±10 Ma) granitic-pegmatitic veins.

The VZP Complex underwent Alpine, Early Cretaceous distinct metamorphic event with the temperatures between 500 and 600 °C at medium pressures 8-10 kbar. Such conditions are compatible with the mid-crustal rheology of rock-forming minerals during the Early Alpine exhumation of the complex. The VZP Complex does not show any signs of typical lower crustal rheology and metamorphism. It was metamorphosed due to Cretaceous collisional-extensional events in the medium pressure Ab-Ep amphibolite facies conditions (e.g. Bucher & Frey, 1994).

The VZP Complex has locally well preserved relic magmatic structures (magmatic layering) of the original rocks. The layered amphibolites mostly formed from dioritic protoliths, with some layers of meladioritic (gabbro-dioritic) rocks, and/or tonalitic/trondhjemitic ones due to previous differentiation of the magmatic complex within the shear zone bound to a detachment fault. Despite the preserved relic magmatic structures (S_0, L_0), the minerals (Hb1, Pyrx, Plg) already have a metamorphic/mylonitic composition due to re-equilibration just after emplacement of the VZP Complex.


1
N = 365
k = 83.11
(Peak - E)/Sigma = 8.6
Peak position : 185.7 / 43.5
E = 4.39
Sigma = 1.46
2
N = 362
k = 82.44
(Peak - E)/Sigma = 7.0
Peak position : 0.0 / 43.7
E = 4.39
Sigma = 1.46
3
N = 249
k = 57.33
(Peak - E)/Sigma = 4.2
Peak position : 22.6 / 28.6
E = 4.34
Sigma = 1.45
4
N = 404
k = 91.78
(Peak - E)/Sigma = 20.3
Peak position : 90.0 / 90.0
E = 4.40
Sigma = 1.47
5
N = 202
k = 46.89
(Peak - E)/Sigma = 8.6
Peak position : 180.0 / 81.0
E = 4.31
Sigma = 1.44
6
N = 291
k = 66.67
(Peak - E)/Sigma = 10.2
Peak position : 90.0 / 85.5
E = 4.37
Sigma = 1.46
7
N = 585
k = 132.00
(Peak - E)/Sigma = 13.6
Peak position : 16.4 / 1.8
E = 4.43
Sigma = 1.48
8
N = 179
k = 41.78
(Peak - E)/Sigma = 12.5
Peak position : 205.0 / 8.9
E = 4.28
Sigma = 1.43
9
N = 62
k = 15.78
(Peak - E)/Sigma = 19.1
Peak position : 3.2 / 0.2
E = 3.93
Sigma = 1.31
10
N = 154
k = 36.22
(Peak - E)/Sigma = 12.1
Peak position : 112.4 / 2.5
E = 4.25
Sigma = 1.42
11
N = 31
k = 8.89
(Peak - E)/Sigma = 8.9
Peak position : 276.7 / 5.5
E = 3.49
Sigma = 1.16

The VZP Complex may be found also in the eastern part of the Nízke Tatry Mts. It overlies tectonically the micaschists of the (Pre-Alpine) Hron Complex of the Alpine Krakľová Nappe. It builds the base of the South

Veporic Kráľova Hoľa Nappe. The VZP Complex was thrust together with (Sihla type) metatonalites of the Vepor pluton over the Krakľová Nappe. The inverted metamorphic zoning thus formed in the North-Veporic (Supratatric) area (PUTIŠ, 1994).

Only the layered Gt amphibolites (overlying the micaschistgneisses of the Pre-Alpine Hron Complex) at the crest between the Veľký Zelený Potok and Malý Zelený Potok valleys could belong to the LAC. Their garnets have relic Alm-rich cores replaced by Gross-rich rims. Thermobarometric calculations: T 614-640 °C (Gt-Hbl thermometer, GRAHAM & POWELL, 1984) at P 8,5 kbar (Gt-Hbl-Plg-Qz barometer, KOHN & SPEAR, 1990) of the prograde trend are not compatible with the results obtained from the VZP layered amphibolites. On the other hand, Gt zoning in these amphibolites is compatible with the Gt zoning in micaschist-gneisses of the underlying Pre-Alpine, supracrustal Hron Complex.

Garnets of the VZP Complex layered amphibolites always exhibit prograde zoning and Gross-rich compositions. Using of Bt and Hbl inclusions in Gt, and Bt-Hbl-Gt geothermometry, T estimates are from 520-530 °C (cores) up to about 600 °C (medium to outer parts of grains). Among early inclusions inside Gt also Chl and Ep-Clz are present. The prograde zoning of central parts of Gt, and the presence of Chl inclusions in Gt exclude any suppositions about manifestation of the preceding higher amphibolite facies in the VZP Complex. Any certain relics of a high-T stage in the VZP Ep-amphibolites are fully absent and their metamorphism appears to be exclusively Alpine in age.

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Pl. VI. Crystallographic mineral preferred orientation (CPO) patterns. 1 - 3 - Qz ribbons c-axes isoline patterns of the layered amphibolite. 4-7 - polygonal Qz grains c-axes isoline patterns of the layered amphibolite. 8-9 Nβ optical direction isoline patterns of Plg of the layered dioritic orthogneiss to amphibolite. 10-11 - Nγ optical direction isoline patterns of Plg of the layered dioritic orthogneiss to amphibolite.

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Footnotes

Mineral abbreviations in text and figures: Ab=albite, Act=actinolite, Alm=almandine, Amph=amphibole, Atg=antigorite, Ap=apatite, Bt=biotite, Cal=calcite, Chl=chlorite, Chtd=chloritoid, Clz=clinosoizite, Ep=epidote, Fsp=feldspars, Gross=grossularite, Gt=garnet, Hbl=hornblende, Ilm=ilmenite, Kf=kalifeldspar, Ky=kyanite, Mgt =magnetite, Ms=muscovite, Olv=olivine, Pgn=paragonite, Phn=phengite, Plg=plagioclase, Pyrx=Pyroxene, Qz=quartz, Rut=rutile, Tit=titanite, Trem=tremolite, Tsch=tschermakite, WhM=white mica, Zoi=zoisite, Zr=zircon.