

Variscan dismembered metaophiolite suite fragments of Paleo-Tethys in Gemic unit, Western Carpathians

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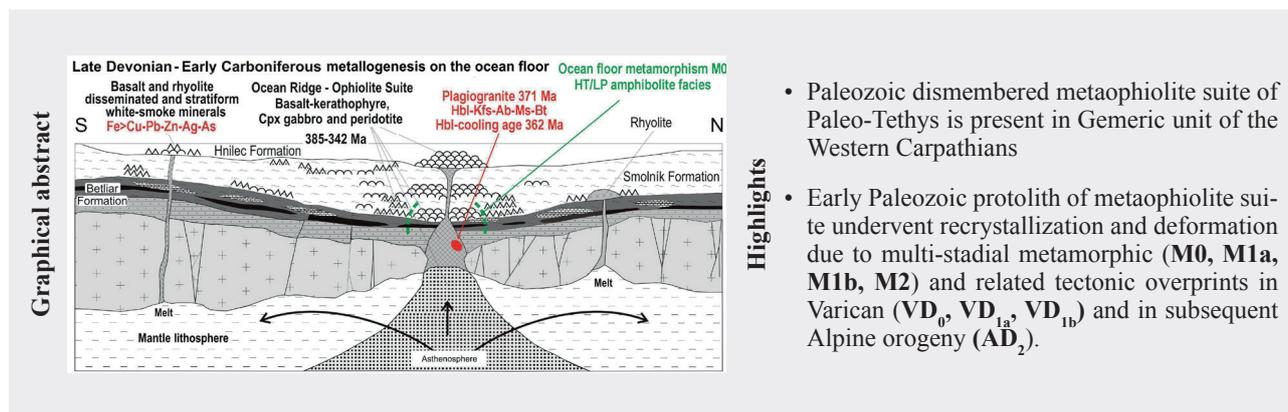
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Abstract: The Variscan dismembered ophiolite suite is exhumed in the northern zone of Gemic unit of the Western Carpathians (so-called North Gemic zone). It consists of variegated lithology of former segment of Paleozoic mid-ocean ridge of Paleo-Tethys, occurring now in three traditional principal localities of the gneiss-amphibolite complex (GAC) in the Gemic unit (Western Carpathians) - the Dobšiná, Rudňany and Klátov localities. Additional smaller occurrences at Jaklovce, Delava and Dobšiná (Cpx metagabbro) and the Strážny vrch hill (serpentinite) were recently also added to this suite.

The Paleozoic ophiolite suite in Gemic unit is built of six polymetamorphosed principal rock types: (1) gneiss with garnet (Alm+Pl+Bt+Ms+Qtz+Act+Chl) and graphite (occurrences at Dobšiná and Rudňany), (2) plagiogranite (Kfs+Ab+Pl+Ms+Bt-Qtz+Zo+Cal; $^{87}\text{Sr}/^{86}\text{Sr}=0.7033$; age 374 Ma Rudňany), (3) gneiss with amphibole porphyroclasts (Cum-Hbl/Prg-Act) and graphite (Klátov), (4) amphibolite (Pl+Hbl+Tnt+Ap+Pmp+Ilm+Act+Ep+Chl; Klátov, Rudňany, Dobšiná); (5) serpentinite (Chl+Dol+Ctl+CrSpl+Hem; Klátov, Strážny vrch hill); (6) metagabbro (Di+Aug+CrSpl+Pl+Hbl/Prg-KPrg-Act+Ep+Qtz+Tnt+Chl+MnIlm+Tnt+Ap+Zrn+Png+Ab+Hyl, Jaklovce, Delava, Dobšiná).

The suite of above listed rocks underwent a multi-stadial tectono-metamorphic overprint. First - Late Devonian to Early Carboniferous low-pressure amphibolite facies metamorphism **M0** (deformation stage **VD0**) of ocean floor is documented by the hornblende cooling age 362 Ma. Later metamorphic recrystallization of the pumpellyite–actinolite facies is related to compressional Variscan orogenic stage **M1a** (**VD1a**) affecting the metaophiolite suite in Late Carboniferous (around 300 Ma). During Permian metamorphism **M1b** (**VD1b**), the tectonic blocks of metaophiolite suite underwent recrystallization in the epidote-amphibolite facies to amphibolite facies by the input of heat at medium pressure. This metamorphism on the hot line was accompanied with the origin of anatectic granite of S-type and corresponding volcanism on the surface. The youngest metamorphic overprint **M2** (**AD2**) in the greenschist facies is the result of Alpine orogenic processes.

Key words: Gneiss-amphibolite complex (GAC), serpentinite, metagabbro, tectono-metamorphic overprint, Variscan orogeny, Alpine orogeny, Gemic unit, Western Carpathians



Introduction

The belt of the Paleozoic (Variscan) metaophiolite suite, built dominantly of amphibolites, gneisses (metapelite-metaseipelite), Cpx metagabbros, as well as ultramafic rocks, crops out in several separated blocks spread in the northern zone of Gemic unit (so-called North Gemic zone) at the municipalities of Dobšiná, Rudňany to Klátov (Figs. 1-4). From the historical perspective, the amphibolite facies rocks of this belt were defined by Dianiška and Grecula (1979) as the gneiss-am-

phibolite complex (GAC). In the Rudňany ore field it was revealed underground in the depth of 300-1100 m (Fig. 3). The Dobšiná and Klátov blocks are present on the surface (Figs. 2 and 4). The Dobšiná body in its southern part contains besides amphibolite and metapelite also metagabbro of the rift zone with preserved magmatic diopside. The Klátov body is bearing at its southern margin also the serpentinite (Fig. 2). The blocks of the GAC are in tectonic contact with other complexes of the lower-grade Early Paleozoic metamorphic rocks (prevalingly metatholeiitic basalts a metapelites) and the Late Paleozoic sequences

of the Gemic unit (Grecula, 1982; Grecula and Kuchaříč, 1985, 1989; Grecula et al., 2009). Because rocks with different metamorphic overprint occur in one group or one tectonic zone, Spišiak et al. (1985) re-named the Klátov gneiss-amphibolite complex to *Klátov Group* and there was distinguished also an individual *Klátov nappe* (Hovorka et al., 1984).

Recent knowledge about the gneiss-amphibolite complex in the North Gemic zone

The metamorphic evolution of the GAC in the *Klátov* area (Fig. 2) was firstly characterized by Grecula and Dianiška (1977), as well as Dianiška and Grecula (1979), and later by Faryad (1986) and Radvanec (1992, 1994a, 1994b). In the *Rudňany* area the amphibolite-gneiss complex was described by Popreňák et al. (1973), Hovorka et al. (1979), Hovorka and Spišiak (1981), Spišiak and Hovorka (1985), Hovorka and Spišiak in Cambel and Jarkovský (1985), Hovorka et al. in Hurný (1982) and Pramuka (1985b, 1986). In the *Dobšiná* area (Fig. 4) these metamorphites were described by Rozložník (1965) and Pramuka (1985a). Individual minerals of metabasites of the Rakovec zone were petrologically characterized by Bajanič and Hovorka (1981).

The southern part of GAC in the *Rudňany* ore field (Fig. 3) was described by Mandáková et al. (1971) as an intrusive body, containing rocks of gabbro and diorite magma with differentiation of both types from ultrabasics through the gabbroic rocks up to granitoid rocks. It was Popreňák et al. (1973) firstly pointing out that the GAC represents metamorphic rocks with P-T conditions close to granitization. Subsequently Hovorka et al. (1979), Hovorka and Spišiak (1981), Spišiak and Hovorka (1985), Hovorka and Spišiak in Cambel et al. (1985), Hovorka et al. in Hurný (1982), Pramuka (1985b, 1986), as well as Radvanec (1992, 1994a, b) described the GAC in details and determined P-T conditions of its metamorphism. According to petrographic study of above stated authors the gneisses and paragneisses of GAC in localities Klátov, Rudňany and Dobšiná can be divided to four types: biotite-plagioclase-, garnet-biotite-plagioclase-, amphibole-biotite-plagioclase- and garnet-amphibole-biotite-plagioclase-gneisses and paragneisses. The dominant part of the GAC is formed of amphibolite, garnet amphibolite, clinozoisite amphibolite, and locally ophthalmitic (eyed) amphibolite. The protolith of this complex was represented by metamorphosed ocean floor tholeiites (basalt and its pyroclastics), as well as metasediments (greywackes and schists), which in *Rudňany* area underwent the thermal overprint of 510-620 °C. The metamorphic process was considered to be chemically conservative at medium pressure conditions (e.g. Pramuka, 1985b).

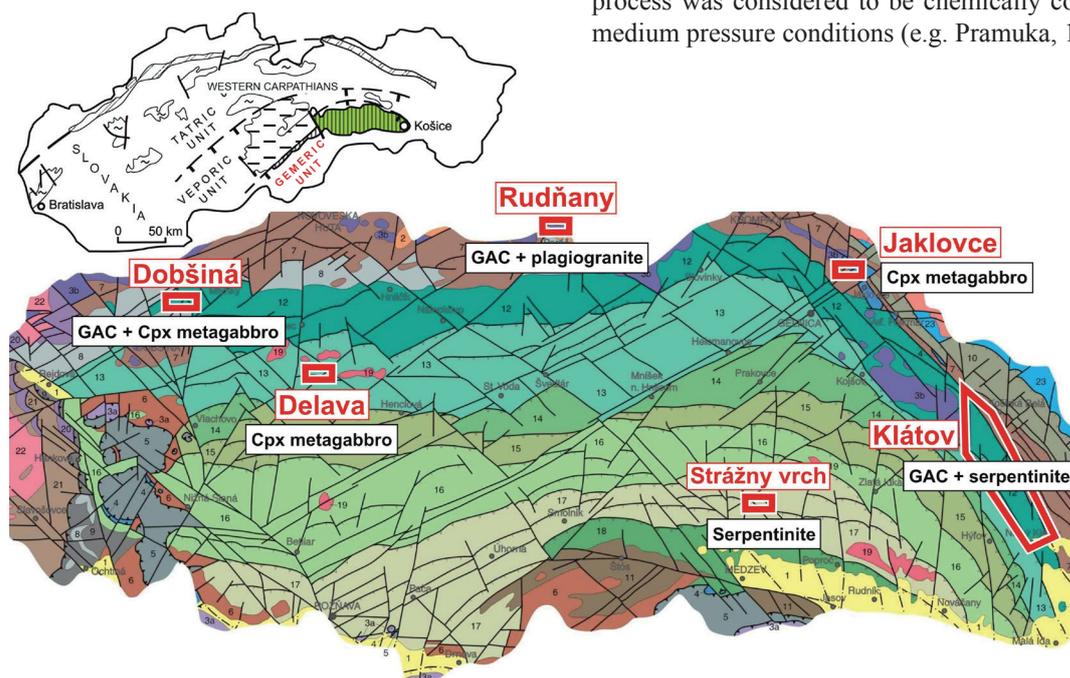


Fig. 1. Location of occurrences of Paleozoic dismembered metaophiolite suite in Gemic unit. 1, 2 - Quaternary, Neogene and Paleogene sediments, 3 - Mesozoic sequences of Silicic unit, 4, 5 - Meliatic unit, 8-19 - Gemic unit: 6-7 - Permian, 8-10 - Carboniferous, 11 - Carboniferous-Upper Devonian, 12 - zone of ocean floor sediments (Rakovec geosuture; protolith - Lower Paleozoic to Lower Carboniferous), including the occurrences of dismembered ophiolite suite, 13-18 - Lower Paleozoic sediments and volcanic products of the Paleo-Tethys southern marginal zone divided according to increased representation of acid volcanic products in volcano-sedimentary sequences towards the south and basic volcanic products towards the north, 19 - granite (Permian), 20-22 - Veporic unit: 20-21 - Triassic and Upper Paleozoic cover, 22 - crystalline basement. The basemap, depicting Gemic unit, is taken from Grecula et al. (2009).

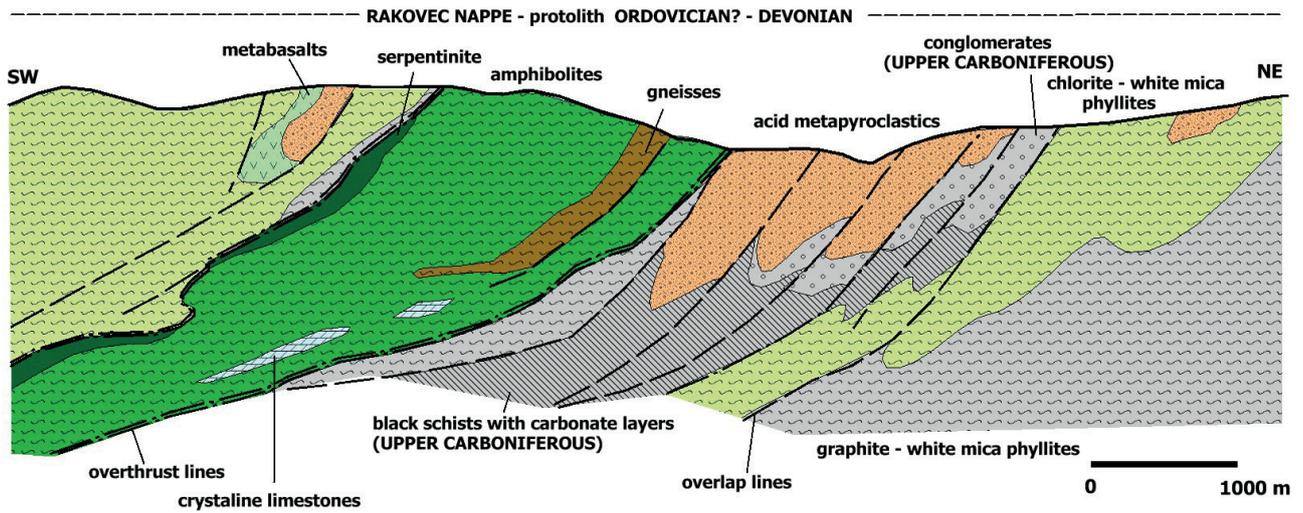


Fig. 2. Cross-section through the metaophiolite suite (gneiss-amphibolite complex) in the *Klátov* area. Modified after Grecula and Daniška (1977) and Daniška and Grecula (1979).

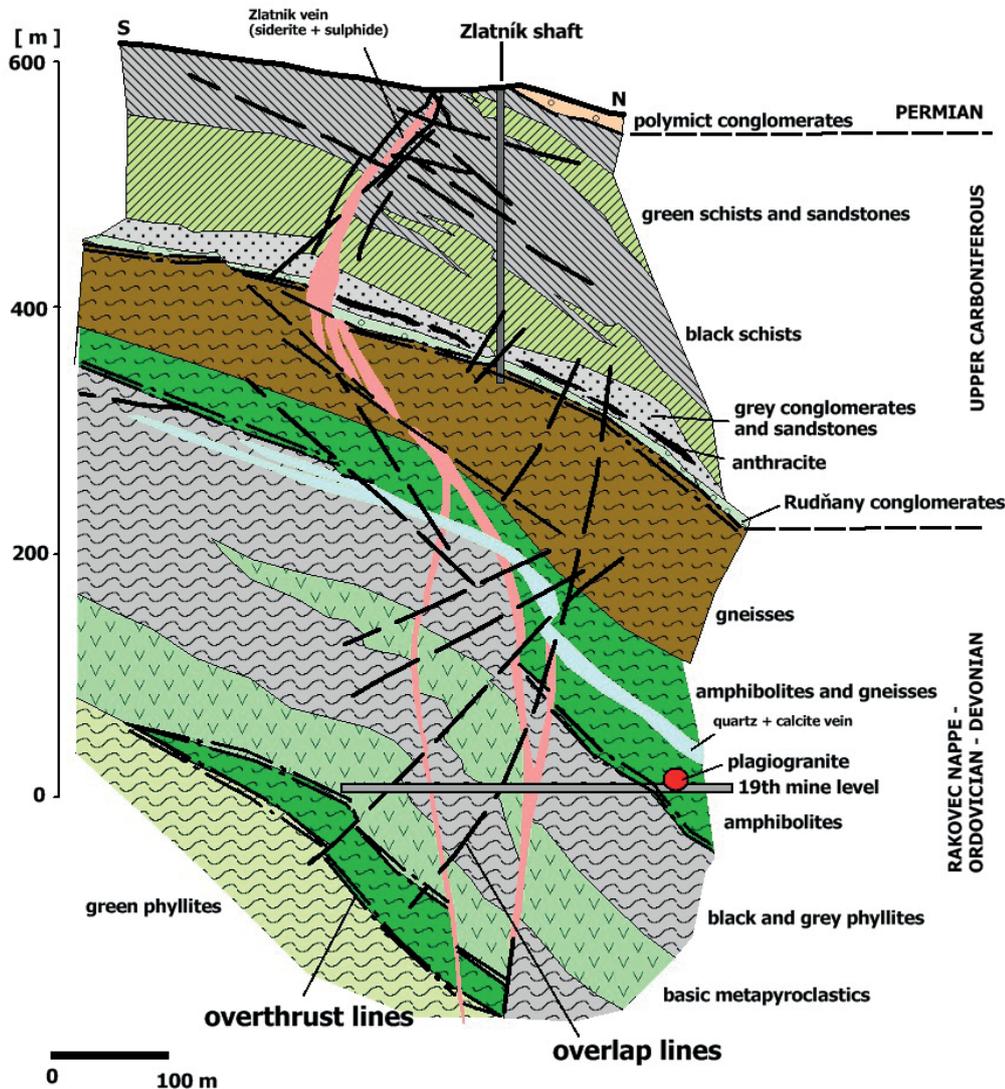


Fig. 3. Cross-section through the metaophiolite suite (gneiss-amphibole complex) in the *Rudňany* area. Adapted after Hudáček et al. in Grecula et al. (1995). Red point represents the position of plagiogranite.

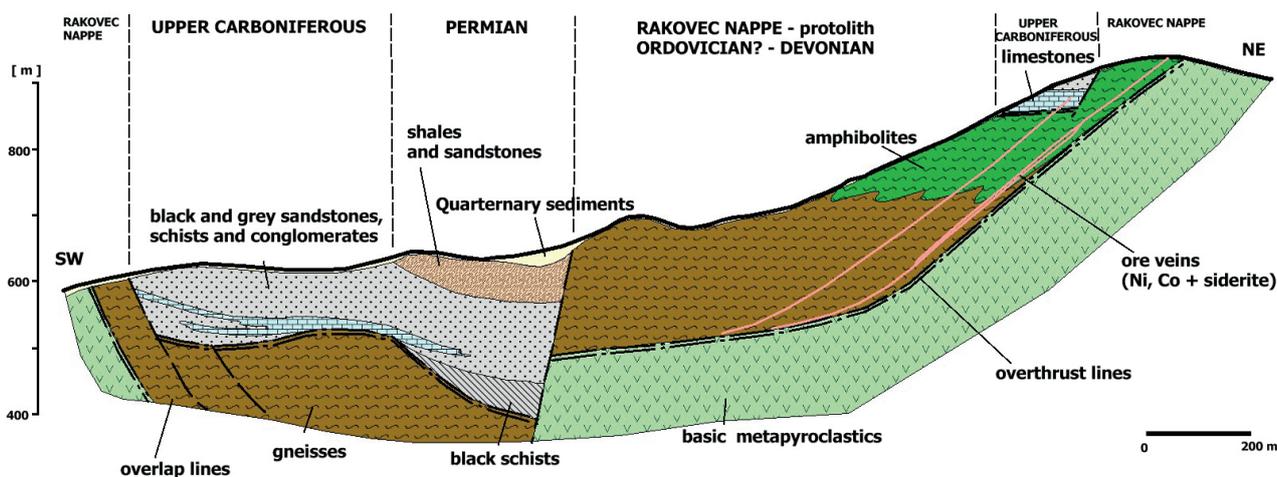


Fig. 4. Cross-section through the metaophiolite suite (gneiss-amphibole complex) in the *Dobšiná* area. Modified according to Grečula et al. (1995).

Above stated studies prevalingly aimed to determine the P-T conditions of metamorphism of the Early Paleozoic metabasites, their pyroclastics and sediments, alternating in one lithostratigraphic unit. Thermal overprint of rocks of GAC in the *Rudňany* reached 500-620 °C (Hovorka et al. in Hurný, 1982; Hovorka and Spišiak in Cambel, 1985), similarly as in the *Dobšiná* area (Pramuka, 1985a). The *Klátov* paragneisses were metamorphosed at 580-620 °C (Faryad, 1986), resp. 400- 650 °C (Radvanec, 1992, 1994a, 1994b).

Concerning metamorphic overprint, it was generally assumed that the GAC had originated at medium-pressure metamorphism (Hovorka in Hurný, 1982). The low-pressure metamorphism of this complexu in the *Dobšiná* area was assumed by Pramuka (1985a), and generally in the whole GAC by Radvanec (1992, 1994a, b).

Assuming the chemically conservative ocean floor metamorphism of amphibolite facies, Hovorka and Ivan (1985) interpreted the Early Paleozoic fore-arc geotectonic evolution of Gemic unit. The interpretation of regional chemically conservative metamorphism in Gemic unit was later proved to be incorrect (Radvanec, 1992; Bartalský and Radvanec, 1993; Radvanec et al., 1994a, b).

The detail petrological study of the whole belt of GAC (*Dobšiná* - *Rudňany* - *Klátov*) revealed that the pre-metamorphic protolith was represented by sediment (pelite) + carbonate (limestone) + organic material + products of tholeiitic volcanism, undergoing regional and polyphase metamorphism in open system for the fluid phase (Radvanec, 1992, 1994a, b). The ratio of the tholeiitic volcanic products to organic substance in former sediment varies in different places, so Radvanec (l.c.) named the protolith of the GAC as **semipelite**. The semipelite has underwent polyphase metamorphism. The first metamorphic overprinting **M1** at P = 2-3 kbar has reached the chlorite-biotite (500 °C, *Dobšiná*), biotite (550 °C, *Rudňany*) and cum-

ingtonite metamorphic zone (650 °C, *Klátov*; l.c.). In the prograde path of the **M1** metamorphism from the CaNKFMASCHTO system there mobilized Ca + Fe ± Mn ± Mg, H₂O and CO₂. These components entered into the fluid phase and at the temperature/pressure decrease in **M1** retrograde path the Fe and Mn carbonates have crystallized. The origin of fluid phase during Permian prograde metamorphic path explains the genesis of the vein siderite mineralization of Gemic unit (Radvanec et al., 2004 and 2010). The superimposed younger metamorphism **M2** in chlorite zone partially re-worked older mineral assemblages of the metasemipelite at higher pressure (P = 4 kbar, T = 400 °C). Metamorphism **M1** was classified as Variscan and metamorphism **M2** as Alpine (Radvanec, 1992, 1994a, b).

Our recent study of the succession of metamorphic events in traditional localities of the GAC in Gemicum (*Klátov-Rudňany-Dobšiná*) was supplemented by new mineralogical-petrological, geochemical, structural and geochronological data from localities of metagabbros (*Jaklovce, Dobšiná*), plagiogranite (*Rudňany*) and serpentinites (*Strážny vrch hill, Klátov*). According to geochronological results, P-T conditions of polymetamorphism, as well as whole-rock chemical analyses, *these new localities belong to Early Paleozoic metaophiolite suite, similarly as the traditional localities.*

Summing up, the Early Paleozoic metaophiolite suite of Gemicum is built of six rock types: (1) gneiss with garnet (Alm+Pl+Bt+Ms+Qtz+Act+Chl) and graphite (occurrences at *Dobšiná* and *Rudňany*), (2) plagiogranite (Kfs-Ab-Pl-Ms-Bt-Qtz+Zo+Cal; *Rudňany*), (3) gneiss with amphibole porphyroclasts (Cum-Hbl/Prg-Act) and graphite (*Klátov*), (4) amphibolite (Pl+Hbl+Tnt+Ap+Pmp+Ilm+Act+Ep+Chl; *Klátov, Rudňany, Dobšiná*); (5) serpentinite (Chl+Dol+Ctl+CrSpl+Hem; *Klátov, Strážny vrch hill*); (6) metagabbro (Di+Aug+Hbl/Prg-KPrg-Act+

Ep+Qtz+Tnt+Chl+Ilm+Chl, *Jaklovce, Dobšiná*). Serpentine and metagabbro in localities *Strážny vrch* hill, *Jaklovce* and *Dobšiná* represent new localities added to the Early Paleozoic metaophiolite suite (Fig. 1). The alternation of gneisses (metapelite/metasemipelite) and amphibolites in localities of *Klátov, Rudňany, Dobšiná* (Figs. 5, 6 and 7) often in bands thick to 1 cm, and their common polyphase metamorphism in amphibolite facies, do not allow to separate both lithotypes. It is the reason why the whole-rock analyses of amphibolites of the GAC are always influenced by mutual interbedding of rocks or contamination. The protolith of gneisses represented a sediment with organic admixture, forming the Early Paleozoic (Silurian-Devonian) footwall of volcanites and gabbros of ophiolite suite (Grecula et al., 2009). This protolith underwent polyphase metamorphism together with further rocks of ophiolite suite (Figs. 5e, 5f, 7a and 7b; Radvanec 1992 and 1994a).

Methodology of the study of polyphase metamorphism

Analytical works

Preferably the oriented samples from the outcrops of the metaophiolite suite were taken in localities *Dobšiná, Rudňany, Klátov, Strážny vrch* hill, *Jaklovce* and *Delava*. In locality *Rudňany* the samples were taken underground from the mine adit wall in the northern part of the ore field (Fig. 3) in the adit segment from the Severná žila (Northern vein) to veins Matej and Jakub (Gonda et al., 1993). Further there were prepared polished thin sections and separated zircons and apatite for geochronological study (based on collaboration with Comenius University, Faculty of Natural Science, Prof. M. Putiš; Putiš et al., 2017). Samples were used also for the whole-rock analyses in Geoanalytical laboratories of ŠGÚDŠ in Spišská Nová Ves.

Further mineralogical-petrological and structural type, being studied in details, represented a contact zone of metapelite/metasemipelite (gneiss) with interbeds of amphibolites. In localities *Klátov, Rudňany* and *Dobšiná* the GAC often contains pseudo-interbeds of gneisses and green amphibolites, thick only several centimetres, so the GAC often acquires a banded structure. This detail study intended to reveal the relics of older mineral assemblage, which in individual interbeds could be replaced by younger more dominant metamorphic process.

Concerning the petrological and geochemical research we have selected the rock type, having in all localities in one thin section the same volume representation of these minerals: quartz 30-40 vol.%, plagioclase 20-25 %, biotite + garnet 15-20 %, amphibole + chlorite 10-20 %, epidote group 5-10 %, phengite - muscovite 5 %. Besides these main minerals, the next important requirement was a presence of ilmenite + rutile + titanite + calcite + apatite and

graphite(?) (former organic material) in each investigated thin section. The volume representation of this assemblage did not overreached 3 %. The next important requirement was that none of above minerals in thin section has to be localized in younger veinlet than the matrix of the rock. The individual rock samples were selected carefully with the demand of petrographic and petrological certainty that we investigate the same rock type in the whole spatial extension of the GAC, i.e. we investigate the same silicate system in different places. Polished thin sections were firstly studied by optical microscopy. According to classification by Hovorka and Spišiak (in Cambel, 1985) the lithotype, we investigated, can be designated as the biotite-plagioclase-, garnet-biotite-plagioclase- and amphibole-plagioclase paragneiss. Despite, regarding the study of metamorphic reactions and metamorphic zonality this petrographic classification is inapplicable, because in the GAC it does not classify the critical mineral assemblages in metamorphic zones. It was the reason why we derived the name of studied metamorphic rock from its protolith, which besides the pelitic sediment (quartz, micas, clay minerals ± carbonates ± organic substance) contained also volcanic tholeiitic admixture (basalt?). Its presence in the metamorphic rock is indicated by amphibole and chlorite.

Mineral assemblages were studied applying the scanning electron microscope Hitachi S 550 with Kevex energy-dispersive X-ray analytical system and programs Magie V and Kevex 7000 in the Kyoto University. In the majority of analyses we used the detector Kevex Si (Li) with Be-window at accelerating voltage 15 kV and 300 picoampere electron beam, applying natural standards.

Next the minerals were studied in back-scattered electrons (BSE) with detector GW-BSE applying the scanning electron microscopes Hitachi S 530 and S 550 at 20 kV and ca 1000 pA (Table 1).

Chemical composition of minerals, resp. mineral assemblages was studied by X-ray mapping, applying the program Kevex Advanced Image. The mapping of chemical composition we did on appropriate plane during 12-15 hours at stable microprobe conditions. Based on this mapping we have selected appropriate places for quantitative analysis. Later the chemical analyses of minerals were completed by the microprobe Cameca SX 100 in the State Geological Institute of Dionýz Štúr in Bratislava. Used mineral standards: Ca - wollastonite, Mn - rodonite, Na - albite, K - orthoclase, Cr - chromite. Synthetic compounds were used for determination of the content of Ti, Al, Fe, Mg, as well as BaF₂ for F. Analytical parameters: 15 kV, intensity of beam 10 nA at analyses of carbonates or 20 nA at analyses of silicates. The 1–5 µm diameter of analysed area changed in relation to mineral dimensions. Measuring time of one element was 10 s or 25 s for F. Detection limit together with an error 1-sigma for individual elements was smaller than 0.05 wt. %

Fig. 5. Mineral assemblages of amphibolite with graphite (C) in GAC in the *Klátov* locality. Ab+Zo – mixture of albite and zoisite (decomposition of former plagioclase); Ab – albite; Ep – epidote; Hbl – hornblende; Ed – edenite, Cum – cummingtonite, Chl – chlorite; Ap – apatite; C – graphite, Pl – plagioclase; Tnt – titanite; Act – actinolite; Zo – zoisite; MnIlm – ilmenite with MnO content, Qtz – quartz, Zrn – zircon. Backscattered electron images.

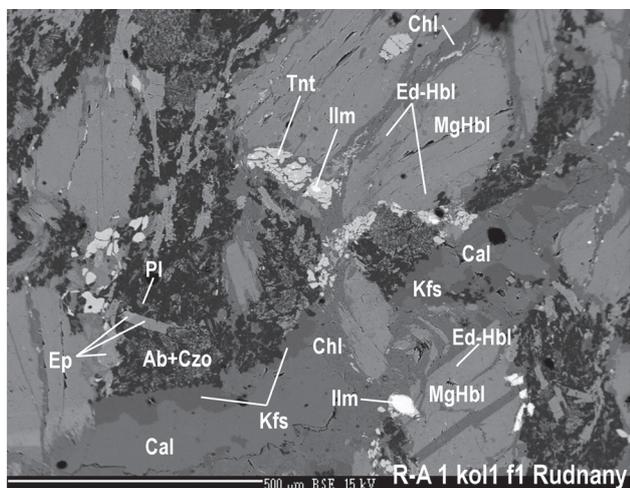
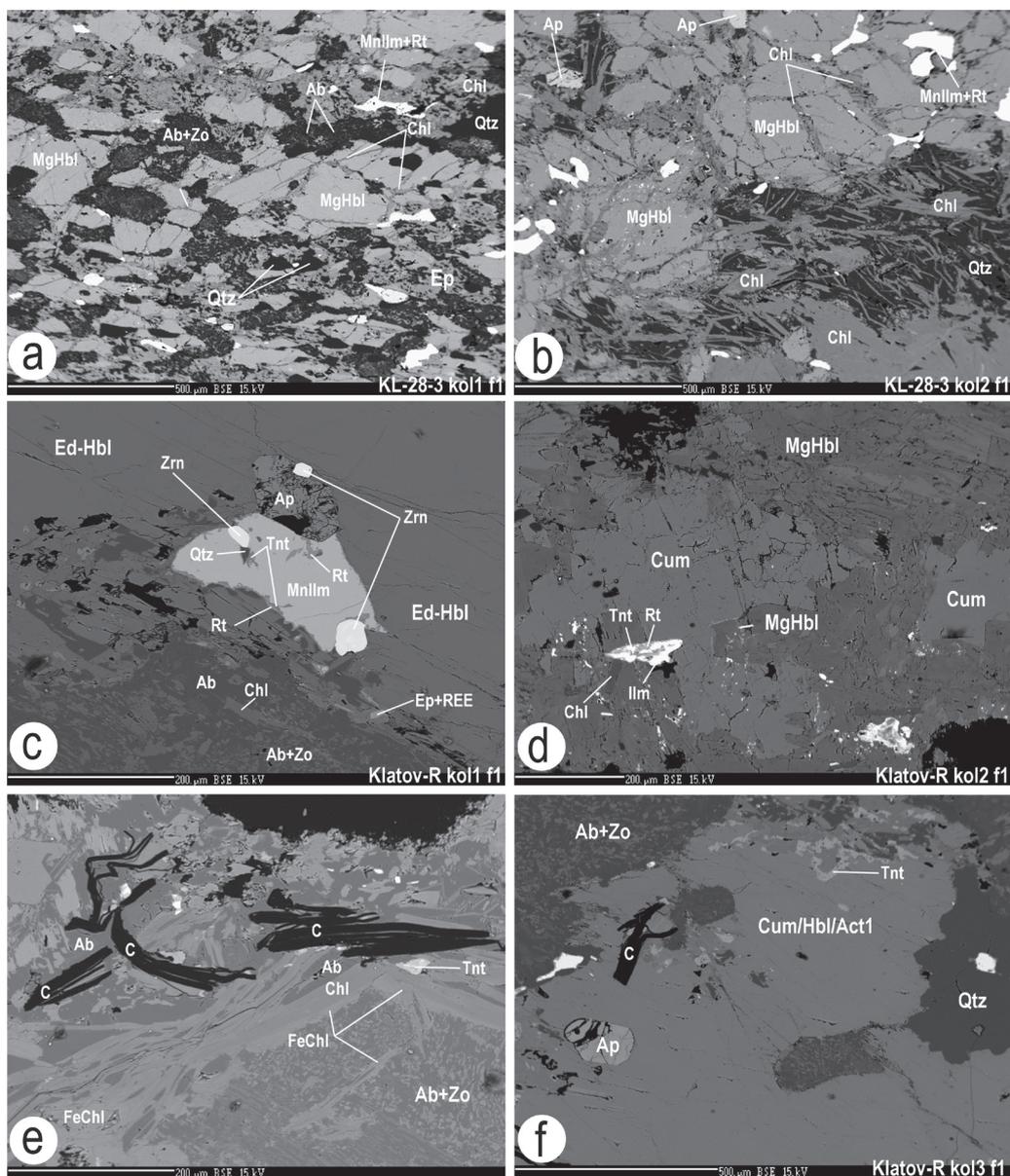


Fig. 6. Mineral assemblages of amphibolite in GAC in the *Rudňany* locality. Ab+Czo – mixture of albite and clinozoisite (decomposition of former plagioclase); Ab – albite; Ep – epidote; Hbl – hornblende; Ed – edenite, Chl – chlorite; Pl – plagioclase; Tnt – titanite; MnIlm – ilmenite with MnO, Cal – calcite, Kfs – K-feldspar. Backscattered electron image.

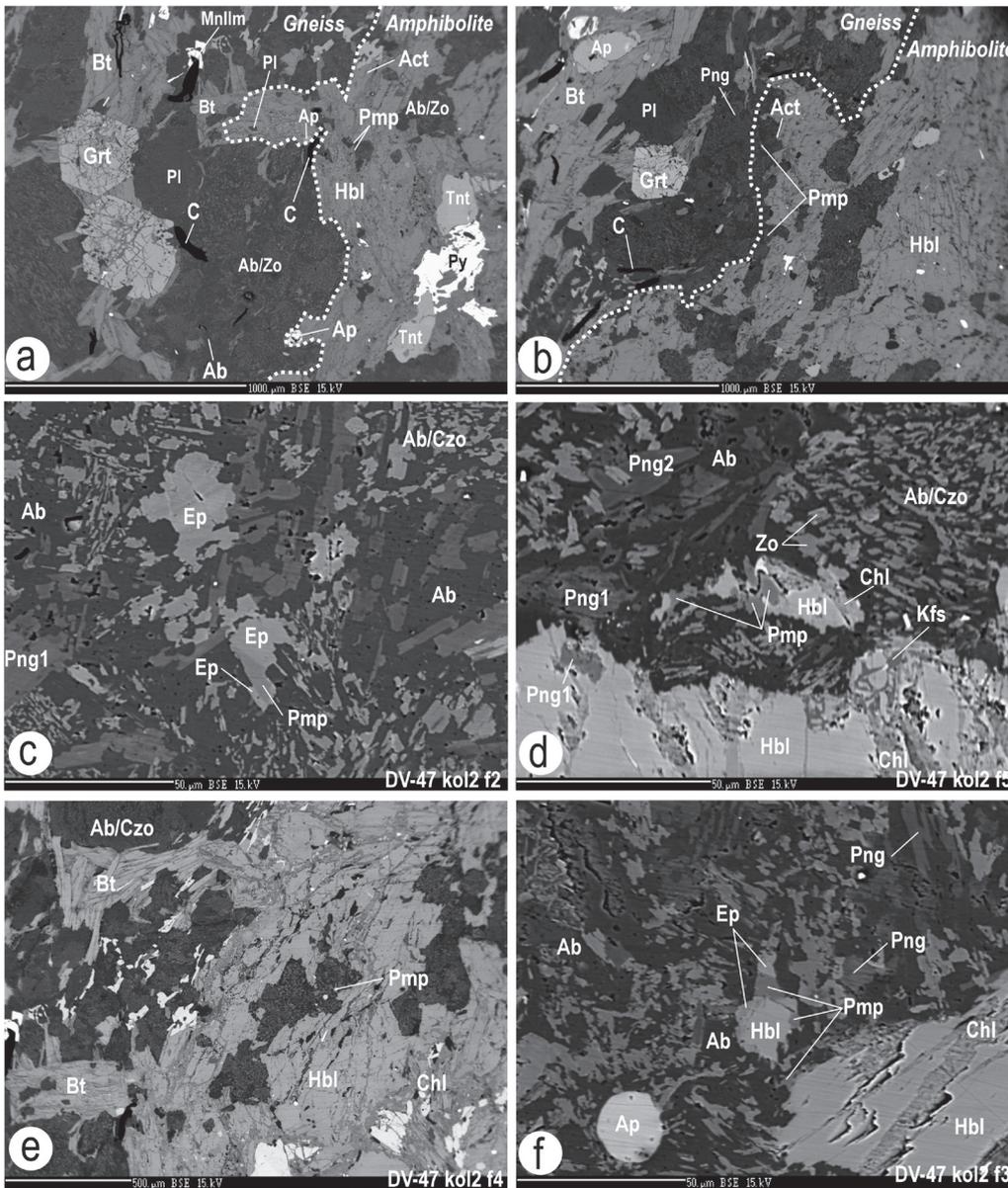


Fig. 7. Mineral assemblages at the contact of metapelite/metasemipelite with the content of graphite (C) and amphibolite in GAC in the *Dobšiná* locality. Bt – biotite; Ab/Czo – mixture of albite and clinozoisite (decomposition of former plagioclase); Ab – albite; Pmp – pumpellyite; Ep – epidote; Hbl – hornblende; Chl – chlorite; Ap – apatite; Png – phengite, white mica; Kfs – K feldspar; Grt – garnet; C – graphite, Pl – plagioclase; Tnt – titanite; Py – pyrite; Act – actinolite. Zo – zoisite; MnIlm – ilmenite with MnO content. Borehole – VD-47. Backscattered electron images.

Main minerals of GAC in localities *Klátov, Rudňany and Dobšiná*

Feldspars

In metasemipelite of GAC the plagioclase prevailingly forms porphyroclasts, but also relic irregularly shaped 3-7 mm large porphyroblasts in the matrix (Figs. 6 and 7a, b). Former porphyroblasts as well as porphyroclasts are often replaced by the metamorphogenic mixture of Ab/Czo or Ab/Zo (Figs. 5, 6, 7 and 9).

In the *Dobšiná* metapelite/metasemipelite (gneiss) we found plagioclase porphyroclast – either andesine/oligoclase or albite (Fig. 8), occurring in assemblage with Png, Grt, Bt, Chl and Qtz in the matrix. Pl porphyroclasts con-

tain inclusions of Png1, Czo and Zo, sometimes also Qtz, Ap and C - graphite (Fig. 7a, b). In the fractures of porphyroclasts the biotite has crystallized. Older plagioclase porphyroblast (P11), which crystallized in the tight vicinity of garnet (Grt) and formed the assemblage with it, is distinctly zonal: core $X_{an} = 0.33-0.47$, contact $X_{an} = 0.1-0.2$ (oligoclase). Rarely the core has values around $X_{an} = 0.24$. The margin of porphyroclast has a value $X_{an} = 0.05-0.07$ (albite). Younger porphyroblast (P12) of allotropic shape is homogeneous, having in its various points $X_{an} = 0.14-0.01$. This porphyroblast is always in assemblage with Bt + Chl + Qtz. From the comparison of the X_{an} contents in P11 and P12 there follows that P12 has crystallized during crystallization of the porphyroblast P11 margin, because the X_{an} value of P11 margin has similar

value as porphyroblast P12. In the matrix of the *Dobšiná* metapelite/metasemipelite (gneiss) the relic grains of the plagioclase P11 have $X_{an} = 0.25-0.33$ (oligoclase, Fig. 8).

In metapelite/metasemipelite to amphibolite from *Rudňany* the plagioclase porphyroblast consists of non-zonal grains in the mixture of plagioclases with X_{an} from 0.61 (labradorite) to albite of metamorphic origin ($X_{an} = 0.07$;

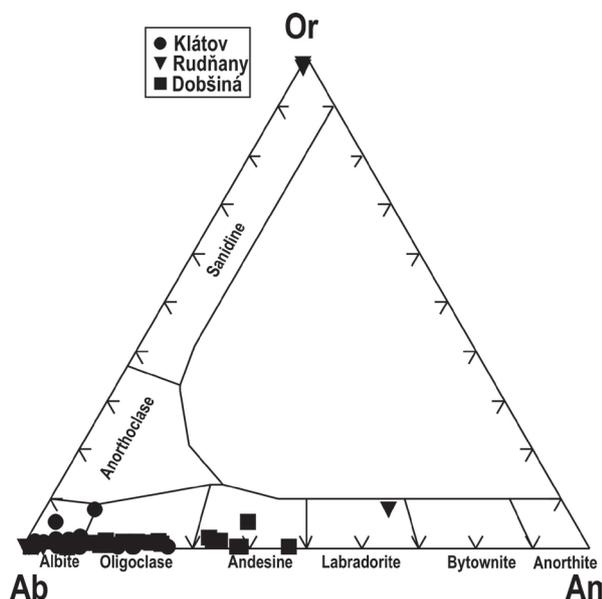


Fig. 8. Chemical classification of feldspars and plagioclases of the GAC of Gemeric unit.

Figs. 6 and 8). After metamorphic overprint the former porphyroblast represents a mixture of Ab+Czo and contains also inclusions of small (<5 μm) non-measurable phenigite grains. In the rock matrix, the metamorphogenic albite together with Bt, Chl, Hbl and Qtz occurs in the form of small non-zonal hypidiomorphic grains. Albite does not contain inclusions. K-feldspar $X_{or} = 0.98-0.99$ occurs at the rim of calcite or together with calcite and chlorite. This mixture is younger than porphyroclasts of former plagioclase and fills tiny fractures (Fig. 6).

In metapelite/metasemipelite to amphibolite from Klátov, the plagioclase occurs, similarly as in Rudňany and Dobšiná, in the form of porphyroblast (P1), consisting of various relics of plagioclases ($X_{an} = 0.16-0.26$), or it is formed of homogeneous grains of metamorphogenic albite ($X_{an} = 0.02$). The porphyroblast contains inclusions of Png and a mixture of Ab+Ep or Ab+Zo (Fig. 5). Some former P1 porphyroblasts in assemblage with amphibole contain only epidote inclusions. In rock matrix we found the hypidiomorphic albite grains (P12; $X_{an} = 0.02-0.09$) in assemblage with Chl + Qtz. In the Klátov GAC albite is often without mineral inclusions.

Garnet

Idiomorphic garnet grains large up to 4 mm were in GAC found in Dobšiná and Rudňany blocks. The garnet grains do not form aggregates. They contain the inclusions of quartz, graphite and rarely also zircon and ilme-

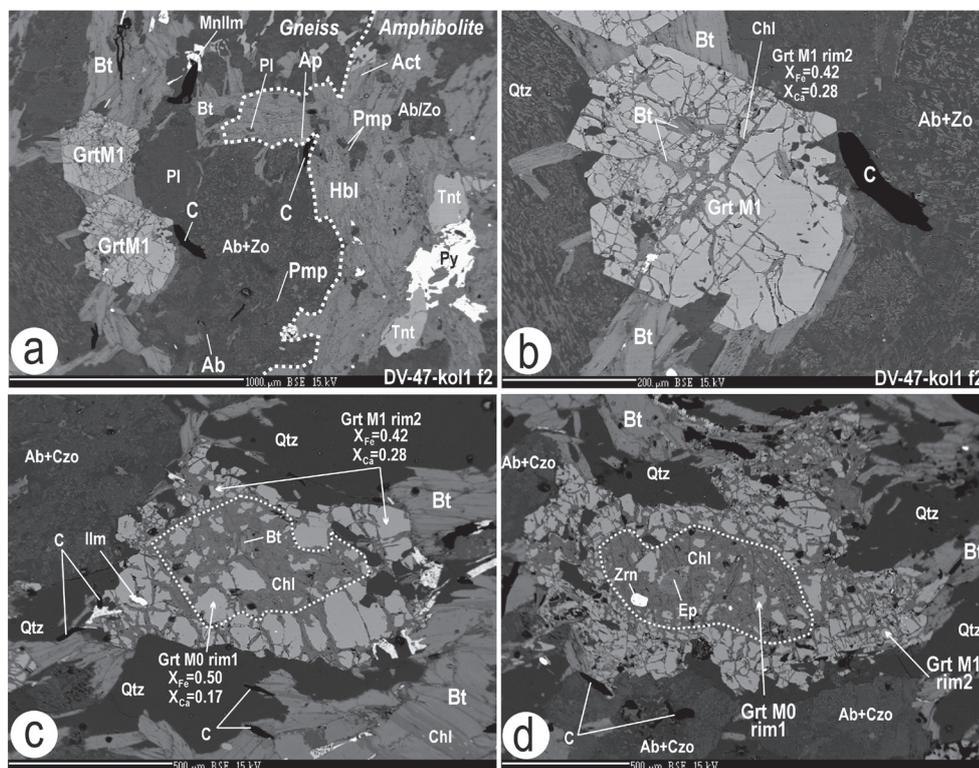


Fig. 9. Relation of garnet and matrix in mineral assemblage of G-A complex in locality of *Dobšiná*. Bt – biotite; Ab+Czo – mixture of albite and clinozoisite (disintegration of former plagioclase); Ab – albite; Pmp – pumellyite; Hbl – hornblende; Chl – chlorite; Ap – apatite; Png – phenigite, white mica; C – graphite, Pl – plagioclase; Tnt – titanite; Py – pyrite; Act – actinolite, Zo – zoisite; MnIlm – ilmenite with the content of MnO, Grt – garnet; M0 – ocean floor metamorphism, M1 – metamorphism on hot line (Radvanec et al., 2007 and 2010). c-d – atoll garnet M1 around relics of older garnet M0. Back-scattered electron images.

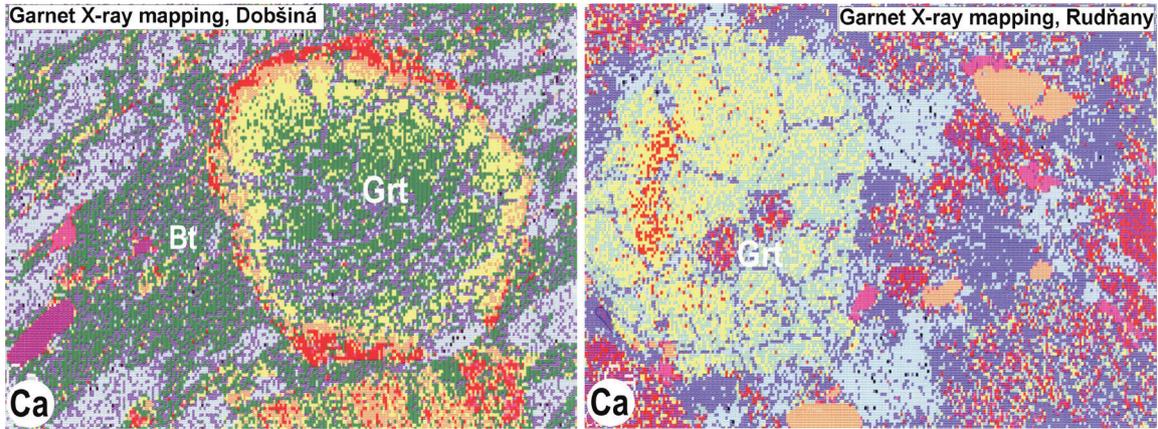


Fig. 10. Distribution of CaO in garnet of GAC in localities of *Dobšiná* and *Rudňany*. Highest content – red. Smaller content – green. Grt – garnet, Bt – biotite.

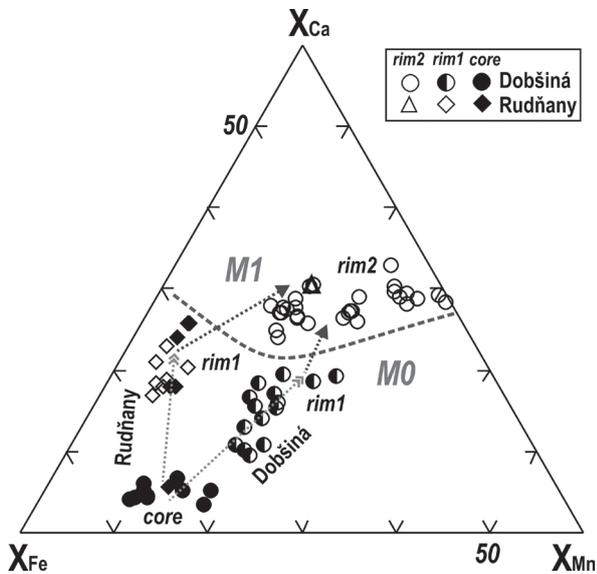


Fig. 11. Chemical classification of garnet in GAC of Gemeric unit. **M0** – ocean floor metamorphism. **M1** – metamorphism on hot line (Radvanec et al., 2007 and 2010).

nite. In fractures of garnet there crystallized Chl, Bt, but also Cal, Mn-Cal, Png and Ttn (Fig. 9). The garnet from *Dobšiná* has also the atol form, when on older garnet core of **M0**, replaced by chlorite, a new garnet was grown in the metamorphic process **M1**. Chemical composition of both garnets differs (Fig. 9c-d).

In metapelite/metasemipelite from *Dobšiná* during the mapping of the garnet chemistry we have revealed its distinct zonation. The Fe content decreases from the garnet core ($X_{Fe} = 0.615-0.718$), through the inner rim1 ($X_{Fe} = 0.440-0.618$; **M0**) to the outer rim2 ($X_{Fe} = 0.360-0.559$; **M1**). On the contrary, content of MnO (3.46-6.56 wt.%) in the core of the grain increases in the inner rim1 (MnO = 6.19-9.44 %) and at the contact of the grain with the matrix (outer rim2) it increases

to 5.19-13.11 wt.%. CaO content increases from the Grt core (0.96-1.96 wt.%) through the inner rim1 (2.89-6.23 wt.%) to outer rim2 (7.90-11.03 wt.%). The changes of $X_{Fe} - X_{Mn} - X_{Ca}$ from the Grt core to rim are visualized in triangle diagram (Fig. 11). According to Banno et al. (1986) the zonation in Mn content indicates the change of temperature during the garnet crystallization, so the core of Grt in metapelite/metasemipelite from *Dobšiná* crystallized at higher temperature than its two rims. The thin (30-50 mm) outer rim2 with high content of Ca + Mn indicates that at the end of Grt crystallization there has occurred the mutual interaction between the solid phase and excess content of Ca + Mn in the fluid phase of the rock. Ca-Mn rim is compact around the whole Grt, i.e. the contents of CaO and MnO, but also of MgO and FeO do not change in any place. Concerning the metamorphic reactions it means that the crystallization of the assemblage Bt + Chl + Qtz (matrix) did not influence the change of the Ca, Mn, Fe, Mg contents in the Grt rim (Fig. 9). From it derives that the prevailing part of the mixture of Bt + Chl has crystallized simultaneously with the Grt core or inner rim1 and before crystallization of the outer rim2. It means that the Grt grain as a whole and the mixture of Bt + Chl in the *Dobšiná* metapelite/metasemipelite are not directly coexisting minerals. The change of mutually conditioned chemical composition among simultaneously crystallizing Grt and Bt was described by Tracy (in Ferry, 1986; Spear 1995). He found that in interacting places in the shape of “bays” the Fe and Mg contents changed in both minerals. This change of chemical composition among simultaneously crystallizing Grt + Bt we did not find in the *Dobšiná* metapelite/metasemipelite. We suppose that probable coexistence of Grt(core) or Grt(rim1) with Bt (**M0**) was obscured by crystallization of outer rim2 in younger and time separated P-T system **M1** (Fig. 9).

The atol type garnet does not occur in the metapelite/metasemipelite to amphibolite from *Rudňany*. During the mapping of chemical composition of individual gar-

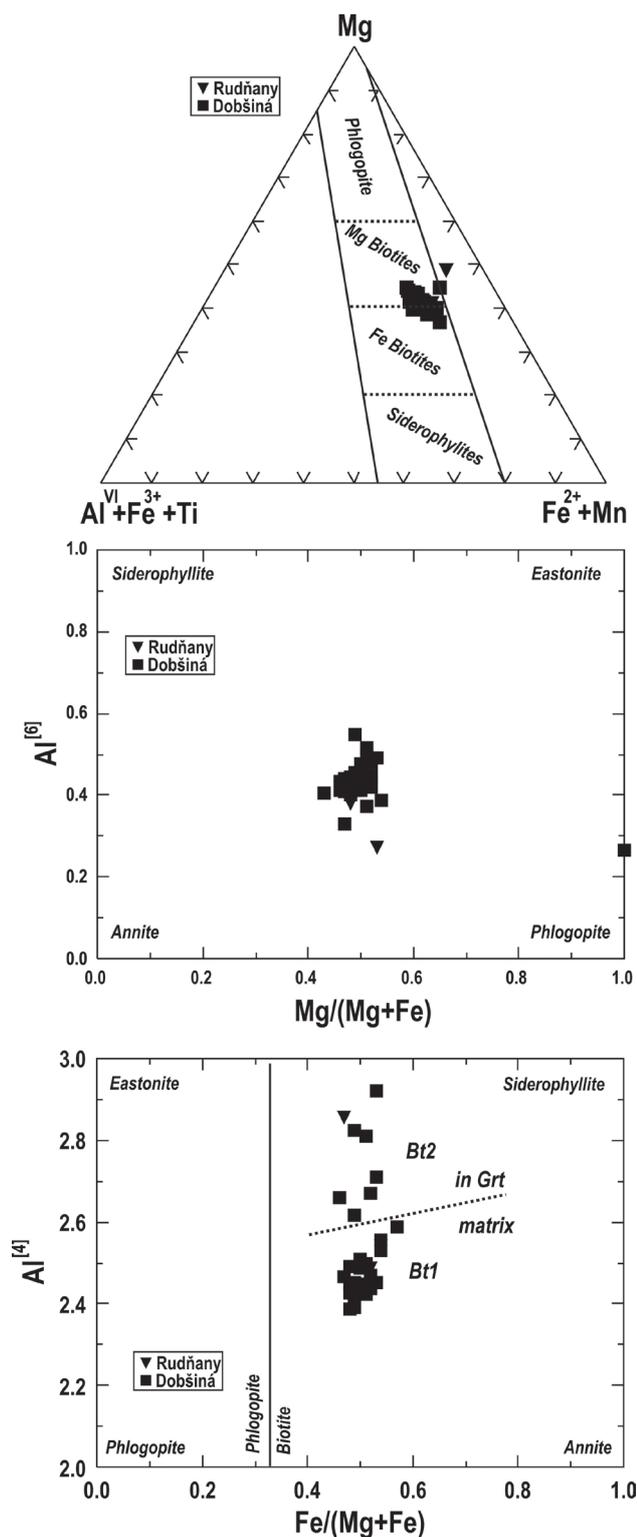


Fig. 12. Chemical classification of dark mica in gneiss-amphibolite complex of Gemic unit and relation of both generations of biotite Bt1 in matrix and Bt2 in garnet.

net grains we revealed the homogeneous distribution of the Ca content (Fig. 10), but also Fe in the garnet cores ($X_{\text{Fe}} = 0.502\text{--}0.652$) and rims (rim1; $X_{\text{Fe}} = 0.572\text{--}0.671$). In garnet from *Rudňany* only in one place there was found the discontinuous younger rim2 thick $10 \times 5 \mu\text{m}$, having identical content of elements ($X_{\text{Fe}} = 0.512$, $\text{MnO} = 6.69\%$, $\text{CaO} = 10.08\%$) as the rim2 in *Dobšiná* garnet (Fig. 11). The garnet of the *Rudňany* metapelite/metasemipelite originated at higher temperature than the garnet from *Dobšiná*, because is homogenous and has smaller content of MnO (Figs. 10 and 11).

Biotite

We have identified the Mg-Fe biotite (Figs. 12) in GAC in the *Dobšiná* and *Rudňany* localities. The GAC in the *Klátov* area does not contain biotite. In the matrix of *Dobšiná* metapelite/metasemipelite we found two biotite modifications: Bt1 ($\text{Al}^{\text{IV}} = 2.588\text{--}2.388$) in assemblage with $\text{Png1} + \text{Chl1} + \text{Qtz} + \text{Czo1}$; and Bt2 ($\text{Al}^{\text{IV}} = 2.921\text{--}2.615$), which crystallized with Chl2. Both alternate in the rock matrix, and we have found them also in fractures in plagioclase and garnet porphyroclasts (Figs. 9 and 12). The Bt2 does not form the “interlayer” mixture with chlorite and is chemically homogeneous (Fig. 12). The biotite in the matrix of *Rudňany* metapelite/metasemipelite (gneiss) has also two modifications: Bt1 ($\text{Al}^{\text{IV}} = 2.486\text{--}2.541$) in assemblage with $\text{Chl1} + \text{Qtz}$ and Bt2 ($\text{Al}^{\text{IV}} = 2.856$) in assemblage with Hbl. Bt2 was identified also in the fractures in plagioclase (Fig. 12). Biotite from both localities has Ti within the range 0.11–0.27, besides part of Bt2 in garnet from *Dobšiná* ($\text{Ti} = 0.352\text{--}0.389$).

Phengite

The phengite-1 (Png1), studied in the *Dobšiná* metapelite/metasemipelite, occurs in porphyroclasts P11 and P12 in inclusions large up to $20 \mu\text{m}$. Phengite-2 (Png2) is present in the rock matrix in assemblage $\text{Qtz} + \text{Bt1} + \text{Gtr} + \text{Chl}$, or in assemblage $\text{Chl} + \text{Ab} + \text{Czo} + \text{Ttn} + \text{Cal}$. Phengite (Png2) was found also in fractures in Grt. Two different phengites occur also in the *Rudňany* metapelite/metasemipelite to amphibolite. In the matrix Png1 occurs in assemblage with $\text{Chl} + \text{Bt}$. Png2 occurs in assemblage with Hbl and Chl, as well as in fractures in Grt. In metapelite/metasemipelite from *Klátov* there prevails one generation of phengite, occurring in plagioclase porphyroclast in inclusions together with $\text{Ep} \pm \text{Zo}$. This phengite has a chemical composition closest to muscovite and according to relation Si versus Al (apfu) it is a product of the highest metamorphic temperature in the whole investigated territory. Png2 occurs rarely (Fig. 13).

All three compared localities of the GAC contain two chemically different phengite generations - Png1 and Png2.

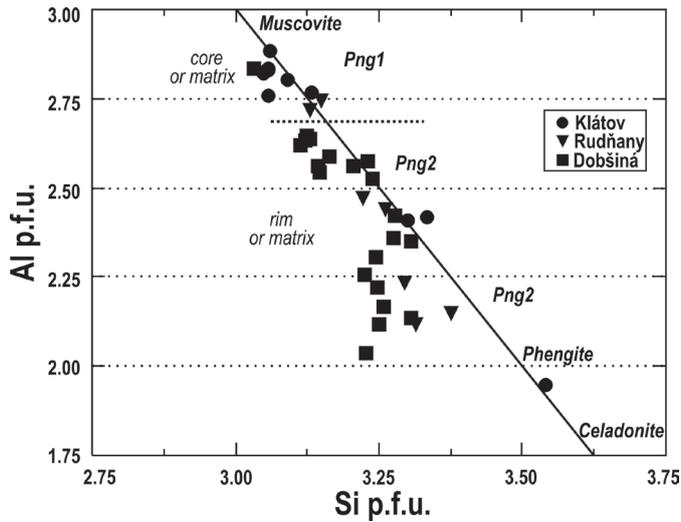


Fig. 13. Chemical classification of white mica in GAC of Gemeric unit and relation of phengite-1 (Png1) and phengite-2 (Png2), as well as core-rim in the matrix.

The phengite grains are sometimes zonal. The inner part of the grain is formed of Png1 and rim of Png2. Part of Png2 belongs among the youngest minerals in GAC. The occurrence of phengite two generations was found in various mineral assemblages, chemical composition of Png1 and Png2 changes in relation to metamorphic temperature and pressure. This change is sensitively reflected by Al_2O_3 content, which in phengite/muscovite increases by the increase of metamorphic temperature. The content of Fe, Mg and Mn decreases with increasing metamorphic temperature (Radvanec and Banno, 1991). All found forms of phengite1 have low content of celadonite molecule (Si = 3.03–3.15 apfu), which reflects the low-pressure conditions of their origin in **M0** metamorphism. Phengite-2 has Si content within the range of 3.11–3.55 apfu, and according this content it originated at conditions of younger and timely separated medium-pressure metamorphism **M1** (Fig. 13).

Amphiboles

In the amphibolite and metapelite/metasemipelite the chemically identical Ca-amphiboles were found in substitution row between pargasite-hornblende and actinolite (Fig. 14a). In all three investigated localities with alternating amphibolite and metasemipelite interbeds, in amphibolite interbeds there prevails the hornblende above the pargasite-edenite hornblende to pargasite and actinolite (Figs. 5–7). In the *Klátov* GAC we have identified also porphyroclasts composed of coexisting lamella of cummingtonite-hornblende-actinolite-1 (Fig. 14b, d), or cummingtonite-hornblende-pargasite/tschermakite-actinolite-1 (Fig. 16). These porphyroclasts were found already earlier by Radvanec (1992). According to the

place of crystallization, chemical classification and the assemblage of coexisting minerals, the Ca-amphiboles originated subsequently in timely separated metamorphic events **M0** and **M1** (Fig. 14), or more precisely **M0**, **M1a** and **M1b** (Fig. 16). All Ca-amphiboles (Hbl-Ed-Prg, Act) have Na(M4) in the range of 0.019–0.144, which indicates low glaucophane substitution in these rocks. Such amphiboles originated at low to medium pressures and have a value Na(M4) beneath 0.25 (Brown, 1977; Goodge, 1989).

In the *Klátov* metasemipelite, the hornblende (Hbl) forms hypidiomorphic, chemically zonal grains in assemblage with Chl (Fig. 5). Hbl we found in porphyroclasts consisting of the mixture of coexisting and homogeneous amphiboles Hbl + Cum in assemblage with Pl + Czo + C. This porphyroclast sometimes encloses also Ap and Czo + C (graphite). Third form of the amphibolite occurrence represents the porphyroclast of coexisting minerals Hbl + Cum + Act1 (Fig. 5f).

This porphyroclast occurs in the assemblage with Pl + Chl + Ttn + Cal + Qtz. All above stated varieties of amphiboles were identified in one thin section. This allows to reconstruct the P-T conditions of metamorphism of the oldest metamorphism **M0** of the *Klátov* metasemipelite-amfibolite. At relatively highest pressure there crystallized the core of the porphyroclast Hbl-Cum-Act1 with Hbl ($A1^{IV} = 1.485$ and $A1^{VI} = 1.104$). The Hbl rim crystallized at lower pressure, because the A1 value in the rim is lower ($A1^{IV} = 1.026$ and $A1^{VI} = 0.770$). At the same pressure and same time of Hbl margin crystallization there crystallized also the porphyroclast of coexisting pair Hbl + Cum. It is indicated by the relation of values $A1^{IV} - A1^{VI}$ in Hbl, which have the same values as the rim of porphyroclast with Hbl-Cum-Act1 (Fig. 16). The coexisting amphiboles Hbl + Cum in porphyroblast have registered beside the low pressure also the temperature of metamorphism **M0**, reaching from 560 to 675 °C (Fig. 15). Earlier studies (Robinson et al. in Veblen and Ribbe, 1982) revealed the crystallization of the mixture of homogeneous cummingtonite and hornblende grains at the metamorphism of epidotite-amfibolite to granulite facies. The most often it was found in sillimanite-K-feldspar zone (Robinson and Jaffe, 1969). Numerous authors consider such mixture of amphiboles as direct geothermometer, which at low pressure of metamorphism (2–3 kbar) indicates the temperature of their crystallization between 600–650 °C (Robinson et al. in Veblen and Ribbe, 1982). This study about the temperature range of crystallization confirms that Hbl-Cum porphyroblast has originated in the amphibolite to granulite facies of metamorphism (Figs. 5d and 15). Some **M0** porphyroclasts of Hbl-Cum contain lamellas of Act1 to form the complex Hbl + Cum + Act1 porphyroblast (Fig. 5f). The Act1 in Hbl + Cum + Act1 porphyroblast originates generally in retrograde metamorphic path as a crystallization admixture

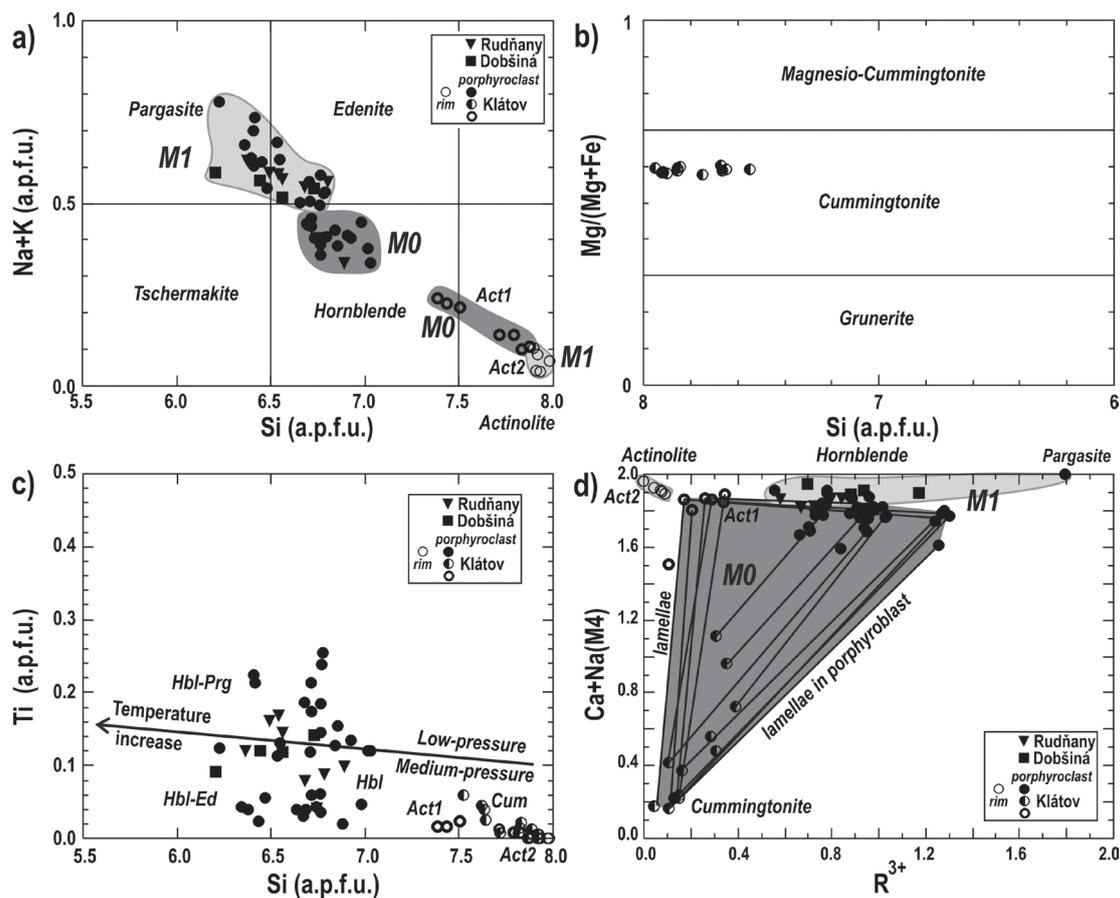


Fig. 14. Chemical classification of amphiboles in GAC of Geric unit. **a)** Classification of amphiboles from the substitution row pargasite-actinolite. **M0** – older metamorphism, being represented by the field of hornblende and actinolite Act1. **M1** – younger metamorphism, being represented by the field of edenite-pargasite and actinolite Act2; **b)** Chemical classification of cummingtonite (Leake, 1978). **c)** Contents of Ti vs. Si and trend of increase of the Ti content in relation to temperature of metamorphism with relative boundary of low and medium pressure metamorphism in amphiboles. **d)** Relation of lamella of coexisting amphiboles of cummingtonite-hornblende-actinolite-1 in amphibole porphyroblast in *Klátov* locality - older metamorphism **M0** and chemical classification of younger edenite-pargasite and actinolite-2 from metamorphism **M1**, occurring in the matrix.

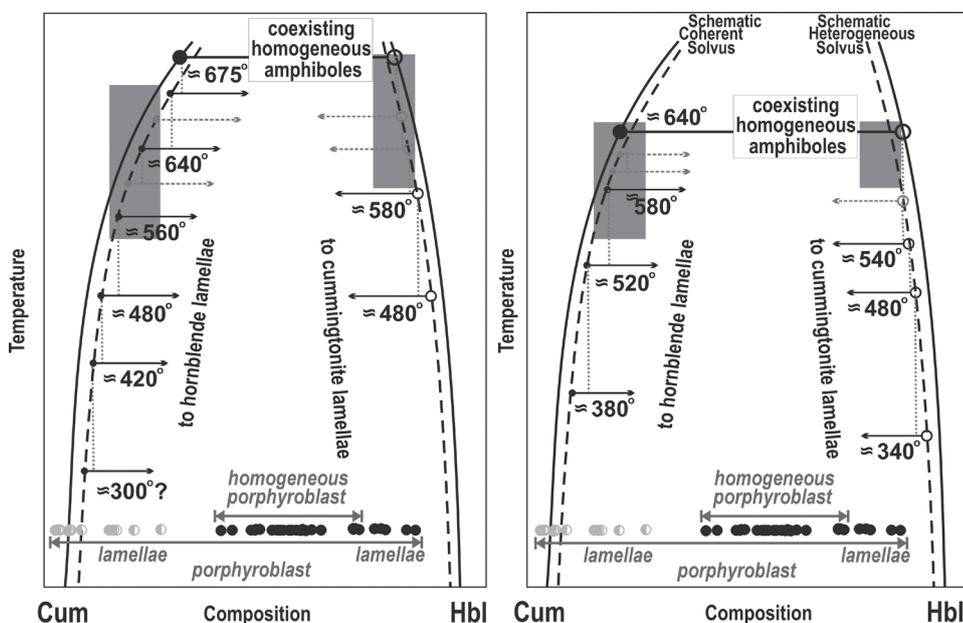


Fig. 15. Miscibility of substitution of solid phases among cummingtonite and hornblende in lamella of porphyroblast in the *Klátov* locality. Changes of chemical composition of cummingtonite and hornblende in relation on temperature are according to the results in two modifications, found by Klein et al. (1996) and Spear (1995). Circles – chemical composition of coexisting amphiboles.

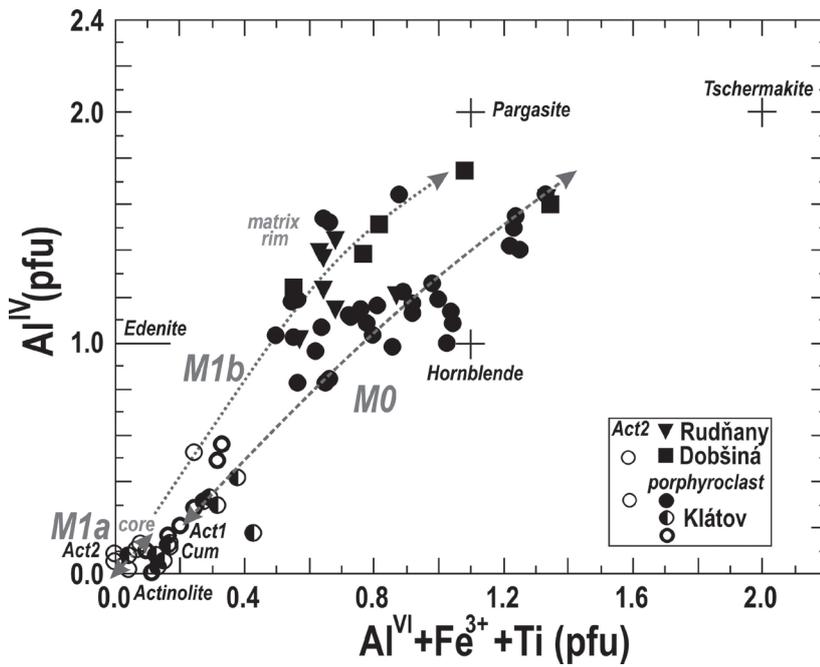


Fig. 16. Chemical classification of subsequent generations of amphiboles from the GAC of Gemeric unit in older process **M0** and two younger processes **M1a** and **M1b**. **M0** – classification of amphiboles in porphyroclast from the substitution row cumingtonite-hornblende-pargasite/tschermakite-actinolite-1 (Act1). **M1a** – field of actinolite-2 (Act2), being in coexistence with pumpellyite, younger metamorphism. **M1b** – field of amphiboles in substitution row edenite-pargasite (rim) envelops Act2 (core) or edenite-pargasite forms matrix of amphibolite, the youngest metamorphism. See text.

at the pressure decrease from the upper boundary of the greenschists facies up to middle amphibolite facies (Sampson and Fawcett, 1977). It was confirmed also by the results of this study. The characteristics of coexisting amphiboles Cum – Hbl – Act1 are for the amphibolite facies metamorphism of metasediment of the GAC expressed in diagram R^{3+} , Ca + Na(M_4) according to Robinson (in Veblen and Ribbe, 1982; Figs. 14d and 16).

Pumpellyite

At the contact of amphibolite and metasediment the relics of pumpellyite were found in assemblage with Ab + Czo + Act2 + Png1 + Hbl1 + Kfs + C + Chl (Fig. 7), being in coexistence with actinolite-2 (Fig. 7b). Pumpellyite often replaces or corrodes younger Hbl2 (Fig. 7d, f), or is enclosed in younger epidote (Fig. 7c, f). Pumpellyite contains Mg, according to chemical classification (Fig. 17) it is projected into the field for natural pumpellyite (Deer et al., 1997).

Epidote group

In the metasediment of the GAC, minerals of epidote group have the non-zonal distribution of elements and neither in one grain, nor in mineral aggregate a variability of the values $X_{Fe} = Fe^{3+}/(Al + Fe^{3+})$ was found from the core of the grain towards its margin (Nakajima et al, 1977; Otsuky and Banno, 1990). Minerals of the epidote group as inclusions occur in albite or relics of former plagioclase porphyroclasts/porphyroblasts. The epidote group has originated by the decomposition of former plagioclase to Czo-Zo-Ep and Ab (Figs. 5, 6, 7 and 9). In the rock matrix they form hypidiomorphic to allotriomorphic grains and clusters. At the contact of amphibolite and metasediment the younger epidote encloses older pumpellyite (Figs. 7 and 9a). The epidote group minerals occur in two subsequent mineral assemblages:

In the matrix of the *Klátov* metasediment, the epidote ($Fe_2O_3 = 7.32-7.96\%$) was rarely identified. More often it occurs in amphibole porphyroclasts Hbl + Cum, Hbl + Cum + Act, and mainly in the matrix there was identified the homogeneous clinozoisite ($Fe_2O_3 = 4.76\%$, $X_{Fe} = 0.099$), which has originated simultaneously with graphitic (Fig. 5e). The *Klátov* metasediment contains in the former plagioclase porphyroclast (Pll) the epidote ($Fe_2O_3 = 7.67-7.99\%$; $X_{Fe} = 0.179$). In this type of porphyroclast the Png inclusions were not found. Other type of Pll por-

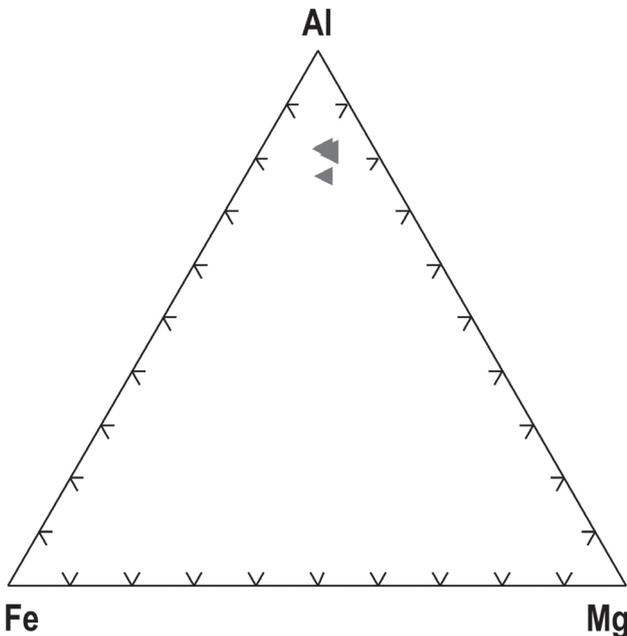


Fig. 17. Pumpellyite in Al-Fe-Mg diagram in the *Dobšiná* locality.

phyroclast occurs usually in assemblage with Hbl + Cum. There was identified the epidote ± zoisite ($\text{Fe}_2\text{O}_3 = 0.08\text{-}2\text{-}27\%$, $X_{\text{Fe}} = 0.02$). Both minerals crystallized as decomposition inclusions (crystallization admixtures) together with phengite-1 and albite.

Minerals of epidote group have in the *Rudňany* metasepilitic the content of $\text{Fe}_2\text{O}_3 = 5.25\text{-}7.90\%$ wt.% and were found in the rock matrix in assemblage with Ap + Chl + Phg. The non-measurable ca 5 µm large grains were identified also in the former porphyroblast P11, which contains also phengite of similar dimensions (Fig. 6). We were not able to perform the quantitative analyses from these grains, but semiquantitative analyses indicate the presence of zoisite and epidote in this plagioclase. In the matrix of *Rudňany* metasepilitic the epidote ($X_{\text{Fe}} = 0.173$) is in assemblage with Chll + Pngl and clinozoisite (Czo1, $X_{\text{Fe}} = 0.122$) forms here the assemblage with Ap + Btl + Grt + P12/Ab + Hbl. In the matrix there was identified also clinozoisite (Czo2) in assemblage with Chl2 + Ttn + Cal + Qtz.

In the *Dobšiná* metasepilitic there was identified the zoisite and clinozoisite. Zoisite ($X_{\text{Fe}} = 0.011$) occurs only in former plagioclase porphyroblast together with Pngl. Clinozoisite (Czo1, $X_{\text{Fe}} = 0.086$) was found also in the form of inclusions in older relic of former porphyroblast P11. In the rock matrix the clinozoisite Czo2 ($X_{\text{Fe}} = 0.078$) occurs in assemblage with Pngl, 2 + Btl + Chl+Ab, being a part of this assemblage, which originated from the decomposition of former plagioclase P11 (Figs. 7 and 9).

Chlorite

In metasepilitic from *Dobšiná* the chlorite occurs in four assemblages. Totally 76 % of its volume is formed by pycnochlorite. Chlorite most often occurs together with biotite. In this assemblage both minerals are coexisting and occur in two forms Btl + Chll (pycnochlorite) and Bt2 + Chl2 (ripidolite), which mutually overgrow in mineral aggregates. Aggregates together with Qtz + Phg form the principal part of the matrix (Fig. 7). Also in the matrix of metasepilitic there occurs the pycnochlorite (Ch13) and ripidolite (Ch13) in assemblage with Phg3 + Ttn + Cal + Czo2. In fractures of garnet and in the matrix we have identified also pycnochlorite (Ch14), belonging to the youngest minerals of the rock (Fig. 9). Pycnochlorite (Ch14) crystallized at relatively higher pressure ($\text{Al}^{\text{VI}} + 2\text{Ti} + \text{Cr} - 1 = 0.207\text{-}0.311$) as crystallized older pycnochlorite (Chll and Ch13) and ripidolite (Chl2, $\text{Al}^{\text{VI}} - 2\text{Ti} + \text{Cr} - 1 = 0.306\text{-}0.364$). The relation of $\text{Al}^{\text{VI}} - 2\text{Ti} + \text{Cr} - 1$ and Mg/(Mg + Fe) for orientation determination of the pressure at the chlorite crystallization was used after Lariad in Bailey (1988).

Chlorite from the *Rudňany* amphibolite crops out in several mineral assemblages (Fig. 6). From the total amount of Chl, pycnochlorite forms 38 %. Ripidolite and

pycnochlorite (Chl2) was found in the metasepilitic matrix in assemblage with Hbl + Ep + Czo2 + Btl + Bt2 + Ap + Phgl, 2 + Kfs + Cal. The youngest Chl represents pycnochlorite (Ch13), which crystallized in the fractures of plagioclase porphyroblast inside the fractures in garnet. We have found it also in the matrix in assemblage with Qtz. It crystallized at higher pressure as Chll, 2 ($\text{Al}^{\text{VI}} - 2\text{Ti} + \text{Cr} - 1 = 0.301\text{-}0.378$). It was registered by the values $\text{Al}^{\text{VI}} - 2\text{Ti} + \text{Cr} - 1 = 0.169 - 0.297$ in Ch13, which are lower than values of Chll, 2.

In the *Klátov* metasepilitic the chlorite (Chll) occurs in assemblage with Hbl, in assemblage with porphyroclasts Hbl + Cum and Hbl + Cum + Act1 and in assemblage with Czo + C + Ttn + Qtz (Fig. 5). Ripidolite (Chll) is older as pycnochlorite (Chl2), which similarly as in the *Rudňany* metasepilitic forms 38 % of the volume of chlorite in the rock. Chl2 originated in higher pressure ($\text{Al}^{\text{VI}} - 2\text{Ti} + \text{Cr} - 1 = 0.224\text{-}0.291$) and crystallized also on older low pressure ripidolite (Chll, $\text{Al}^{\text{VI}} - 2\text{Ti} + \text{Cr} - 1 = 0.325\text{-}0.345$). Chl2 has equivalent in Chl4 in the *Dobšiná* metasepilitic and in *Rudňany* it corresponds to Ch13. These chlorites belong to youngest minerals, which originated in timely separated and younger metamorphic process **M2**.

Other minerals

Among other minerals of the GAC there belongs titanite, calcite and quartz. Calcite from *Rudňany* has higher content of $\text{FeO} + \text{MnO} + \text{MgO} = 7.20\%$ wt.% as calcite from *Dobšiná* and *Klátov* and can be classified as Mn-calcite. Carbonates were found in the rock matrix in the shape of allotriomorphic clusters large up to 0.1 mm and were found also in fractures in garnet and former plagioclase porphyroblasts.

Approximately the same content of $\text{MnO} = 4.55\%$ wt.% as calcite has also ilmenite, which together with rutile belongs among the oldest minerals (Figs. 5, 6, 9 and 9). In the process of polyphase metamorphism the ilmenite was replaced to titanite (Figs. 5b, 6, 7 and 9). The titanite analyses have low content of Al_2O_3 , while Ttn has similar chemical composition in all studied localities.

Facies of gradual metamorphism in ACF diagram

According to metamorphogenic mineral assemblage the metapelite/metasepilitic to amphibolite of the metaophiolite suite of Gemeric unit in localities *Klátov*, *Rudňany* and *Dobšiná* was gradually metamorphosed firstly in amphibolite facies (**M0**), next in pumpellyite–actinolite facies (**M1a**) and during the last event of polymetamorphism in epidote–amphibolite to amphibolite facies (**M1b**). Three subsequent metamorphic events are according to chemical composition of found metamorphogenic minerals classified in CFA diagrams (Fig. 18a, b, c).

Successive metamorphic events, overprinting relations and kinematics in deformation stages VD_0 (M0), VD_{1a} (M1a) and VD_{1b} (M1b)

The mineral assemblages in ACF diagrams (Fig. 18a, b, c) were confirmed also by microtectonic researches. Each successive metamorphic stage is accompanied with corresponding deformation, recrystallization and kinematics, produced by the stress field in particular geodynamic processes (Fig. 18d). The succession of Variscan deformation events was numbered correspondingly with that of metamorphic events - VD_0 (related to metamorphism M0), VD_{1a} (M1a) and VD_{1b} (M1b). Geochronological SIMS data of the GAC (Klátov) yielded magmatic ages of zircon in amphibolite ranging from ca. 410 to 380 Ma (Putiš et al., 2009a).

Above described multi-stage ductile deformation of the rocks of metaophiolite suite was revealed by the study of spatially oriented thin sections, which corresponded with the real situation of the rock in the outcrop. The ductility of deformation was directly dependent on individual metamorphic stages (cf. ACF diagrams in Fig. 18a, b, c): Differing of two amphibolite facies overprints - M0 (def. stage VD_0) and M1b (VD_{1b}), inbetween these two in tectono-metamorphic succession there occurred the “harder” (less ductile) overprint of cooler pumpellyite-actinolite facies M1a (Fig. 18b; VD_{1a}). In this paper, these overprinting relations in the microscale we document on oriented amphibolite sample from the Klátov metaophiolite body (Fig. 18d): The hornblende (Hbl) M0 porphyroblasts in oriented thin section manifest sinistral overthrust shearing during the VD_{1a} deformation phase at M1a metamorphic condition, producing their σ -porphyroclasts. The shape-preferred orientation of these porphyroclasts indicates the top-to-the SSW thrusting. This deformation stage in the hornblende porphyroclasts terminated with the origin of the fragments of brittle micro-cleavage, being parallel

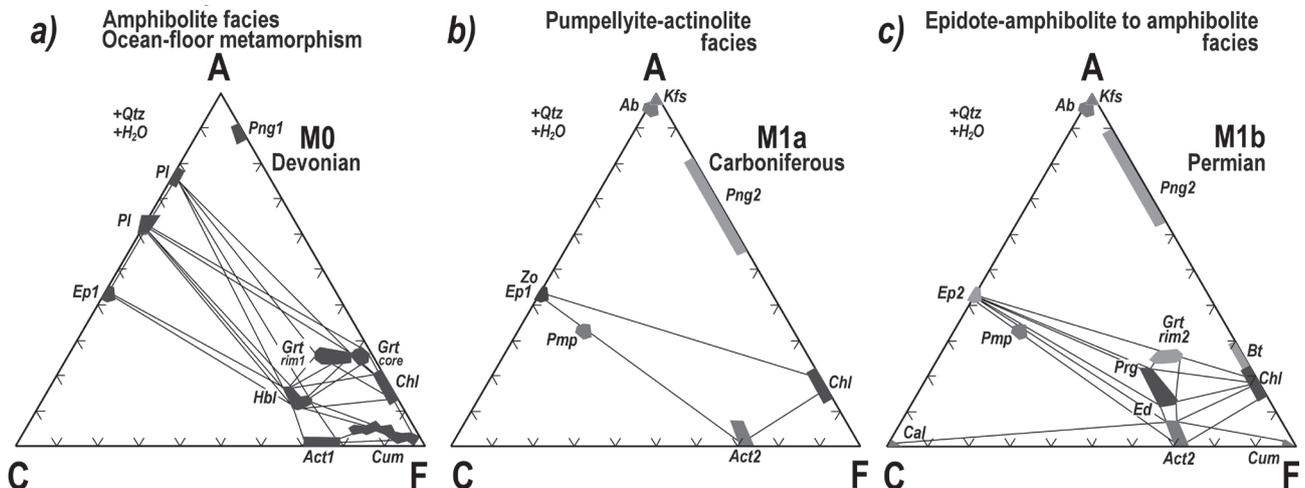
to both - the elongation of these minerals and mesoscopic foliation planes. The relics of M0 plagioclases were decomposed to mixture of Ab+Czo+Tnt, being abundantly present in the matrix. At the end of VD_{1a} deformation due to the switch of kinematics from thrusting top-to-the SSW to unroofing towards the NNE there originated the vertical brittle micro-fissures in the thin-section scale, being infilled with albite (Ab; cf. the middle of thin section).

The subsequent “softer” deformation stage VD_{1b} in amphibolite facies (M1b; Fig. 18c) has produced the extensional normal micro-faulting with the origin of foliation planes, partly utilizing already existing earlier VD_{1a} discontinuities. The extension along these VD_{1b} foliation planes manifests well the unroofing kinematics (top-to-the-NNE), similarly as transport of older mineral fragments into opening spaces. The former vertical VD_{1a} brittle micro-fissures were overgrown by new VD_{1b} assemblage of Ed/Prg + Ep + Act2.

2 Plagiogranite of the metaophiolite suite of gneiss-amphibolite complex at the Rudňany village

Introduction

In the northern part of the zone of siderite veins in the Rudňany ore field - the area between Severná žila (Northern) vein and veins Matej and Jakub, we have found during the study of GAC on 19th mining level the sample of granite, occurring on the adit wall (area of ca 100 cm²) within the amphibolite facies rocks as their integral part. This occurrence of granite in GAC represents a local phenomenon – other similar occurrence has not been yet revealed (Figs. 1, 3 and 19). Prior the discovery, the mine gallery was excavated by the tunneling machine and therefore the whole segment of the gallery has excellent strength and there is no need of the wall support. A great advantage for the macroscopic study was that in the GAC



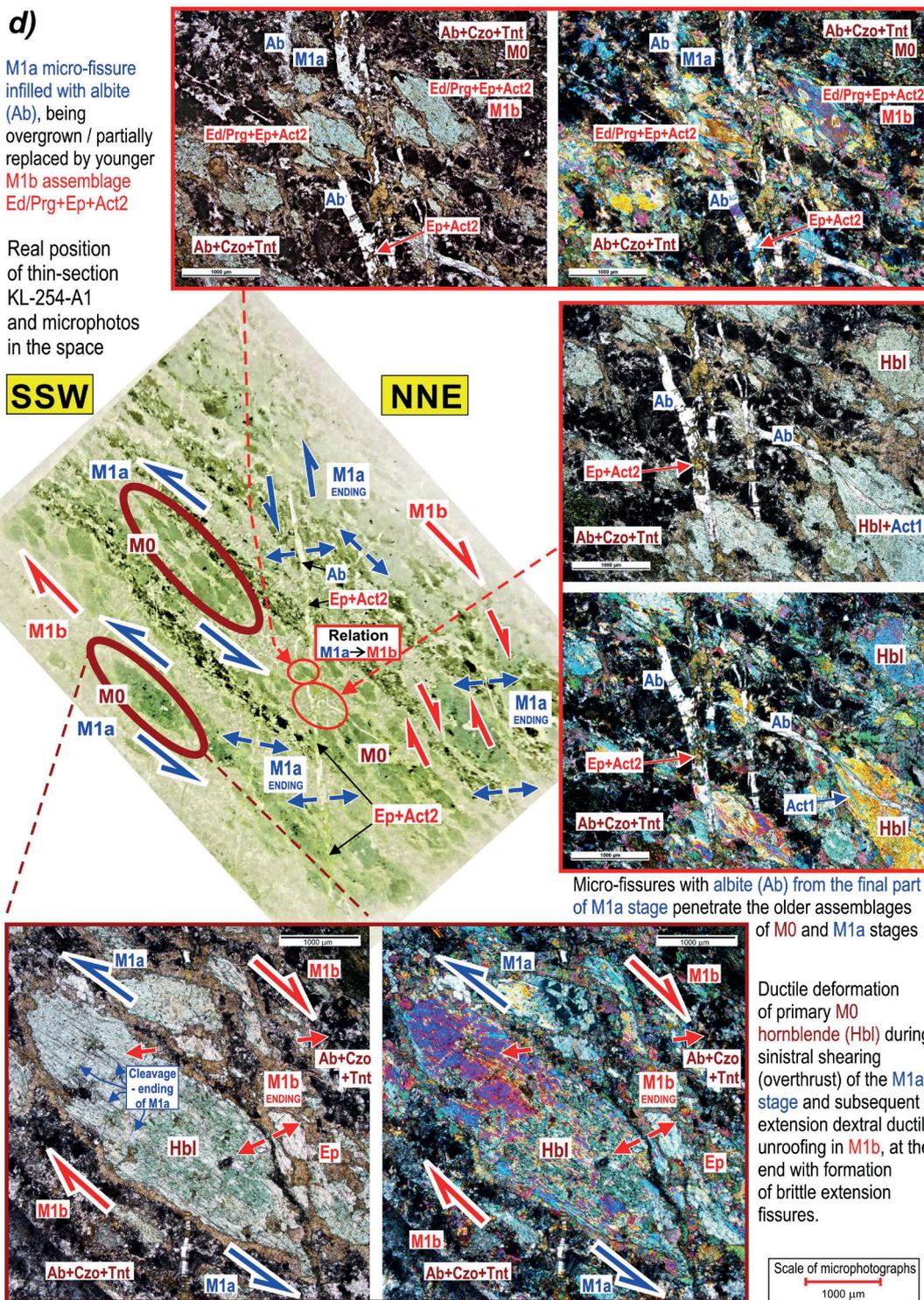


Fig. 18. Mineral assemblages and evolution of polymetamorphism of the GAC of the ophiolite suite of Gemicer unit in localities *Dobšiná*, *Rudňany* and *Klátov* in ACF diagrams and concerning the gradual recrystallization and origin of microstructures of **M0**, **M1a** and **M1b** tectono-metamorphic stages. **a** - Ocean floor metamorphism - amphibolite facies **M0**; **b** - Pumpellyite-actinolite facies **M1a**; **c** - Epidote-amphibolite facies to amphibolite facies **M1b**. **d** - Kinematics and sense of shearing in real recent coordinates are indicated by the blue (**M1a**) and red (**M1b**) arrows. Individual microtectonic phenomena, manifested by microphotographs, are described directly in the picture (part **d**) and in the text. Pl – plagioclase, Grt – garnet, Cum – cummingtonite, Ab – albite, Chl – chlorite, Png – phengite, Pmp – pumpellyite, Ep – epidote, Act – actinolite, Prg – pargasite, Ed – edenite, Hbl – hornblende, Bt – biotite, Cal – calcite, Kfs – K-feldspar.

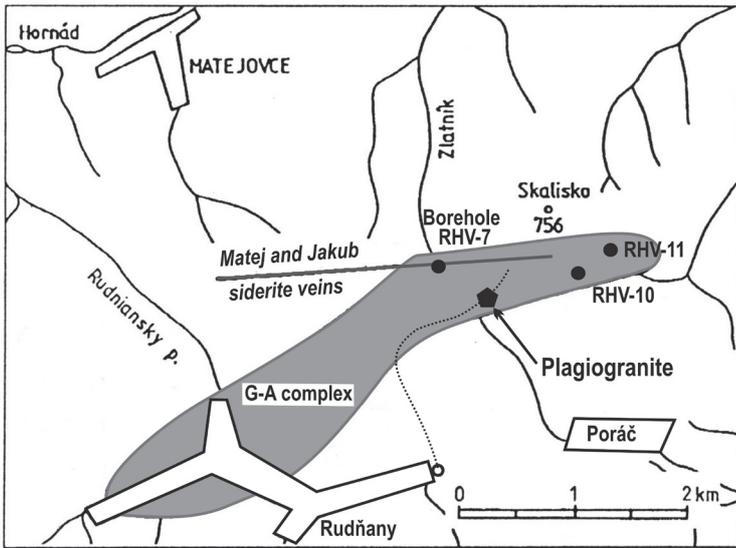
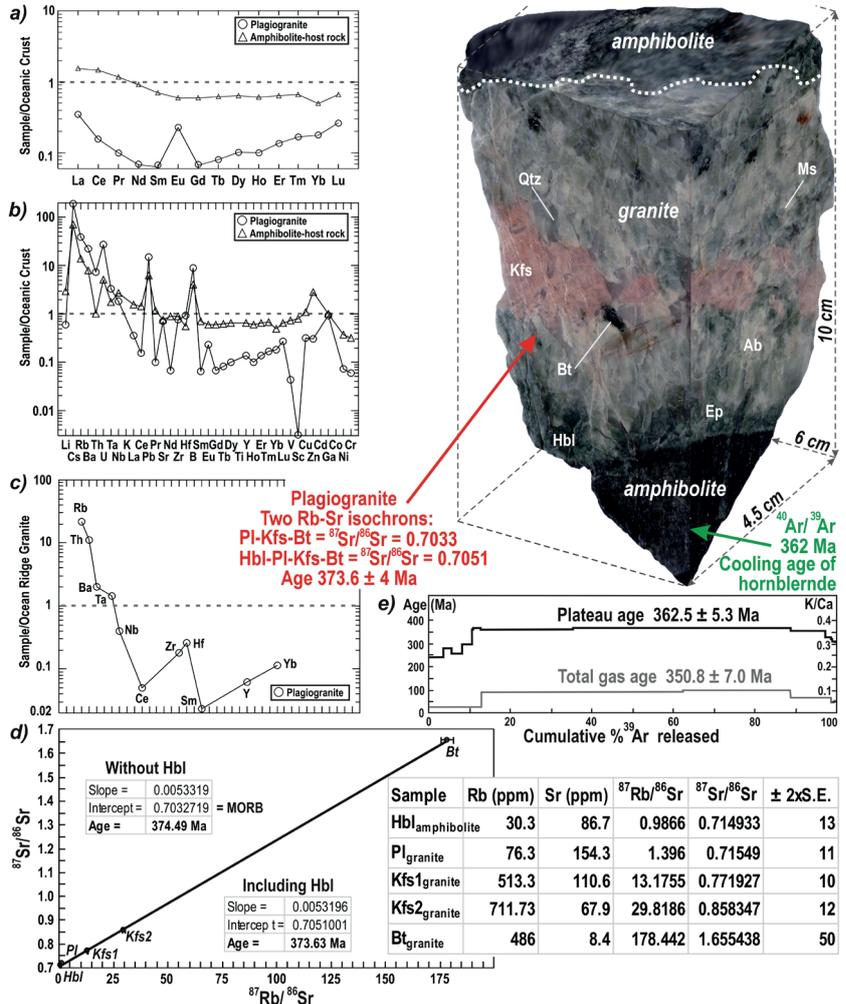


Fig. 19. Position of the plagiogranite sample in GAC on 19th mining level of the Rudňany ore field, 107 m a.s.l. For detail cross-section of the occurrence see Fig. 3.

the excavated circular profile corridor had very smooth walls. It allowed to investigate the varieties and structural relations between clusters of mineral in the whole occurrence with the confidence that all varieties and inhomogeneities in amphibolite will be documented properly.

Our new research has brought new mineralogical, isotopic and age data, significantly completing previous study of plagiogranite and amphibolite in this locality (Radvanec, 1994a, b).

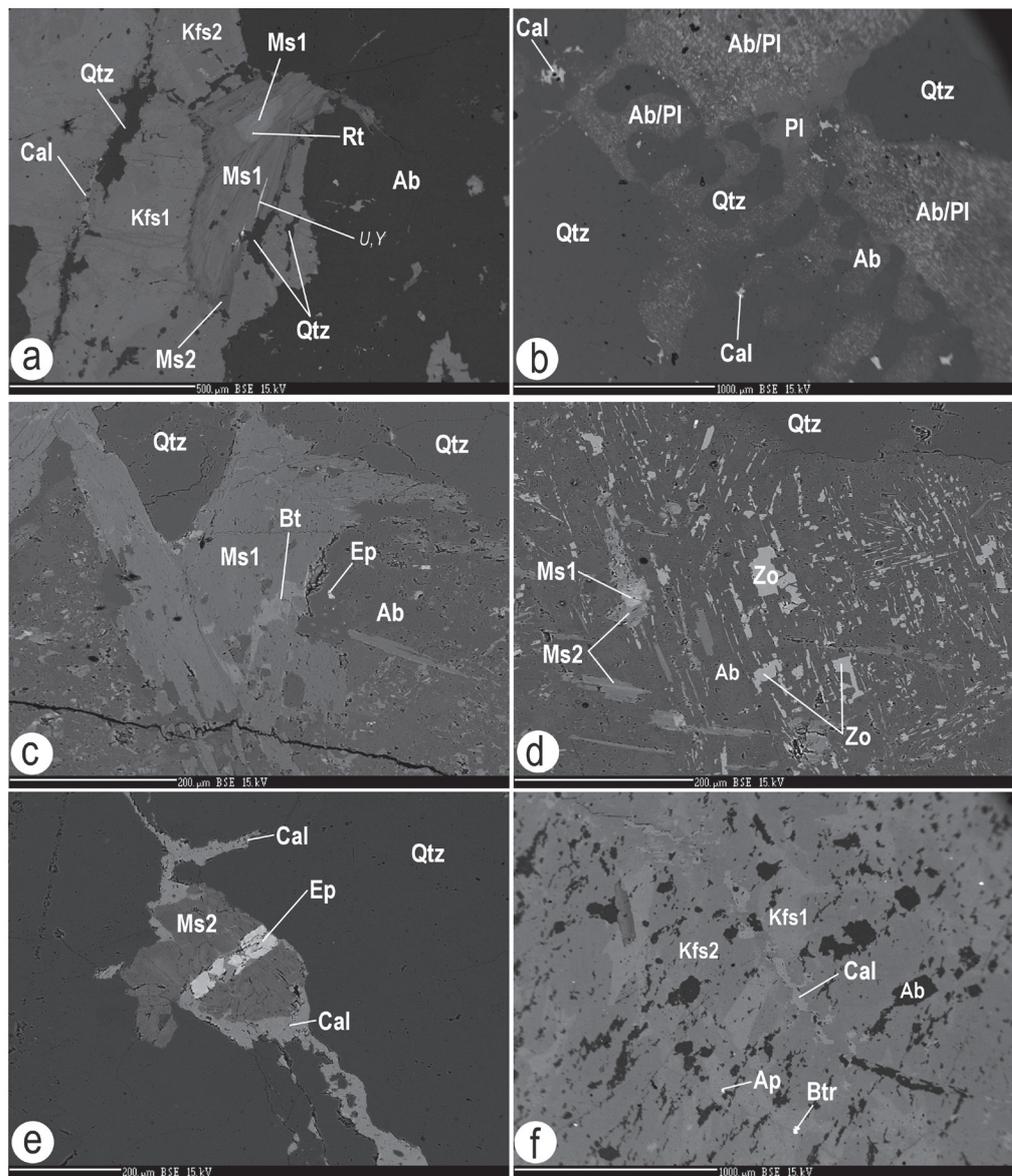
Fig. 20. Relations of minerals of plagiogranite and amphibolite in GAC on the 19th mining level of the Rudňany ore field and comparison of chemical composition of plagiogranite with the host amphibolite. **a)** and **b)** – the whole-rock analyses of plagiogranite and host amphibolite are normalised to oceanic crust and **c)** – to ocean ridge granite. **d)** – two Rb-Sr regression data of plagiogranite: 1. **Including Hbl** – Rb-Sr regression line is composed of the isotopic ratios of hornblende (Hbl) - plagioclase (Pl) – K-feldspars (Kfs1, Kfs2) and biotite (Bt). 2. **Without Hbl** – Rb-Sr regression line is composed of the isotopic ratios of Pl, Kfs1, Kfs2 and Bt. The intercept of 0.7033 shows the MORB source of plagiogranite. The ages 374.5 Ma and 373.6 Ma of plagiogranite is identical for both variants of mineral Rb-Sr analysis in the diagram. The high ratio values of Bt are significantly affected the identical ages. **e)** $^{40}\text{Ar}/^{39}\text{Ar}$ spectrum ages diagram from Hbl. Plagioclase-albite (Ab), muscovite (Ms), Qtz – quartz, Ep – epidote.



Petrographic description of plagiogranite

Optical microscopy proved that granite does not produced any thermal effects on surrounding amphibolite and crystallized with it in equilibrium (Fig. 20). The mineral composition of plagiogranite: plagioclase (oligoclase), albite, quartz, biotite, K feldspars (Kfs1, Kfs2), muscovite (Ms1, Ms2), chlorite, zoisite, epidote, rutile, titanite, apatite, barite, chalcopyrite and calcite (Fig. 21). The detail petrographic study revealed that crystallization of quartz and plagioclase formed myrmekitic structure, and crystallization of plagioclase with K feldspar formed the microperthite (Fig. 21). The origin of microperthite we interpret as mutually conditioned crystallization of two immiscible silicate solutions containing Na and K. The simultaneous crystallization of both mineral pairs is generally interpreted as petrographic evidence of crystallization from grani-

Fig. 21. Relations of minerals in plagiogranite of the GAC on the 19th mining level of the Rudňany ore field. **a** - Relation of muscovite-1 (Ms1) with muscovite-2 (Ms2), K feldspar, K feldspar-2 (Kfs2), rutile (Rt) and albite (Ab). Quartz (Qtz), calcite (Cal) and U, Y infill tiny fractures. **b** - Myrmekitic structure, originating during simultaneous crystallization of quartz and plagioclase (Ab/Pl) from the minimum granitic melt. **c** - Muscovite-1 infills biotite (Bt). **d** - Decomposition of plagioclase to albite and zoisite (Zo). Muscovite-1 is enveloped by muscovite-2. **e** - Epidote (Ep) envelops muscovite-2 and calcite infills the fractures in quartz. **f** - K feldspar and albite in the form of microperthite. Albite crystallized simultaneously with K feldspar from the minimum melt, structure is a result of the recent crystallization of two immiscible components with Na and K in the minimum melt of granite composition. Calcite infills the fractures, being present only in granite. Ap – apatite, Btr – barite. Backscattered electron images.



toit melt. Johannes (1989) considers the existence of Pl + Qtz in the myrmekite structure as a sign of partial melting. The contact of granite with amphibolite is formed with epidote, plagioclase and quartz. In the immediate contact of amphibolite with granite, the hornblende, plagioclase, epidote, clinozoisite and quartz are present. Both mineral assemblages have sharp boundary, being mapped in details applying the quantitative chemical analyses (Fig. 20). In minerals in the frame of one grain, or mineral assemblage, we have not found any changes or extreme values in the content and composition of elements. Minerals have homogeneous chemical composition. Optical and macroscopic study of the position of sample within the mine gallery has confirmed that mineral assemblages of granite

and amphibolite crystallized in the same process and at the same P-T conditions.

Procedure of the plagiogranite research

From the granite through the contact with surrounding amphibolite we did the polished thin sections (Fig. 20). Petrological characteristics, temperature and pressure of crystallization of minerals in granite we have revealed from quantitative chemical composition of minerals and from the crystallization sequence of mineral assemblages in granite. The results of P-T-x conditions of phase reactions we have compared with the same characteristics in the surrounding GAC.

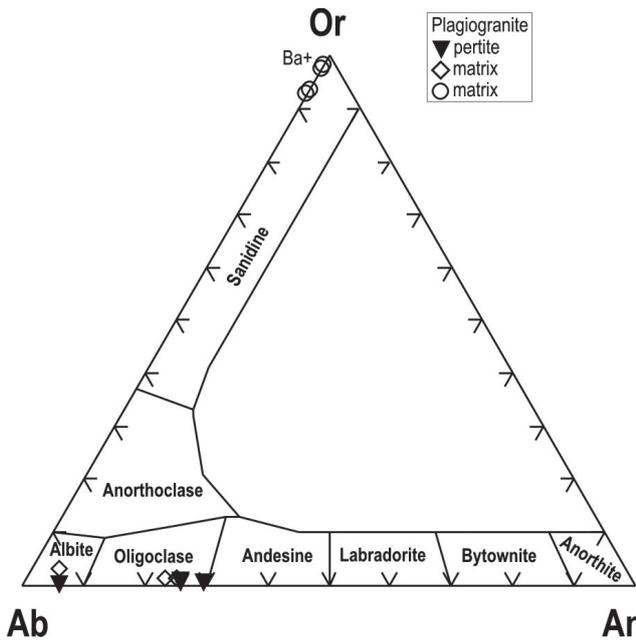


Fig. 22. Chemical classification of feldspars in plagiogranite of GAC on 19th mining level of the Rudňany ore field.

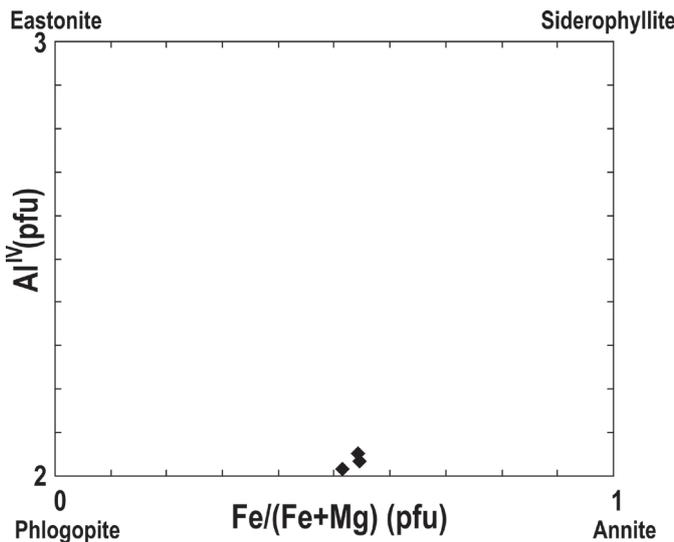


Fig. 23. Chemical classification of biotite in plagiogranite of GAC on the 19th mining level of the Rudňany ore field.

Mineral composition of plagiogranite

Plagioclase

The plagioclase ($X_{an} = 0.229-0.295$; oligoclase), occurring in the middle of the plagiogranite sample, has usually hypidiomorphic shape and the grain-size up to 1 cm. It is in assemblage with K feldspar, quartz, muscovite and epidote. In other places between the core and margin

of the granite, the plagioclase phenocrysts consist of al-
lotriomorphic to hypidiomorphic grains and clusters of albite reaching dimensions up to 1.5 cm with the value $X_{an} = 0.012-0.062$ (Fig. 22). The oligoclase-albite grains ($X_{an} = 0.050-0.210$) contain inclusions of muscovite exsolutions of 30 μm dimensions (Fig. 21). At the immediate contact with mineral phases of amphibolite the plagioclase of granite - albite ($X_{an} = 0.029-0.063$) occurs in the form of allotriomorphic exsolutions (micro-pertite; droplet shape) of dimensions up to 150 μm in K feldspar ($X_{an} = 0.020-0.033$; Fig. 22).

K feldspar

Relatively older micropertitic hypidiomorphic to allotriomorphic K feldspar $An_{0.0.2}Ab_{1.6-2.3}Or_{97.7-98.2}$ (Kfs-1), occurring in clusters of dimensions up to 2 cm crystallized simultaneously with plagioclase ($X_{an} = 0.020-0.033$; Figs. 21 and 22). Recent crystallization of two immiscible solutions with the content of Na and K (micropertite) has occurred without binding of the Ca (An_0) content in solid phases of simultaneously crystallizing PI and Kfs. Significant Na and K miscibility occurred during the pertite crystallization (Fig. 21). Second relatively younger and usually allotriomorphic form of K feldspar (Kfs-2) has in comparison with older forms lower content of the albite molecule $An_{0.0.2}Ab_{6.3-7.3}Or_{92.7-93.5}$ and crystallized in matrix within an assemblage of epidote + quartz + plagioclase + muscovite. The contents of BaO are in both Kfs generations variable (0.14-1.44 wt.%).

Dark mica - biotite

In the granite matrix the dark mica forms irregular clusters in assemblage with albite, muscovite, epidote, plagioclase and K feldspar (Figs. 20 and 21). The grains of the dark mica contain chlorite, muscovite-1, titanite and calcite in the inter-layer lamella. The dark mica is enveloped by muscovite-1 (Fig. 21). Chemically the dark mica is homogeneous and represents a transitional type between phengite and eastonite or annite and phlogopite (Fig. 23).

Muscovite

Similarly as in the surrounding GAC (Ch. 1; Radvanec, 1992, 1994a), also in plagiogranite we have found chemically different phases of white mica (muscovite). The oldest Ms1 crystallized in plagioclase as tiny inclusions (Fig. 21). In the flakes in rock matrix there crystallized Ms1 in assemblage PI + Kfs + Ep + Qtz. Ms1 contains Fe and Mg, so this form of the white mica can be classified as phengite (Fig. 24). The size of chemically homogeneous

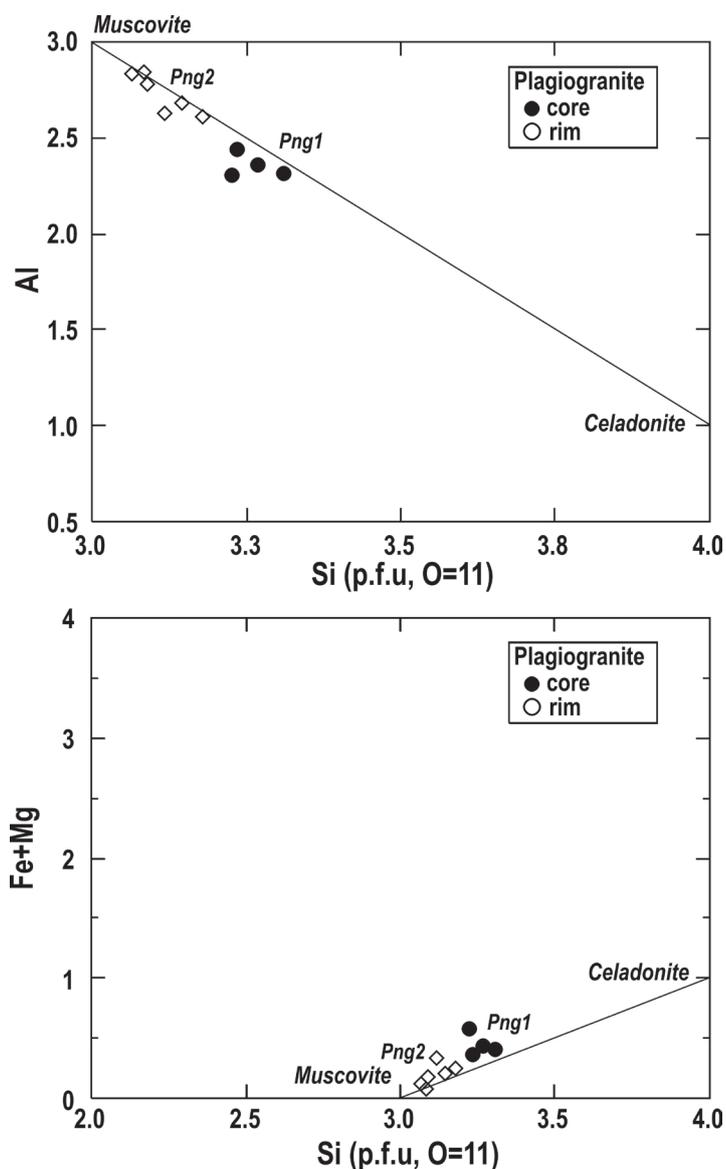


Fig. 24. Chemical classification of the white mica in plagiogranite of the GAC on the 19th mining level of the *Rudňany* ore field.

and well crystallized Ms1 in the granite matrix is up to 0.5 cm. Muscovite-1 crystallized after biotite, enveloping it (Fig. 21c). Muscovite-2 represents the younger form of the occurrence of white mica, forming the margin of the muscovite-1. It was found also in veinlets with Cal and Qtz and in assemblage with Bt + Tnt + Chl (Fig. 21).

Both generations of the muscovite-phengite row indicate gradual cooling of the plagiogranite melt. At the highest possible temperature, when a relative equilibrium of the granite melt and subsolidus (existing crystallized solid phase) was in the system, the plagioclase with inclusions of Ms1 has crystallized. We estimate that this couple together with K feldspar and micropertite has registered temperature around 600-650 °C, i.e. the tempera-

ture of gradual crystallization of solid phases from the granite melt. Crystallization of these coexisting minerals took place also in the intersection of the phase curve of the melting of pelite saturated by the water and the phase curve of the stability $Ms + Ab + Qtz = K \text{ feldspar} + And + V\text{-fluid}$ phase at the temperature around 650 °C. The muscovite-2 has crystallized in gradually cooling granite, prevailingly in subsolid and solid phases.

Chlorite

The pycnochlorite and ripidolite of the similar chemical composition, as present in the GAC surrounding the plagiogranite (Radvanec, 1994a), we have found also in the granite. Chlorite forms interbed lamella with biotite and muscovite-2, which enclose titanite. These minerals form aggregates large up to 1 cm, having optical parameters of biotite.

Epidote group

Epidote - the main mineral of this group - occurs in hypidiomorphic grains large up to 100 μm , which often form clusters of the flake shape (Fig. 21). Grains and clusters are chemically homogeneous. In the epidote in direction from the contact of amphibolite with plagiogranite towards the middle of granite in the distance of ca 5 cm the content of $X_{\text{Fe}^{3+}} = \text{Fe}^{3+}/(\text{Al} + \text{Fe}^{3+})$ increases from 0.2 to 0.3. Epidote has crystallized in the assemblage Plg + Kfs + Ms1 concordantly with the Bowen crystallization succession of solid phases from the acid magma. According this, directly from the melt there crystallized first the solid phases with the highest content of Ca (Ca-Pl+Ep+Sph). Crystallization of epidote in assemblage with Pl in plagiogranite was conditioned by the content of Ca and Fe in the melt, as well as Fe^{3+} activity. The Fe content entered into the granite melt probable from the rest of unbound Fe^{3+} from metamorphic reactions in surrounding amphibolite. The metamorphic reactions in amphibolite have controlled the crystallization of epidote group minerals with binding of Fe^{3+} on the epidote-clinzoisite row, and locally also to hematite (Radvanec, 1992, 1994a). In the plagiogranite there occur the zoisite together with albite, being separated from epidote. This assemblage of zoisite-albite is metamorphogenic and originated in plagiogranite by the decomposition of former plagioclase (Fig. 21b, d).

Titanite

In plagiogranite we found frequently occurring titanite, crystallizing among biotite lamella in tiny allotriomor-

phic grains large up to 20 μm . Only in one case we have found in the assemblage Bt + Chl + Ms + Cal the titanite of dimensions 250 μm , which fully replaced the former ilmenite. The exchange reaction of the ilmenite recrystallization to titanite took part perfectly with the participation of Si and Ca in the early phase of crystallization of minerals from the granite melt. The same exchange was found in the distance of 1 cm from the contact of granite in amphibolite with hornblende. The exchange of ilmenite to titanite in amphibolite did not take part perfectly, because the ilmenite in the centre of titanite is well preserved. Titanite in plagiogranite has low content of Al_2O_3 and similar chemical composition as titanite in surrounding GAC (Radvanec, 1994a).

Calcite

Calcite was found in plagiogranite most often in the assemblage with Ms2 and Qtz, forming young up to 1 cm long and several μm thick veinlets, occurring only in granite, but not entering into the surrounding amphibolites (Figs. 20 and 21). Allotriomorphic form of calcite is enclosed also in titanite. In the rock matrix the calcite has crystallized in the similar form together with chemically pure chalcopyrite in assemblage with Ms2 + Kfs2 + Qtz. In all forms the calcite is without more important content of Fe, Mg and Mn.

The sequence of crystallization of mineral assemblages in plagiogranite

Plagiogranite is characterized with this sequence of crystallization of mineral assemblages:

- A) $\text{Pl}_{(\text{OLIG ALB})} + \text{Qtz} + \text{Ms1} + \text{Kfs1} + \text{Bt} + \text{Tnt} + \text{Ep}$
 B) $\text{Ms1} + \text{Pl}_{(\text{ALB})} + \text{Qtz} + \text{Kfs2} + \text{Czo} + \text{Bt} + \text{Cal} + \text{Ms2} + \text{Ab} + \text{Zo} + \text{Qtz} + \text{Cal} + \text{Chl} + \text{Ccp}$

Our petrographic and petrological studies revealed that part of mineral assemblage A has crystallized directly from the melt and in “magmatic phase” of granite crystallization it represents the highest temperature stage. At the end of solidification of the granite melt, i.e. at the beginning of subsolidic crystallization during gradual cooling there crystallized other part of minerals of the mineral assemblage A: Ms1 + Bt + Tnt + Ep. The mineral assemblage B crystallized in subsolidic stage and the end of crystallization from the minimum melt is represented by third group of minerals - C, representing in granite the subsolidus to solidus stage of crystallization and metamorphism due to the decomposition of former oligoclase to albite and zoisite.

The often occurrence of titanite and calcite in plagiogranite together with epidote indicates the Ca excess in the granitic melt. At the beginning of direct crystallization from the melt, Ca was bound in plagioclase. During the cooling in subsolidic and solidic stages, there became dominant the Ca binding to carbonate, because in the gradually cooling crystallization system the phase silicate reactions changed to reactions, where CO_2 was applied. This change caused the crystallization of carbonates in the rock matrix in the final stages of granite crystallization and finally also in fractures. The relation of granite mineral assemblages visualizes the phase diagram (Fig. 25).

Crystallization of AKF mineral assemblages

The oligoclase inclusions in Kfs (microperthite), inclusions of Ms1 in Pl, perfect conversion of Ilm to Tnt and crystallization of small Ep clusters in the granite matrix (mineral assemblage A) we interpret as the initial crystallization of the mineral assemblage in the AKF system ($\text{A} = \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$, $\text{K} = \text{K}_2\text{O}$, $\text{F} = \text{FeO} + \text{MgO} + \text{MnO}$) from the minimum melt (Fig. 25). The crystallization of matrix, i.e. part of the assemblage B – Ms2 + Pl + Bt + Kfs we interpret as the last stage of the existence of liquid in the AKF crystallization system. This mineral assemblage crystallized also in the subsolidus state, when the chemical composition of minerals formed from the A melt has changed. It is e.g. the change of the Mg and Fe content in muscovite, content of Or molecule in K feldspar or change of X_{ab} in plagioclase. In the subsolidic state there crystallized also remaining minerals of assemblage B (Czo + Cal). All AKF

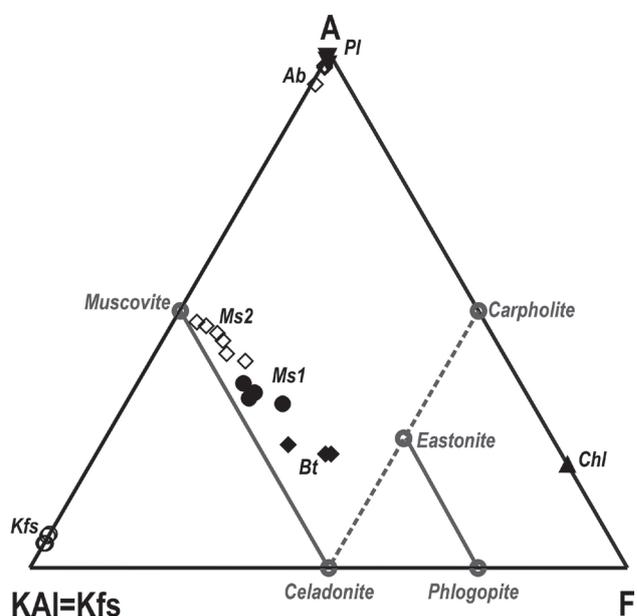


Fig. 25. AKF diagram depicts the position of the white mica (Ms1 and Ms2), dark mica (Bt) between phengite and eastonite and the position of feldspars (Kfs, Ab, Pl).

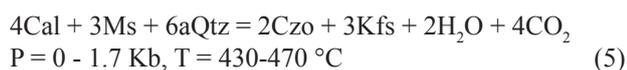
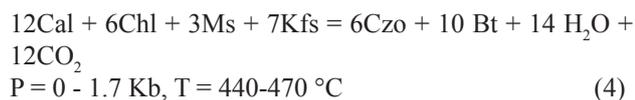
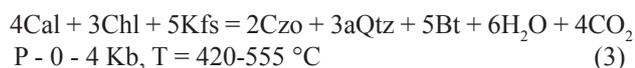
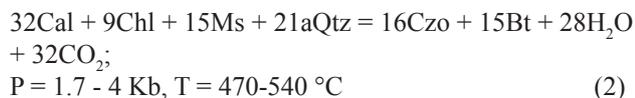
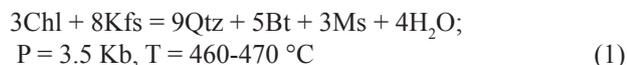
minerals in mineral assemblage C crystallized in the granite subsolidic state. Biotite and chlorite are not - as we have already mentioned - the coexisting minerals, because they have different ratios $Mg/(Mg+Fe)$ ($Bt = 0.36$, $Chl = 0.55$). Muscovite-2, occurring with Bt and Chl between the lamella of both minerals (Fig. 21), has this ratio 0.45. It is a value between the marginal values of Bt and Chl and it indicates the partial exchange of biotite to chlorite and Ms2, which took part at the end of the granite subsolidic crystallization, together with further minerals of C assemblage (Fig. 25).

P-T-x phase equilibria in subsolidic phase of granite crystallization

P-T-x conditions of the stability of phase equilibria and the sequence of crystallization of minerals after direct crystallization from the granite minimum melt we have modelled in the subsolidic crystallization stage applying the Geocalc program (Berman, 1987). The input conditions of the modelling were:

3. Element assemblage found in minerals: Si, Al, Fe, Mg, Ca, Na, K, O, H and C.
4. Mineral assemblage, i.e. the end members, which were found in the subsolidic stage mineral assemblage: albite + quartz + clinozoisite + calcite + K feldspar + phlogopite (Bt) + muscovite + clinocllore (Chl) + H_2O + CO_2 .

The composition of the fluid phase $H_2O + CO_2$ was in the ratio 0.6 H_2O + 0.4 CO_2 . An estimate of this composition was derived from the composition in secondary fluid inclusions. The calculated stable crystallization reactions 1-5 are as follows:



The optimum course of these reactions at constant pressure 3 kbar is related on the change of mole fraction $X(CO_2)$ in fluid phase at 400-530 °C. The stability of

reaction 1 is related on the decrease of temperature from 500 °C to 400 °C, when simultaneously increases the molar fragment $X(CO_2)$ in reacting fluid phase. Reactions 3 and 5 relate on change of $X(CO_2)$ and run optimum at constant temperature 490-530 °C. At the constant temperature of 500 °C there was calculated the optimum pressure of the phase reactions 2 and 5 2-2.8 kbar. Reaction 1 took part at the temperature of 500 °C in tight pressure field 0.5-2.6 kbar and at very low molar fragment $X(CO_2)$ in fluid phase.

Reactions 1-5 represent the lower P-T limits of the stability fields of solid phases of crystallization of minerals in the subsolidic to solidic stage of the granite. Part of mineral assemblage B and C ($Czo+Qtz+Bt$) from the reaction 3 originated at higher temperature, as is its course, namely at the boundary of granite solidus (580-600 °C). This limit in similar P-T conditions (P = 1 to 3 kbar and T = 500-750 °C) of the granite melt crystallization with the H_2O , F and B content was experimentally determined by Pichavant et al. (1987). Crystallization of minerals in subsolidic stage took part under the control of the fluid phase with the content of $CO_2+H_2O+H_2S$. The presence of H_2S in final crystallization stages of the granite solid phases is indicated by chalcopyrite. The stability of Ep to Czo with Bt (reaction 2) and Ep to Czo with Kfs (reaction 5) reached in the area of the highest pressure of the subsolidus to solidus crystallization system P = 2-2.8 kbar. At the decrease of the pressure beneath the 2.5 kbar to 0.5 kbar the mineral assemblage biotite + muscovite + quartz is not stable (reaction 1). The stability conditions of crystallized mineral assemblage B and C were similar as P-T-x conditions of the origin of mineral assemblages in the regional metamorphism of epidote-amphibolite to amphibolite facies or biotite zone (Radvanec, 1994 a, b), which we have found in amphibolite surrounding the plagiogranite (see Ch. 1). The crystallization reactions leading to origin of mineral assemblages in the subsolidic stage of the granite took part at the pressure decrease of regional (orogenic) metamorphism from 3 kbar to 2.8 or even to 2 kbar at the ocean floor metamorphism. During the temperature and pressure decrease in the retrograde branch of regional metamorphism, which in this stage had the same P-T conditions as solid stage of granite, partly the high-temperature solid phases ($Kfs+Pl+Bt$) from the mineral assemblage A and B were replaced by mineral assemblage C ($Chl+Qtz+Ms-2$) according to reaction 1.

The estimate of P-T conditions of the origin of minimum melt of granite composition in amphibolite facies regional metamorphism M0

Estimation of P-T conditions of the origin of the minimum melt of granite composition in amphibolite with hornblend was derived from the stability of mineral assem-

blages in calculated P-T-x conditions of the phase reactions in the subsolidus and solidus stages of crystallization. These reactions describe the “coolest” part of the granite genesis in the solid state. The crystallization sequence of the mineral assemblages A, B and C represented the next limit, which provides an information about the genesis and crystallization state in plagiogranite immediately after the origin of minimum melt from the beginning of its solidification to the end of plagiogranite crystallization. The determination of P-T conditions of the origin of the melt is limited by the boundaries of P-T-x conditions of the phase reactions in the epidote-amphibolite to amphibolite facies or biotite zone of regional metamorphism, being studied in details in individual varieties of metamorphic rocks of GAC in the surrounding of the granite (c.f. Chs. 1 and 6). Only by this study there was firstly possible to distinguish the gradual metamorphic events in GAC and therefore the melt stage and subsequent subsolidus stages of the plagiogranite are included into the oldest metamorphic event **M0** (Devonian-Lower Carboniferous). The subsolidus stage is an equivalent of epidote-amphibolite or biotite zone of metamorphism **M0**. Radvanec (1994a) derived from it the temperature in the lower boundary: 530-580 °C and low pressure. Regarding the fluid phase, the metamorphism **M0** represents an open system. The upper temperature interval of the subsolidus stage of plagiogranite is bordered by cummingtonite zone of amphibolite facies **M0** at T = 600-640 °C and pressure 1 - 2 kbar (Radvanec, 1992). In the amphibolite from the northern part of the Rudňany ore field we have not find the mineral assemblages of cummingtonite zone. Therefore the origin of the minimum melt of granitic composition by partial melting of amphibolite with hornblende was limited only by the P-T conditions of amphibolite facies, i.e. temperature about 650 °C and simultaneously tight pressure interval of 3.0-3.5 kbar. The melting of amphibolite proceeded in its temperature and pressure peak. Besides the found P-T-x conditions derived from subsolidus stage, the upper P-T boundary of melting was limited by the intersection of the phase reaction of melting of metapelite saturated with water (Huang and Wyllie, 1975; Thompson and Algor, 1977) and phase reaction $Ms + Ab + Qtz = Kfs + And + V$ (Thompson, 1974). We have not find the simultaneous crystallization of Ms and Pl (Ab) in the plagiogranite. The intersection is on boundary T = 640-650 °C and P = 3-3.5 kbar. The lower P-T boundary, at which in crystallizing system still can exist or there originates the granite melt, was experimentally found by Pichavant et al. (1987) to T = 580 °C. Experiments by Pichavant et al. (1987), Manning and Pichavant (1984) with crystallization of granite melt having higher content of B, F, (Li) and H₂O have demonstrated that the presence of these elements in the melt lowers the eutectic point from 650 °C by 30 or even by 130 °C, resp. there is stated the temperature of the local existence of low

temperature granite melt at 3 kbar and 550-580 °C. The occurrence of tourmaline and locally also fluorite in GAC of Gemic unit is widely known in the matrix of individual rock varieties and short veins with quartz.

All above stated findings prove that the minimum and anatectic melt of plagiogranite composition from the local partial melting of amphibolite with hornblende has originated on upper limit of **M0** amphibolite facies metamorphism in the temperature range 650-700 °C and tight pressure field P = 3-3.5 kbar, while the last melt stage was at the subsolidic boundary around T = 580 °C.

Rb-Sr isotopic data from plagiogranite

The Sr isotopic analyses were performed on separated minerals: two populations of K- feldspar (according to optical characteristic and colour), biotite (partly chloritized, but manually separated under binocular microscope, purified in agate mortar with methanole and repeatedly cleaned ultrasonically), plagioclase with the share of unseparated quartz (overgrowth) and amphibole (hornblende) from the host rock that is the contact of amphibolite and granite.

The concentration of Rb and Sr in mineral samples (Pl, Kfs1, Kfs2, Bt, Hbl) were obtained by ID method according to the standard laboratory procedure. Sr isotopic composition was measured on VG 54E MS installed at ING PAN, Warsaw. Used decay constant for $^{87}\text{Rb} = 1.42 \times 10^{-11}/\text{a}$, $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$. Raw data were adjusted to NIST 987 standard ($^{87}\text{Sr}/^{86}\text{Sr} = 0.710248$ (see tables in Fig. 20d).

The ordinary regression analysis is shown in Fig. 20d. The linear correlation of the analytical points on the Rb-Sr graph does not really meet the criterion for true isochron according to Isoplot version (Ludwig, 2003). Two variants of linear regressions can be obtained: The first variant assumes that the Hbl from host amphibolite is isotopically equilibrated with Pl, Kfs1, Kfs2 and Bt (minerals of plagiogranite), resulting in an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio = 0.7051. The slope of that regression corresponds to the age of 373.6 Ma. The second variant of regression is calculated only for plagiogranite minerals without the Hbl influence of values. The Hbl related to main minerals of the host amphibolite. The calculated intercept of the plagiogranite regression is equal to 0.7033 and corresponds to the age of 374.5 Ma. The obtained $^{87}\text{Sr}/^{86}\text{Sr} = 0.7033$ is the typical MORB value showing the “MORB-source” of magma to form the plagiogranite during Devonian in the oceanic rift. (Fig. 20e).

The plagiogranite initial ratio of $^{87}\text{Sr}/^{86}\text{Sr} = 0.7033$ represents the lowermost value in the frame of Western Carpathian granitoids. The second lowermost value manifested the Tribeč tonalite (0.7055; Cambel et al., 1990).

The initial ratio $^{87}\text{Sr}/^{86}\text{Sr} = 0.7033$ vs. the age 374.5 ± 4 Ma is very close to the boundary of the mantle and the basalt field. The mutual interaction of the mantle melt,

basalt melt of MORB type and oceanic crust can be best explained by the model of oceanic rift. From this mutual interaction there is possible to derive the fractionation of “plagiogranite melt” in the oceanic rift with the $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratio = 0.7033.

The Rb/Sr analysis of separated hornblende from amphibolite (immediate surrounding of plagiogranite) is isotopically not exactly reequilibrated with plagiogranite. It means that no gneisses from the GAC represented the source of granitic melt, but it was the mixture of mantle rocks and oceanic crust (i.e. amphibolites). The melting of the mantle rocks and differentiation of magma could occur in the oceanic rift during the ocean floor metamorphism **M0**. Besides Rb-Sr analyses, from the same separated hornblende there were done also analyses of Ar isotopes (Fig. 20e). The $^{40}\text{Ar}/^{39}\text{Ar}$ analysis were performed at CEAL laboratory (GÚ SAV, Bratislava) according to the standard laboratory procedure (see e.g. Putiš et al., 2009b). The highest amount of deliberated argon, around 80 %, gave the “plateau” age of $362.5 \text{ Ma} \pm 5.3 \text{ Ma}$, which can be supposed as the age of degassing or the cooling age of hornblende at cca 550 °C. From it results that the age of melting out of plagiogranite $373.6 \pm 4 \text{ Ma}$ corresponds with the solidification of the granite melt and the melt must originate at temperature about 650 °C but not more than 700 °C. The cooling age 362.5 Ma of hornblende (app. Devonian-Lower Carboniferous boundary), registered at 550 °C and represents the terminating of the melt interaction with the ocean floor metamorphism in the Early Paleozoic rift. However a rough evidence for reequilibrium of hornblende indicates the Permian ages (cca 250 – 300 Ma) at the beginning of cumulative % Ar released values (Fig. 20e).

Geochemical characteristics of the whole-rock analyses and geotectonic background of the origin of amphibolite and plagiogranite

Normalized contents of the trace elements and normalization of the REE contents confirm the origin of plagiogranite and surrounding amphibolite in the rift in oceanic crust (Fig. 20a; Table 2). The plagiogranites are characterized by the positive Eu anomaly and the course of the elements content from Rb to Yb in normalization to granites originating in the oceanic rift (Fig. 20c). Normalized trends of the contents of elements of both rocks - amphibolite and plagiogranite - are parallel and in plagiogranite are systematically lowered (Fig. 20b). Both these trends are equally enriched by Cs, Rb, Ba, U, Pb and B in the host amphibolite and in plagiogranite. The plagiogranite is deficient in Sc in comparison to amphibolite, as well as to normalized oceanic crust (Fig. 20b). Systematic lowering of the normalized contents of elements in plagiogranite in comparison to source amphibolite we explain by the

depletion after partial or anatectic melting of amphibolite, from which the granite melt has originated. New “plagiogranite” melt has preserved in lowered trend of normalized IE contents, which are well comparable with the protolith (amphibolite). The source of granite melt from the amphibolite melting is demonstrated not only according to isotopic data, but also according to the comparison of IE contents normalization to amphibolite and oceanic crust (Fig. 20).

3 Metamorphosed gabbro at *Jaklovce*, *Delava* and *Dobšiná*

The metagabbro in localities *Jaklovce* (N48° 52.763' E20° 59.787'), *Delava* (N48° 48.940' E20° 32.664') and *Dobšiná* (N48° 50.149' E20° 23.523') represents a part of the Paleozoic metaophiolite suite in Gemeric unit, together with GAC, plagiogranite and serpentinite. In first two localities, the metagabbro was revealed in the field in tectonically isolated blocks. In locality of *Dobšiná* the metagabbro crops out in the southern part of GAC. The location of metagabbros occurrences is provided by Ch. 1. Geochemical proofs for enlistment of this metagabbro into the metaophiolite suite provides Ch. 6, the mineralogical-petrographic-petrological evidences are presented in this chapter.

Metamorphosed gabbro to amphibolite at the *Jaklovce* village

In position NW and SE of *Jaklovce* two metagabbro blocks were verified by mapping, being in tectonic contact with surrounding rocks. The metagabbro from the *Jaklovce* locality, described in this paper, locally encloses the violet jaspilites, belonging to Lower variegated volcanic horizon of Early Paleozoic rift (cf. Grecula et al., 2009, 2011). These local enclosures differ from Mesozoic violet radiolarites located in the close vicinity of our studied occurrence. The Early Paleozoic rhyolites and dacites were also revealed in position above the studied metagabbro. It was surveyed already earlier by boreholes, shafts and exploration adits because of their close position to metaperidotite-serpentinite, which is supposed here to be a part of the tectonic block of Meliatic unit (Fedor and Tomko, 1968; Zlocha et al., 1980). Kamenický (1957), Fedor and Tomko (1968) and Zlocha et al. (1980) described the metagabbro at *Jaklovce* as paleobasalts or diabases. Mineralogical and petrological investigation revealed that this rock contains the multidirectional phenocrysts of augite and plagioclase and the crystals have often an acicular habitus (Fig. 26a, d). The metagabbro contains primary “magmatic” and secondary “metamorphogenic” assemblages (Figs. 26 and 27). Magmatic assemblage consists of augite ($\text{TiO}_2 = 0.46\text{--}1.75 \text{ wt.}\%$; $\text{FeO} = 7.48\text{--}21.28 \%$), plagioclase (lab-

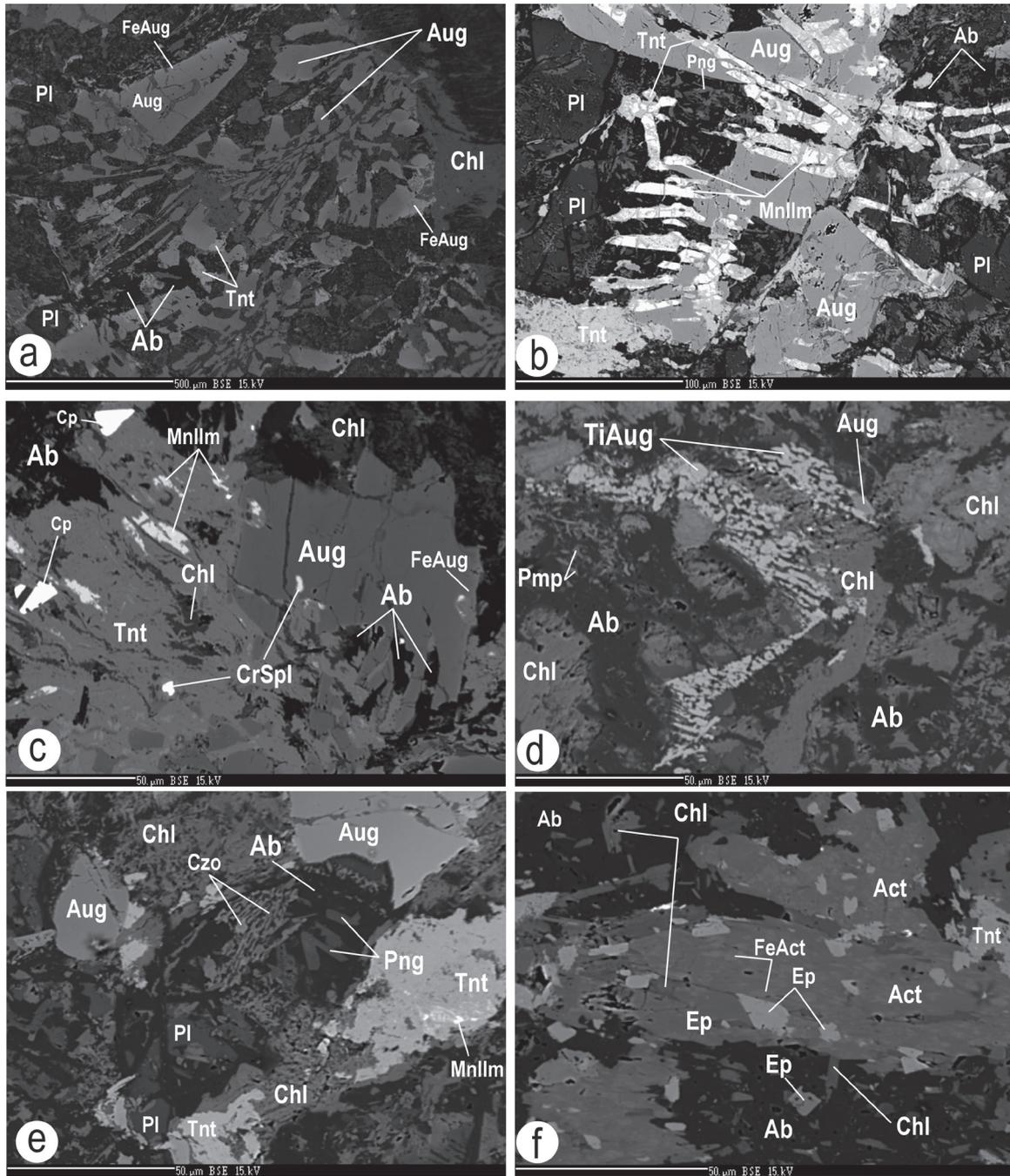


Fig. 26. Relation of minerals in polymetamorphosed gabbro from the *Jaklovce* locality. Aug - augite, FeAug – augite with the content of Fe, Pl – plagioclase, Ab – albite, Chl – chlorite, Tnt – titanite. Png – phengite, MnIlm – ilmenite with the content of Mn, CrSpl – chromite-Mg-chromite, Cp – chalcopyrite, TiAug – augite with a high content of Ti, Pmp – pumpellyite, Czo – clinozoisite, Ep – epidote, Act – actinolite, FeAct – actinolite with the high content of Fe. Backscattered electron images.

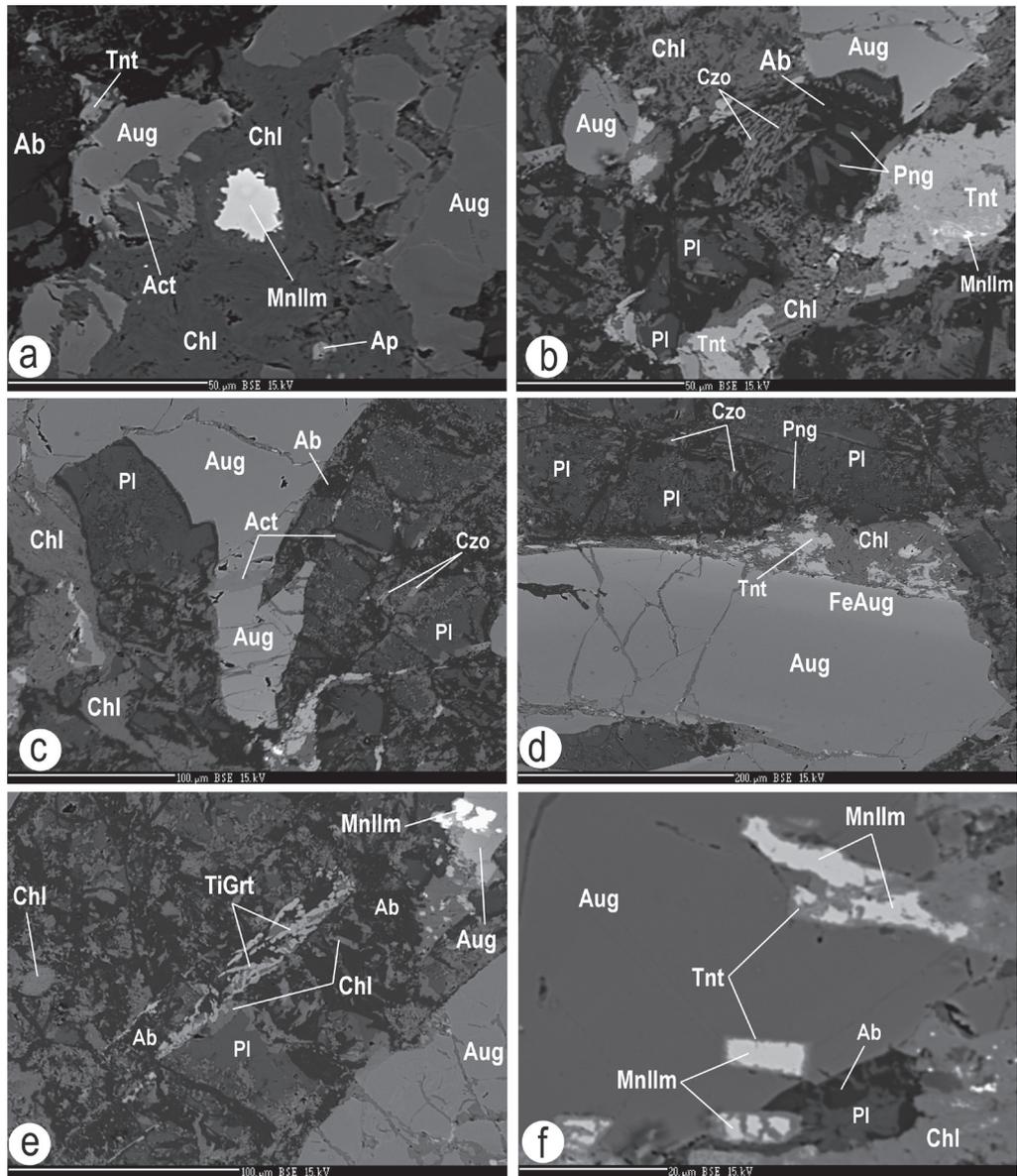


Fig. 27. Relations between minerals of the *Jaklovce* metagabbro in backscattered electrons. Magmatogenic minerals: augite (Aug), Fe augite (FeAug), chromite (CrSpl), labradorite (Pl), Mn ilmenite (MnIlm) and apatite (Ap). Metamorphogenic minerals: titanite (Tnt), albite (Ab), clinozoisite (Czo), chlorite (Chl), phengite (Png), Ti garnet (TiGrt) and chalcopyrite (Cp).

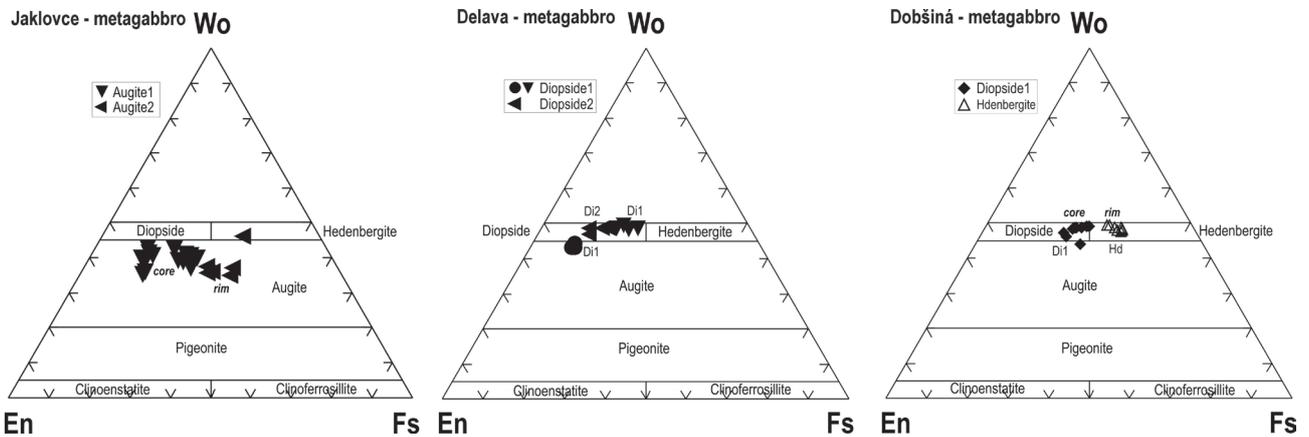


Fig. 28. Chemical classification of clinopyroxenes in triangle diagram En-Fs-Wo in localities *Jaklovce*, *Delava* and *Dobšiná*. Polymetamorphosed gabbro of the ophiolite suite of Gemeric unit.

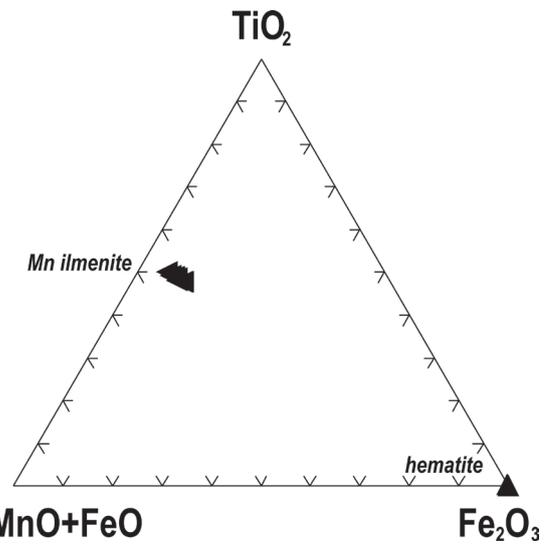
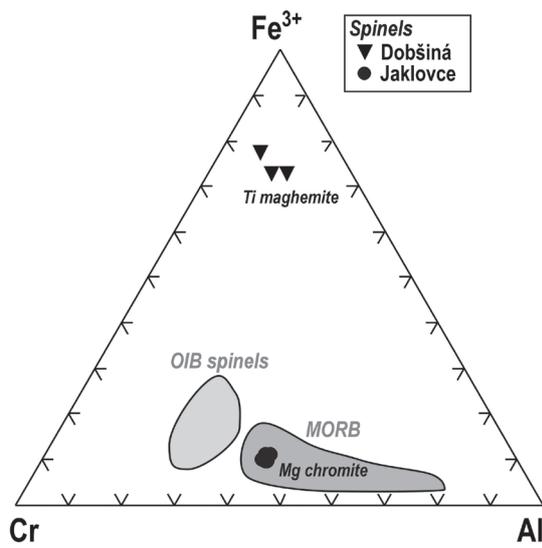


Fig. 30. Chemical classification of Mn ilmenite and hematite from the *Jaklovce* metagabbro in classification triangle diagram.

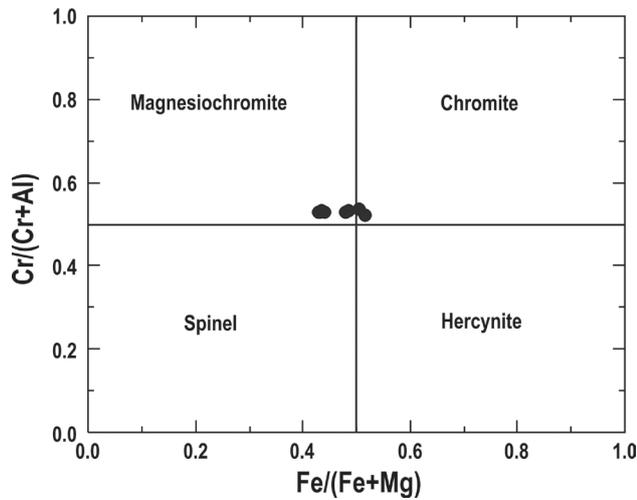


Fig. 29. Chemical classification of chromite from the *Jaklovce* locality and Ti of maghemite from the *Dobšiná* metagabbro.

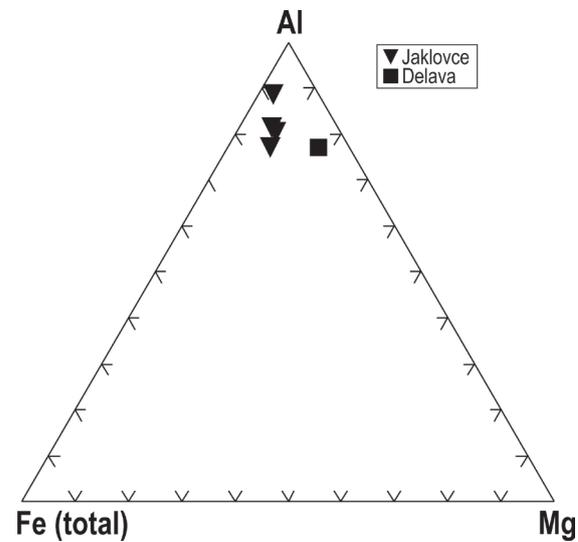


Fig. 32. Chemical classification of pumpellyite from the *Jaklovce* and *Delava* metagabbro in triangle diagram Fe-Mg-Al.

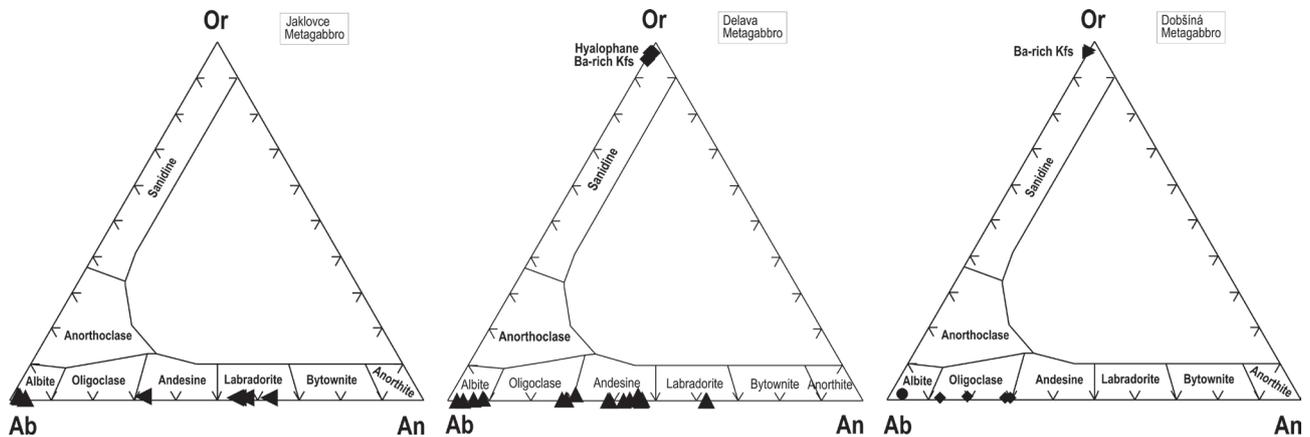


Fig. 31. Chemical classification of feldspars from the *Jaklovce*, *Delava* and *Dobšiná* metagabbro in the classification triangle diagram Ab-An-Or.

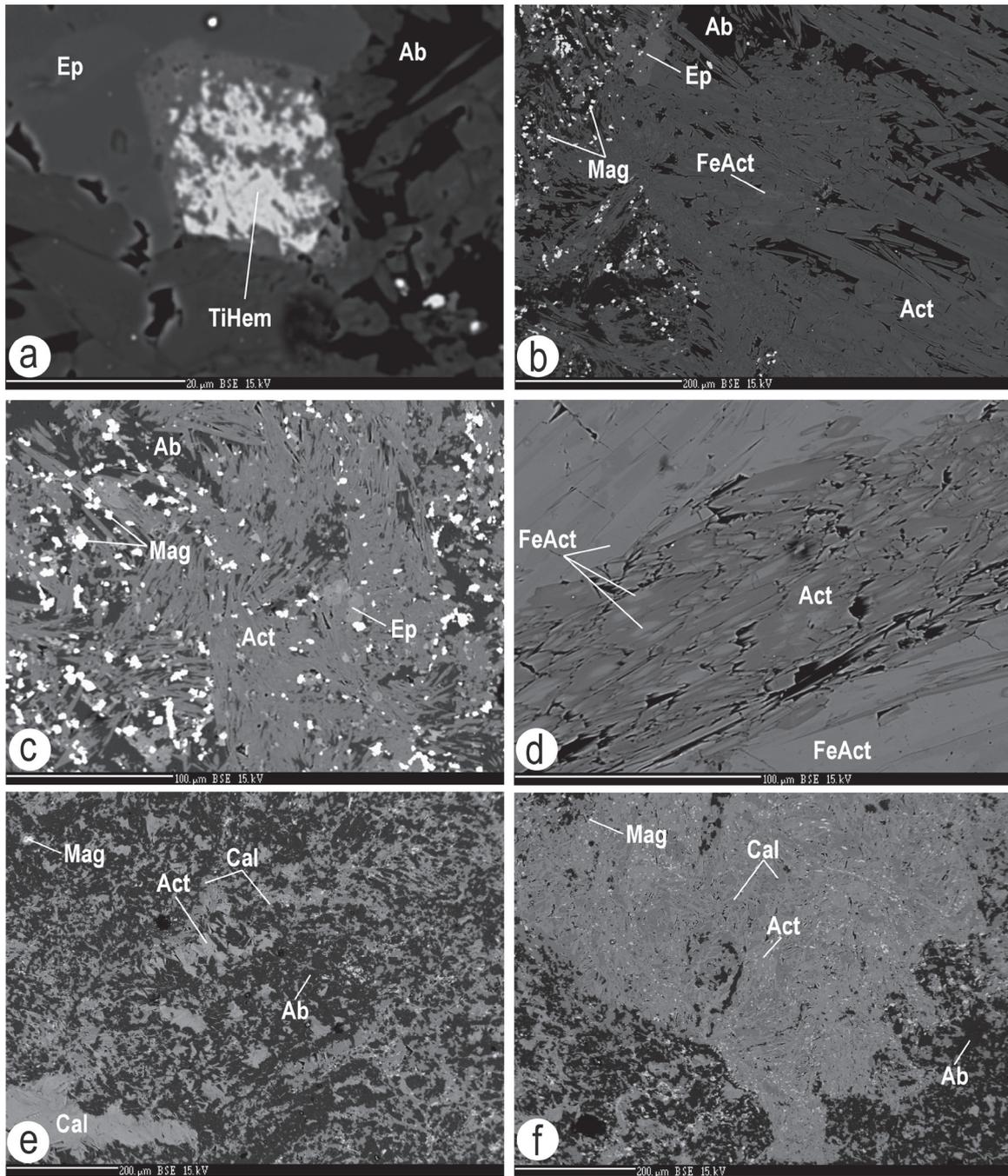


Fig. 33. Relations among minerals of the *Jaklovce* metagabbro - amphibolite in backscattered electron images. Former metagabbro was totally recrystallized to amphibolite. Actinolite (Act) – Fe actinolite (FeAct), epidote (Ep), titanite (Tnt), albite (Ab), chlorite (Chl), calcite (Cal), hematite has a shape of former magnetite (Mag), *a* - Ti hematite (TiHem) - detail of the former shape of Ti magnetite is shown also in further Figs.

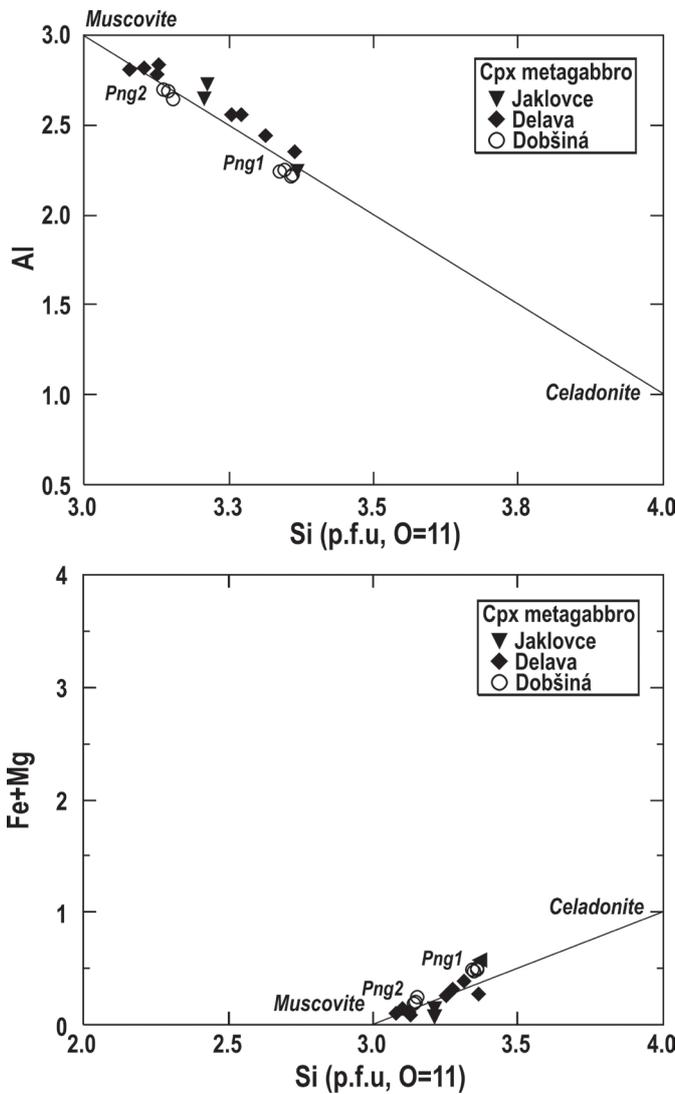


Fig. 34. Chemical classification of white mica in polymetamorphosed gabbro of the ophiolite suite of Gemeric unit in localities *Jaklovce*, *Delava* and *Dobšiná*. Png1 – first generation of phengite. Png2 – second generation of phengite. Recalculation of chemical composition on O = 11.

radiorite-core, andesine-rim of grains), apatite, zircon, Mg chromite - chromite ($Mg_{0.53}Fe_{0.50}Mn_{0.01}$)_{1.04}($Ti_{0.03}Fe_{0.21}Al_{0.8}Cr_{0.91}$)_{1.95}O₄, Mn ilmenite $Ca_{0.02}^{2+}Fe_{0.69}Mn_{0.20}Ti_{0.91}^{3+}Fe_{0.16}O_3$, and rutile. According to chemical classification of augite and chemical classification of Mg chromite-chromite and Mn ilmenite the former gabbro represented originally the pyroxene-plagioclase cumulate, which crystallized in oceanic rift (Figs. 28 and 29). According to chemical classification of the chromite, the former gabbro originated from the melt of the MORB type (Fig. 29).

The metamorphogenic mineral assemblage originated during the gradual polyphase recrystallization of gabbro: Fe augite-hedenbergite replaces at the margins magmatic augite, next it consists of titanite, pumpellyite, clinozoisite, epidote, albite, actinolite – Fe actinolite, Ti hydroandradite,

phengite, chlorite, hematite – Ti hematite, chalcopyrite and pyrite. Mn ilmenite is at margin replaced to titanite (Figs. 26 and 27) and a substantial part of titanite in the rock is a result not only of replacement of Mn ilmenite but also former rutile. According to chemical classification of amphiboles two generations of actinolite have originated, being divided according to successive metamorphic events in Fig. 37. We have found two generations of the white mica, occurring with albite (Fig. 34). According to metamorphogenic mineral assemblage, the gabbro was successively metamorphosed firstly in pumpellyite–actinolite facies (**M1a** metamorphism), then in epidote–amphibolite facies (**M1b**) and then in retrograde greenschist facies (**M2**). These gradual metamorphic events were according to chemical composition of revealed metamorphogenic minerals classified in CFA diagrams (Fig. 42). Metamorphism in the frame of individual metagabbro blocks has differing intensity. In the NW part of the metagabbro body in the area of tectonic contact with limestone, the metagabbro is nearly totally recrystallized to actinolite amphibolite (Fig. 33). Due to tectonic overprint of the rock, this prevalingly fine-grained amphibolite has macroscopic and petrographic signs of “pseudobedding”, pseudolamination or schistosity, being by earlier authors interpreted as signs of primary effusive basalt, tuffite.

Age of the gabbro at Jaklovce

The age of the metagabbro was revealed by U – Pb (U-PB SIMS SHRIMP) method, applied on separated zircons (Putiš et al. 2011). The results significantly contributed to reconstruction a geotectonic model a metagabbro at Jaklovce.

The age of subsolidic or magmatic zircon in the metagabbro is 342 and 359 Ma. The zircon from the metagabbro contains in samples also relic of the zircon core old 490 and 505 Ma. According to mineralogical-petrological study the metagabbro in the magmatic stage was a part of oceanic crust. The zircon age determines the Lower Carboniferous termination of magmatic activity of a mid-oceanic ridge. In earlier geological maps, or even the recent ones (e.g. Grečula et al., 2009), this metagabbro was considered to be a part of the Triassic-Jurassic oceanic crust of Meliatic unit. Similarly also the zircon Carboniferous age from this rock was interpreted as represented the hereditary grains, entering to the Triassic basalt magma from unknown Carboniferous source. These Carboniferous zircons were found in two different samples of the metagabbro from Jaklovce area. Question is, why only the Carboniferous zircons have entered into the Triassic basalt magma, when sedimentary rock of the same Triassic age contains mainly the Permian and older zircons (Ch. 7). These detritic zircons should be present similarly also in

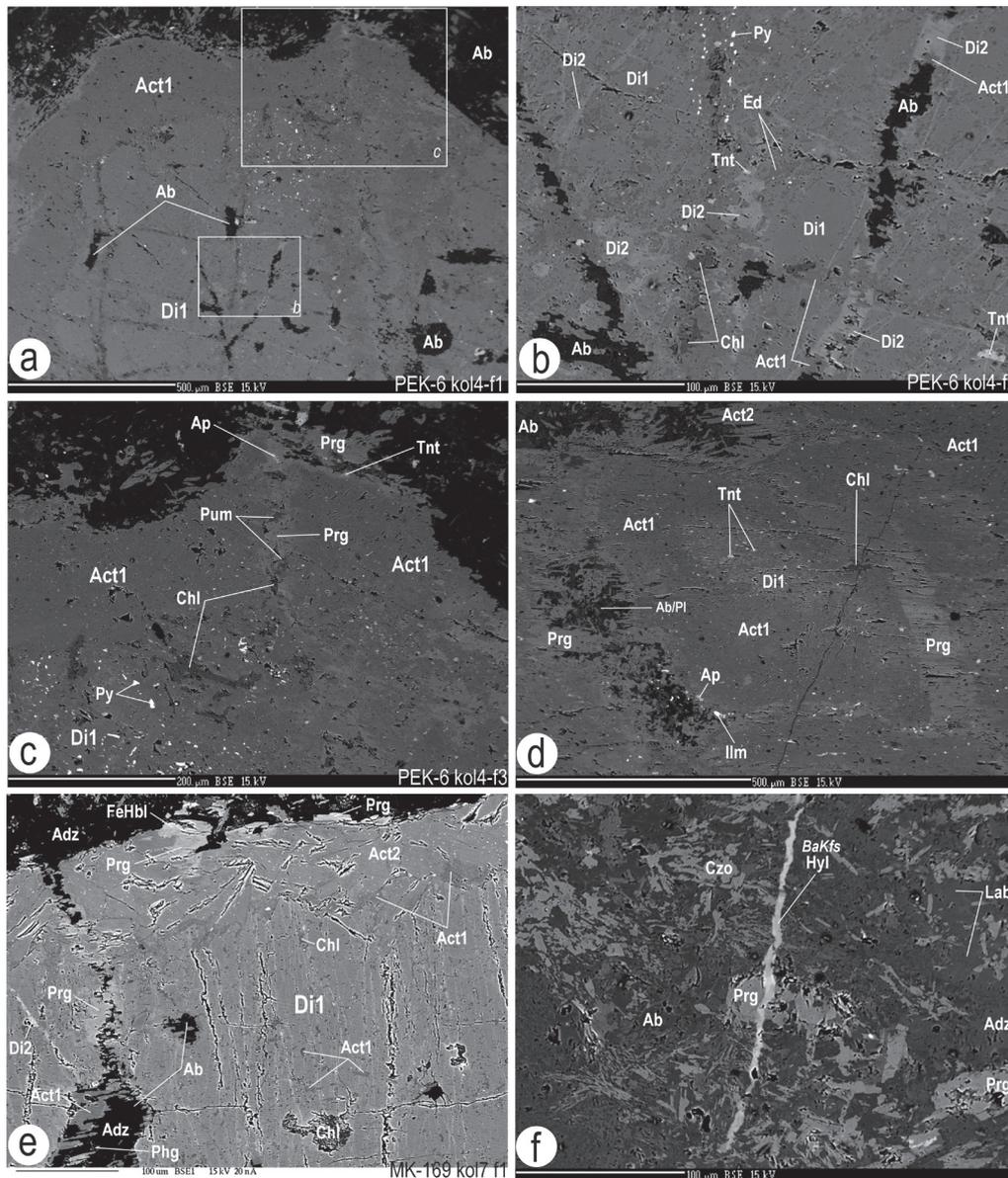


Fig. 35. Relation of minerals in polymetamorphosed gabbro from the *Delava* locality. **a** – Porphyroclast of magmatic diopside (Di1) on the rim replaced by actinolite (Act). Albite is present in fractures and matrix. Squares – details in parts **b** and **c** of this Fig. **b** – Diopside-2 replaces the diopside-1 in individual fractures or it is replaced together with Ab and actinolite-1 (Act1) or edenite (Ed). Chl – chlorite infills the individual fractures in Di1, Tnt - titanite, Py – pyrite. **c** – On the margin of Di1 the assemblage pumpellyite (Pum) with Act1 fills the fractures and younger pargasitic amphibole (Prg) rims Act1 at the contact with the matrix. Ap – apatite. Tnt – titanite. **d** – Relation of gradual replacement of Di1 to Act1, Prg and Act2. Ilm – ilmenite. Ab/Pl – mixture of original plagioclase with new albite. **e** – Gradual change of the rim of porphyroclast Di1 to Act1 and relation of younger assemblage Act2, Prg and Fe hornblende (FeHbl) to Act1 on the rim of Di1. Pargasitic amphibole (Prg) – infills the fractures in Di1 together with albite (Ab). Di1 encloses andesine (Adz), which in fractures replaces the Act1, Fe phlogopite (Phg), Ab and Prg. **f** – Decomposition of plagioclase (Adz), originally crystallized from the magma, on the mixture of albite (Ab), clinozoisite (Czo) to epidote. Hyalophane (Hyl, BaKfs) or Ba K feldspar crystallized in short veins. Backscattered electron images.

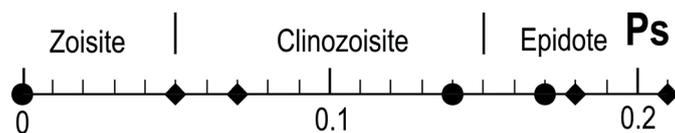


Fig. 36. Chemical classification of the epidote group minerals present in polymetamorphosed gabbro of the *Delava* locality.

the hypothetical Triassic magma as they occur in the Triassic sediment in the vicinity of the metagabbro.

The former gabbro represented a part of the magmatic MORB-cumulate of the oceanic crust, being a part of the Early Paleozoic ophiolitic suite (see Chs. 5 and 7). During the gradual crystallization of the cumulate melt, the magmatic zircon crystallized together with Cr spinel and Mn ilmenite. These magmatic zircons have the Early Carboniferous age (from 359 to 342 Ma). The age corresponds to the cooling age 362 Ma of amphiboles that were formed around the plagiogranite (371 Ma, see Ch. 2).

Mineral composition of the clinopyroxene metagabbro at *Delava*

In the *Delava* locality, the porphyroclasts of diopside-1 and plagioclase (oligoclase to labradorite) represent former pre-metamorphic magmatic mineral assemblage

of the gabbro. The former labradorite rarely preserved, being enclosed in diopside-1 (Fig. 35e). In the fractures of porphyroclasts of the diopside-1 there crystallized the younger generation of Fe diopside-2, which originated during the metamorphism of the gabbro (Fig. 35b). The porphyroclasts together with the metamorphogenic albite and epidote group form around 70 % of the rock volume. The remaining matrix of this metamorphic rock is formed of pumpellyite, chlorite, actinolite, titanite, ± calcite and Fe oxides. Porphyroclasts of diopside-1 are in the inner rim changed to actinolite-1 with low content of Fe and gradually toward the matrix the diopside-1 is corroded by the paragasitic amphibole, Fe hornblende and actinolite-2 with high Fe content (Fig. 35). These metamorphogenic amphiboles partially or fully replace diopside-1 or it is often totally replaced to actinolite-1 and chlorite (Fig. 35). Pumpellyite was found only rarely in the metagabbro. It occurs together with actinolite-1, which originated after the de-

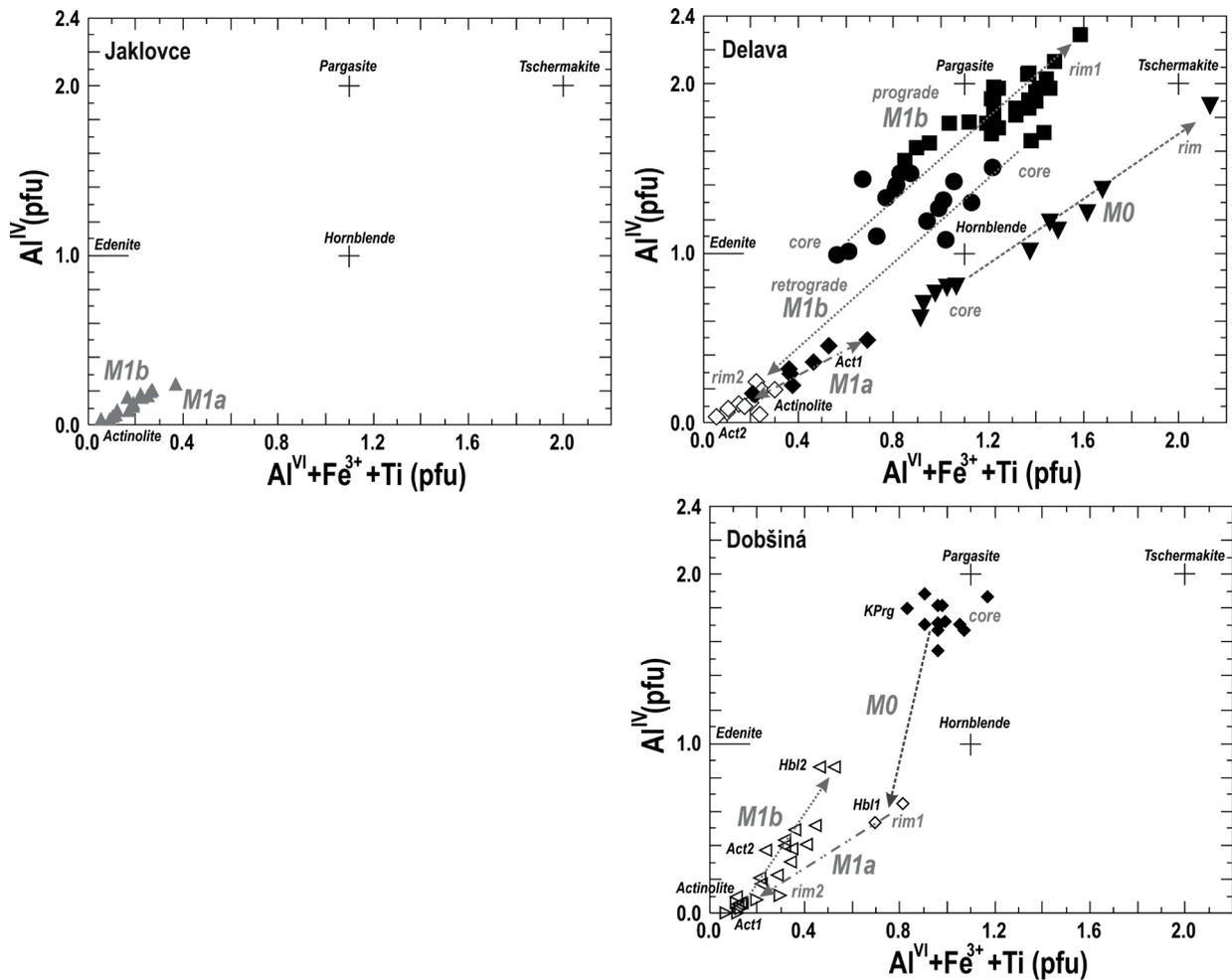


Fig. 37. Chemical classification of various generations of amphiboles in polymetamorphic gabbro of ophiolite suite of Gemicum in localities *Jaklovce*, *Delava* and *Dobšiná*. **M0** – amphiboles from the ocean floor metamorphism, oldest metamorphism – Devonian to Lower Carboniferous. **M1a** – amphiboles of pumpellyite-actinolite facies, younger - Upper Carboniferous metamorphism. **M1b** – amphiboles of epidote-actinolite to amphibolite facies, the youngest metamorphism – Permian. Act – actinolite. Hbl – hornblende. KPr – pargasite with K content.

Fig. 38. Mixture of ilmenite (Ilm), rutile/antase (Rt) and titanite (Tnt) in metagabbro from the *Delava* locality. Couple ilmenite – rutile/antase has originated by the decomposition of the primary oxide, “ferropseudobrookite” FeTi_2O_5 . Further minerals: scutterudite (Sku), zircon (Zrn), andesine (Adz), pyrite (Py), albite (Ab), actinolite (Act), pargasitic amphibole (Prg). Backscattered electron images.

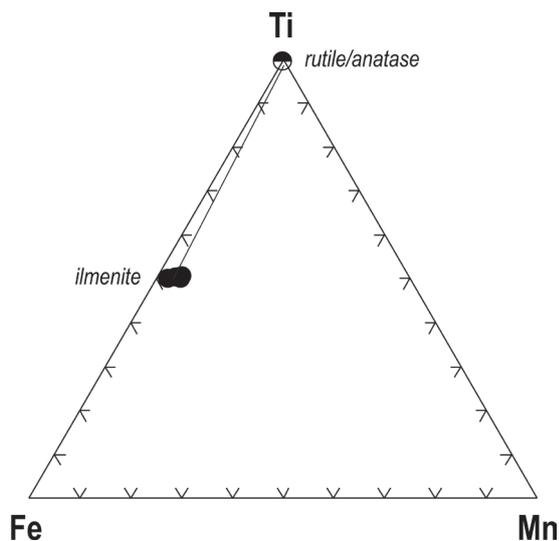
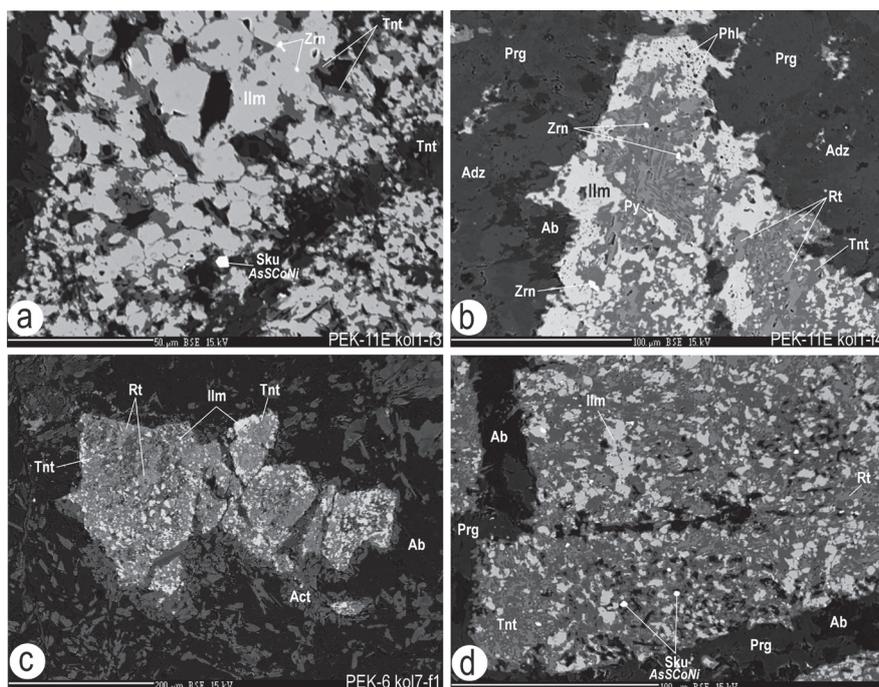


Fig. 39. Chemical classification of ilmenite and rutile/anatase in triangle diagram Fe–Mn–Ti from the polymetamorphosed gabbro from the *Delava* locality.

composition of diopside-1 (Fig. 35c). Pargasitic amphibole crystallized not only at the margin of diopside-1, but also in fractures in it, where during new metamorphic stage it replaced older actinolite-1 (Fig. 35e). The classification of amphiboles to individual metamorphic events is based on their chemical parameters (Fig. 37). The decomposition of Ca plagioclase produced the zoisite and clinozoisite during older metamorphic recrystallization. Epidote is a product of younger metamorphism. The epidote group has in matrix the variegated content of the Ps ratio from zoisite to epidote (Fig. 36).

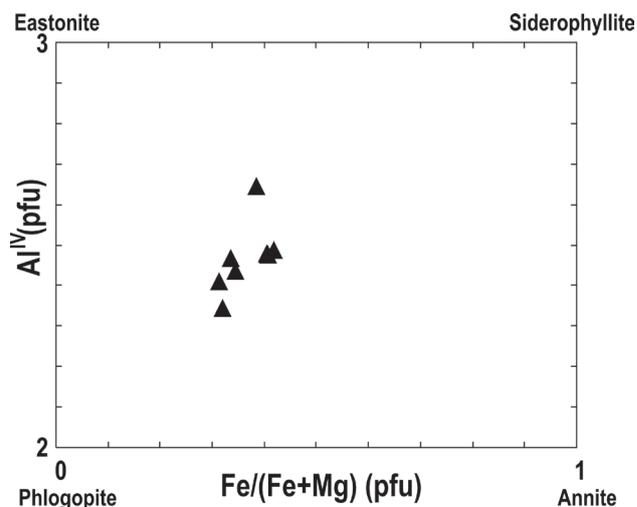
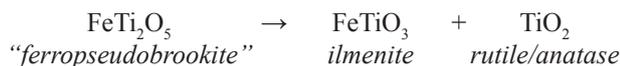


Fig. 40. Chemical classification of phlogopite in metagabbro in the *Delava* locality.

Phengite-1 in metagabbro occurs together with actinolite-1 and albite in the matrix. Phengite 2 was found in the fracture in diopside-1 together with pargasitic amphibole, albite and Fe phlogopite (Figs. 34, 35e and 40).

In the metagabbro the ilmenite FeTiO_3 and rutile/anatase form TiO_2 clusters, large several mm. This mixture of Ti oxides encloses the Fe phlogopite, zircon and scutterudite. Ilmenite and rutile/anatase represent a co-existing couple, which has originated by the decomposition of former “ferropseudobrookite” FeTi_2O_5 - oxide from the group of armalcolite, according to the reaction:



Ilmenite contains Mn up to 10 mol.% (Fig. 39). In the process of polyphase metamorphism the rutile/anatase on the margin of grains has changed to titanite (Fig. 38). Titanite was found also in the matrix in assemblage with chlorite, albite, actinolites, pumpellyite and clinozoisite to epidote.

In the matrix we have found short (to 300 μm) hyalophane veinlets (Fig. 35f). The metamorphogenic assemblage albite, actinolite, chlorite, calcite and titanite forms in the metagabbro the irregular aggregates. Albite forms also porphyroblasts together with the white mica-phengite. Chlorite and calcite originated by the replacement of the epidote group at the end of polyphase metamorphism.

According to metamorphogenic mineral assemblages, the gabbro was gradually metamorphosed – at first in amphibolite facies (M0), then in pumpellyite–actinolite facies (M1a) and finally in epidote–amphibolite to amphibolite facies (M1b). Three gradual metamorphic events are classified in CFA diagrams (Fig. 42).

Metamorphosed gabbro at the town of Dobšiná

The metagabbro block at *Dobšiná* belongs to SW part of the local occurrence of GAC (Grecula et al., 2009; Bajanič et al., 1984). Mineralogical-petrological-geochemical study of metagabbro at *Dobšiná* as a part of the Paleozoic ophiolite suite of Gemeric unit was focussed on its gradual metamorphic recrystallization and comparison with the metagabbro at *Jaklovce* and *Delava*.

Mineral composition of the clinopyroxene metagabbro at Dobšiná

In locality of *Dobšiná* the porphyroclasts of diopside, plagioclase and K-feldspar represent the primary pre-metamorphic magmatic mineral assemblage of the gabbro. Porphyroclasts of primary minerals together with metamorphogenic albite and epidote form around 80 % of the rock volume. The remaining matrix of metagabbro is formed of chlorite, Ca-K amphiboles, actinolite, Ti maghemite, Mn ilmenite, white mica, titanite ± calcite, Fe oxides and quartz.

Original oligoclase is rarely preserved in individual porphyroclasts, being replaced by albite, epidote and quartz (Fig. 41). Besides primary plagioclase porphyroblasts the former gabbro contained K feldspar with variable content of BaO (0.78-3.34 wt.%) and Mn ilmenite with variable content of MnO (5.44-6.92 wt.%) (Fig. 41a, f). K-feldspar was replaced by white mica and quartz. In the cleavage, the diopside was replaced by the mixture of actinolite-1 and calcite (Fig. 41b, d). This assemblage is

older than metamorphogenic assemblage, which changed the diopside rim (Fig. 41a). Diopside porphyroclasts are at the rim changed to hedenbergite (Fig. 41b). Hedenbergite is corroded and replaced by the assemblage of amphiboles - K pargasite (core) – hornblende-1 (core-rim) – actinolite-2 (rim). The K₂O content in K pargasite is variable (1.02- 1.97 wt.%) (Fig. 41a). Actinolite-2 occurs on the rim of diopside, but also separately, as well as together with hornblende-2. Both these amphiboles are product of the youngest metamorphic overprint of the metagabbro (Fig. 41c). Concerning the chemical classification of amphiboles, their various generations are classified and divided according to successive metamorphic events in Fig 37. Diopside porphyroclast at the contact with the former porphyroclasts of plagioclase and K-feldspar is rimmed by the symplectite of the quartz and zoisite mixture (Fig. 41b, c and f). This symplectite is younger than the amphibole rim of K pargasite–hornblende-1–actinolite-2 at the margin of diopside and hedenbergite. Symplectite probable originated by the decomposition of plagioclase and K-feldspar during the last metamorphism, together with hornblende-2, actinolite-2 and albite. Due to the polymetamorphism of metagabbro, the rim of the Mn ilmenite and Ti maghemite is replaced to titanite (Fig. 41a, d a f).

4 Mineral composition of serpentinite on Strážny vrch hill and in gneiss-amphibolite complex at Klátov

Serpentinite of the Paleozoic ophiolite suite occurs together with GAC in localities *Klátov* (N48° 45.068' E21° 07.411') and *Strážny vrch hill* (N48° 44.993' E20° 50.348'; this occurrence is located ca 380 m to NE of the Jedľovec elevation point 954 m.a.s.l.), where serpentinite occurs in tectonic blocks, being isolated within the graphitic phyllites of the Holec Beds of Betliar Fms. of the Silurian-Devonian age (Grecula et al., 2009, location is in Ch. 1).

Serpentinites in both localities are a product of total hydration and polymetamorphism of former peridotite. From the original mineral assemblage of the peridotite, the olivine and pyroxenes are in serpentinite represented only by their pseudomorphoses. The former peridotite probable had porphyroblastic and neoblastic fabric with dimensions of former Mg silicates to 1-2 mm. The spinfex fabric of former peridotite cannot be excluded (Fig. 43), too.

Serpentinite in the *Strážny vrch* contains talk > Mg chlorite > tremolite > actinolite, calcite and ilmenite with exsolution lamella of hematite (Figs. 43 and 44). Hematite lamella in ilmenite originated probable in the subsolidus stage or during the peridotite metamorphism by disintegration of original Fe-Ti oxide from the former magmatic assemblage of the peridotite (Fig. 44b). In the process of polyphase metamorphism, the former Mg silicates of the peridotite were replaced by talc and Mg chlorite. During the younger metamorphism there crystallized the tremolite

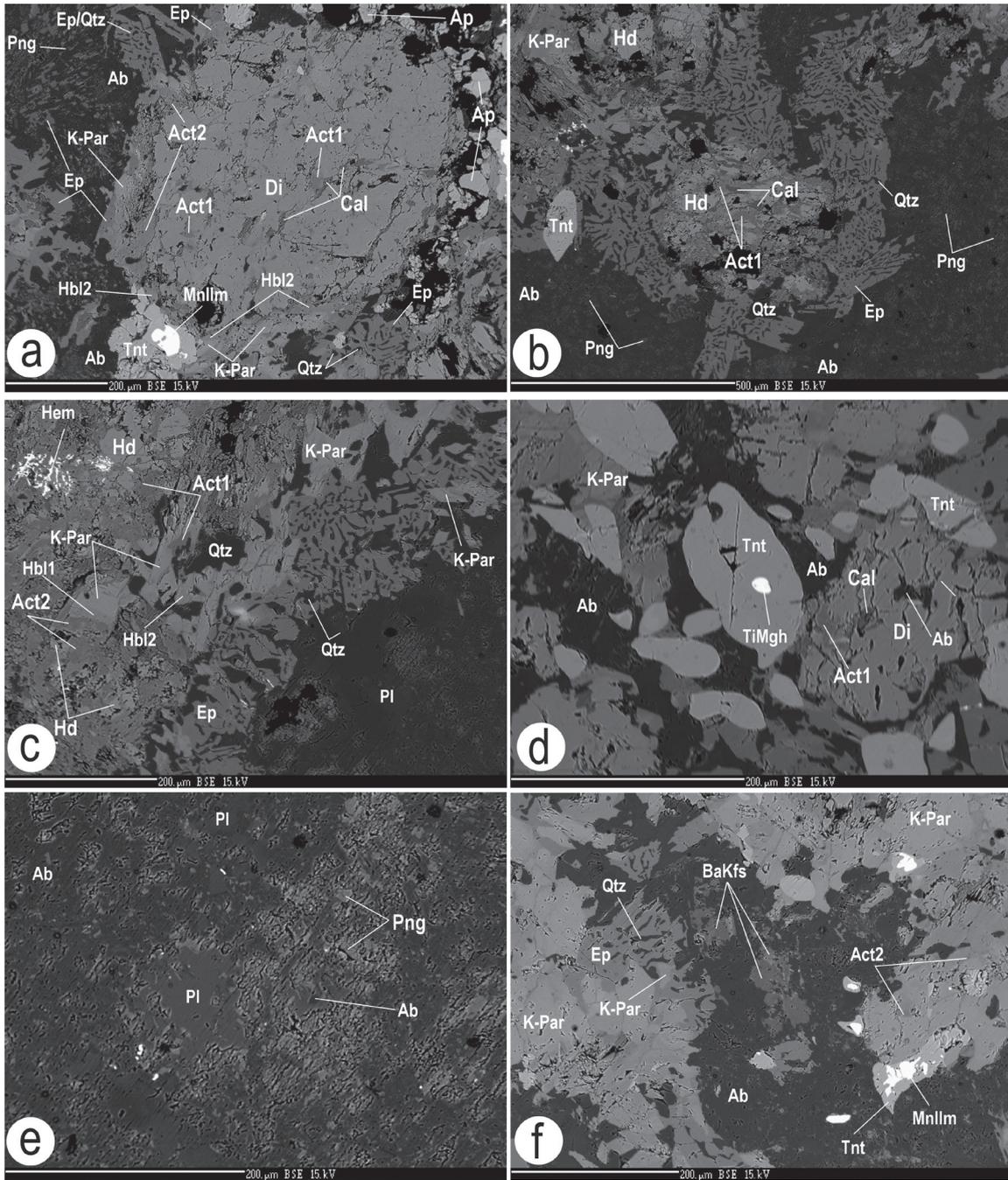


Fig. 41. Relations of minerals in the polymetamorphosed gabbro from the *Dobšiná* locality. Di - magmatic diopside, Ab - albite, Pl - plagioclase, Chl - chlorite, Tnt - titanite, Cal - calcite, Png - phengite, MnIlm - ilmenite with the content of Mn, Ep - epidote, Act1-Act2 - actinolite of two generations, Ep/Qtz - symplectite of quartz and epidote, K-Par - pargasite with the content of K, Hbl1-Hbl2 - two generations of hornblende, Hd - hedenbergite, TiMgh - maghemite with the high content of Ti, BaKfs - K feldspar with a high content of Ba-hyalophane (Hyl). Backscattered electron images.

Fig. 42. Mineral assemblages and evolution of the metagabbro polymetamorphism of ophiolite suite of Gemeric unit in the localities *Jaklovce*, *Delava* and *Dobšiná* in A-F-C triangles. **a** - magmatic stage and the ocean-floor metamorphism - amphibolite facies **M0**; **b** - Pumpellyite-actinolite facies **M1a**; **c** - epidote-amphibolite to amphibolite facies **M1b**. Aug - augite, Pl - plagioclase, Ab - albite, Chl - chlorite, Tnt - titanite. Png - phengite, Mnllm - ilmenite with the content of Mn, MgChr - chromite-Mg-chromite, Pmp - pumpellyite, Ep - epidote, Act - actinolite, TiMgh - maghemite, KPrg - pargasite with the content of K, Prg - pargasite, Ed - edenite, Hbl - hornblende, Bt - biotite, Hd - hedenbergite, Cal - calcite, Kfs - K feldspar, Hyl - hyalophane.

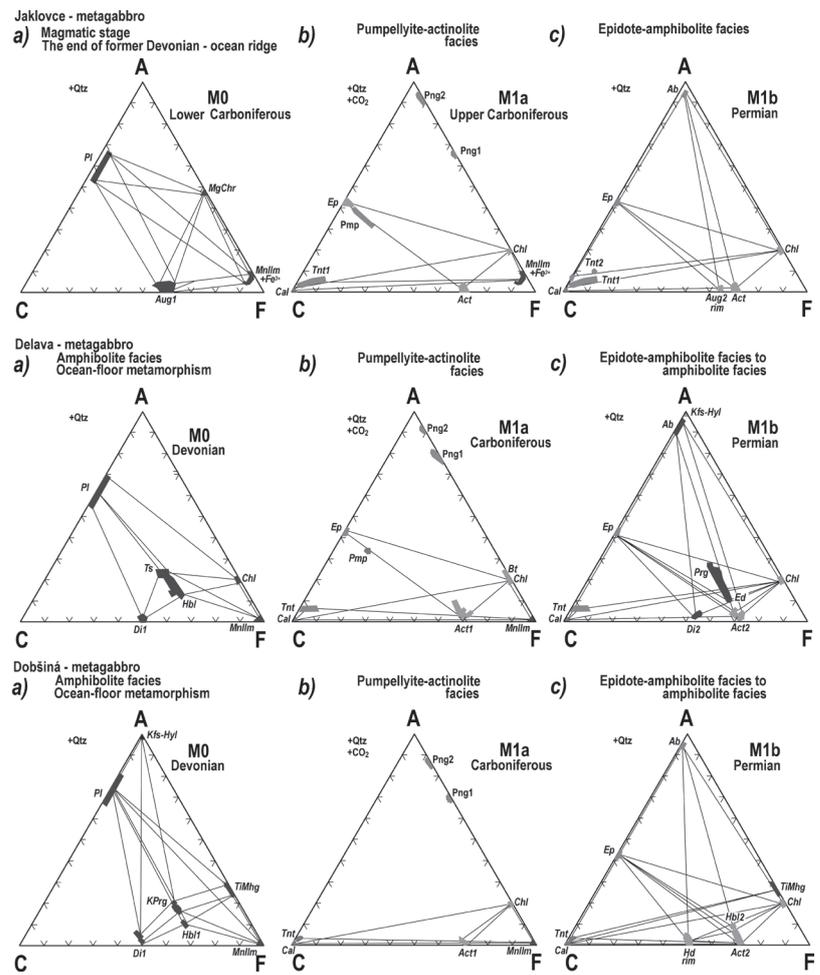


Fig. 43. Serpentinite in locality *Strážny vrch* hill. Older dark parallel foliation planes are infilled with talk.

and in new metamorphism actinolite originated at the rim of tremolite (Fig. 44a). The structural formula of tremolite and actinolite has a balance $Si(apfu) = 8$ (Fig. 46). According this mineral assemblage, the polymetamorphism of peridotite underwent in the P-T conditions firstly of the sub-facies/facies of green schists and later actinolite facies as equivalent of epidote-amphibolite facies (Spear, 1995). The metamorphogenic assemblage talc-tremolite-chlorite characterizes the komatiite replacement (Fig. 43).

Serpentinite at Klátov contains chrysotile, dolomite and Mg chlorite. From the former peridotite there were preserved the cores of chromite-1, containing Al. During metamorphism there originated the chromite-2. Both generations of chromite are replaced along the margins by metamorphogenic hematite (Figs. 47 and 48). From the process of hydration and polyphase metamorphism the older assemblage is dolomite, chromite-2 and Mg chlorite and younger is represented by chrysotile and hematite.

According to this mineral assemblage, the polymetamorphism of former peridotite took place in P-T conditions of the greenschist facies (Spear, 1995). Chemical classification of the whole-rock analyses of serpentinite are stated in Ch. 6.

5 Whole-rock chemical analyses of metamorphic rocks and geotectonic background of the origin of ophiolite suite protolith in Gemic unit

The lithotypes of the GAC (localities Klátov, Rudňany, Dobšiná), as well as the primary Cpx gabbro (localities of Jaklovce, Delava and Dobšiná) of the ophiolite suite were during polyphase metamorphism recrystallized to rocks with prevailing Ca amphiboles, epidote group minerals, chlorite, titanite and albite (cf. Chs. 1 and 3). Serpentinites of this suite were on the Strážny vrch hill recrystallized to mixture of talc, Mg chlorite and tremolite, at the Klátov

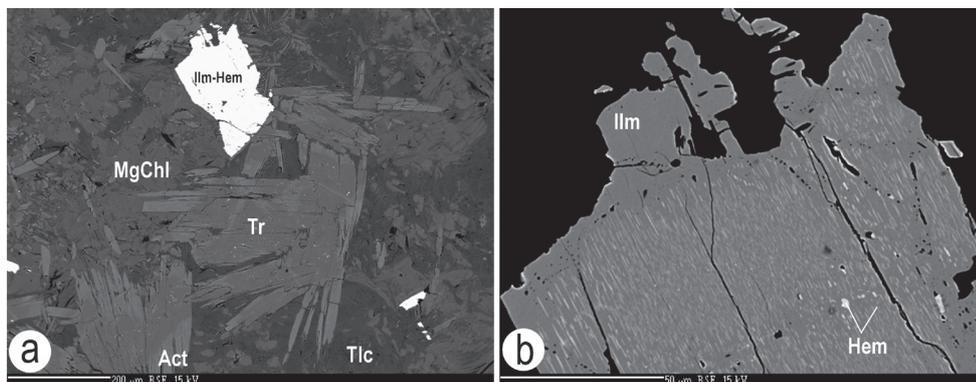


Fig. 44. Mineral assemblage of serpentinite on Strážny vrch hill. **a** - Tlc - talc, MgChl - Mg chlorite, Tr - tremolite, Act - actinolite, Ilm-Hem - ilmenite-hematite. **b** - Exsolution lamellas of hematite (Hem) in ilmenite (Ilm), detail of the grain in **a** - Ilm-Hem grain. Backscattered electrons.

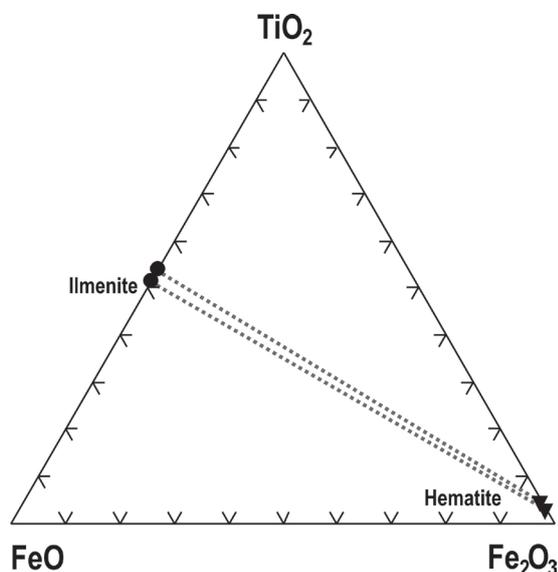


Fig. 45. Chemical classification of ilmenite and hematite in serpentinite. Locality Strážny vrch hill. The relation of oxides in presented in Fig. 44b.

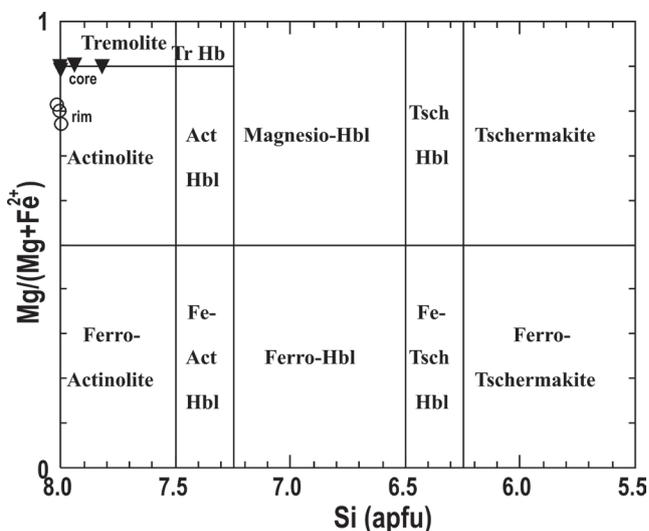


Fig. 46. Chemical classification of tremolite (core) and actinolite (rim) in serpentinite from the locality of the Strážny vrch hill. The relation of amphiboles see in Fig.44a.

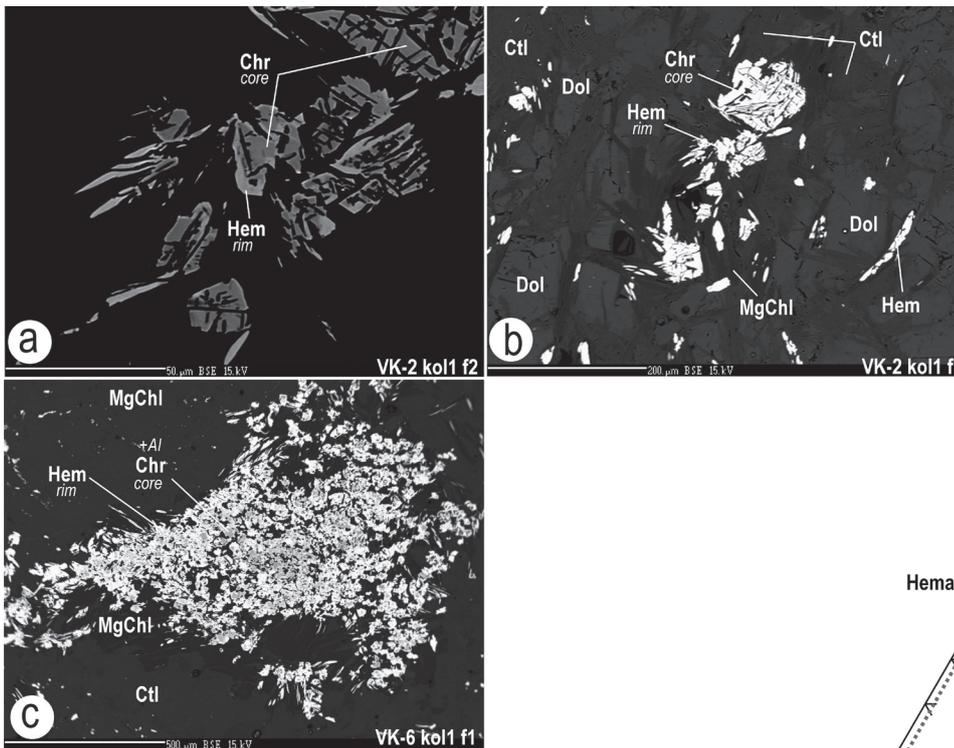


Fig. 47. Mineral assemblage of serpentinite from GAC at Klátov. **a** - Chromite (Chr) – second generation of spinel, at the margin it replaces hematite (Hem). **b** – Relation of chromite-hematite and association dolomite (Dol), Mg chlorite (MgChl) and chrysotile (Chl) in the matrix. **c** - Chromite with the content of Al – first generation of spinel, at margin it replaces hematite. Backscattered electrons.

the recrystallization products were chrysotile, dolomite and Mg chlorite (Ch. 4). In the case of GAC localities, the whole-rock analyses were applied on characteristic amphibolite samples. In metagabbro, the analysed part of rocks had preserved the primary magmatic clinopyroxene. In serpentinite, there were analysed samples with chrysotile, talc and tremolite, resp. with the assemblage chrysotile, dolomite and Mg chlorite. The whole-rock chemical analyses have contributed to decipher the geotectonic background of the origin of protoliths of GAC amphibolites, gabbro and serpentinite (Figs. 49-53).

According to normalized curves of REE; Table 2 immobile elements during metamorphism (IE) and chemical classification of rocks in Nb/Y vs. Zr/TiO₂ diagram (Winchester and Floyd, 1977), the primary gabbro and basalts - protoliths of amphibolites - crystallized in oceanic crust (Fig. 49). Normalization of elements (REE) and (IE) shows affinity of the primary basalt magma source to oceanic crust (Fig. 50). The long-time crystallization of the melt in the depth produced large porphyroblasts of diopside and augite, as well as Ca plagioclase in metagabbro. During subsequent polyphase metamorphism these former magmatic porphyroblasts suffered ductile deformation and became unstable (see mineralogical part), they rotated and changed to porphyroclasts of the mylonite (Ch. 3). Normalization of chemical composition on oceanic crust revealed that the metagabbro and amphibolites of the GAC are enriched in Ba, Pb, Zn and Cd due to crystallization of stratabound disseminated sulphidic mineralization of the

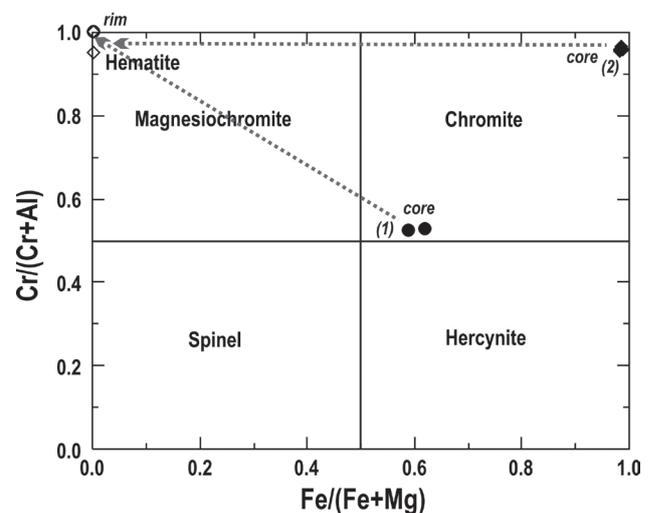
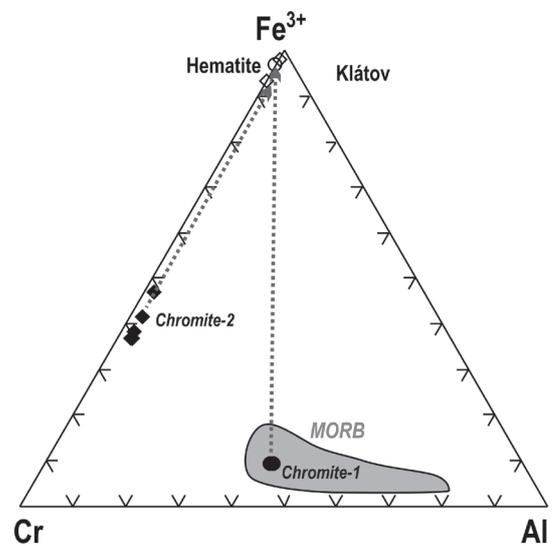


Fig. 48. Chemical classification of two generations of chromite (core) and hematite (rim) in serpentinite at Klátov. Relation of spinels and hematite see in Fig. 47.

Smolník type in the Early Paleozoic rift (Grecula et al., 2009, Radvanec and Grecula, 2016). The enrichment of metagabbro and amphibolites by B and Cs is a result of the last - Permian stage of the metagabbro and metabasalt polymetamorphism. The epidote-amphibolite to amphibolite facies of Permian metamorphism correspond with orogenic medium-pressure metamorphism with anatectic melting on the hot line (cf. Chs. 6 and 7). In Gemic unit this metamorphism has a regional reflection in common occurrence of tourmaline veinlets and the origin of S-type granite (Radvanec et al., 2009). Tourmaline represents a boron mineral.

Serpentinite, similarly as amphibolite and metagabbro of GAC, are enriched by Cu, Pb and B (Fig. 51). Serpentinite contains SiO₂ (34.7-47.5 wt.%), MgO (25.1-28.8 %), Na₂O + K₂O = 0.03, content TiO₂ is within the range of 0.03-0.56 % and ratio CaO/Al₂O₃ is 0.33-4.12. The TiO₂ content <1 %, sum Na₂O + K₂O <2 %, CaO/Al₂O₃>1 and SiO₂ range (30-52 %) characterize this ultramafic rock as komatiite/metakomatiite (Le Bas, 2000). Komatiites represent volcanic, eventually hypoabyssal rocks. Known komatiite occurrences are always metamorphosed

and occur in Archean terranes. Because the temperature of komatiitic melts reached values above 1400°C and more, and recently such hot melts cannot generate due to the lower temperature gradient in the lithosphere.

According to chemical composition, the protolith of serpentinite – the “high-temperature (HT)” metaperidotite, being investigated by us, is corresponding with komatiite or layered dykes with a high Mg content (Fig. 51). The course and normalized REE contents show that serpentinite in locality of Strážny vrch hill has the same characteristics as chondrite depleted in Eu and Tm (sample from the Strážny vrch, Fig. 52). The normalization of the REE contents at the same time clearly indicates the origin of HT-peridotite – komatiite in the primitive mantle (Figs. 51 and 52). The occurrence of serpentinite in locality Klátov in the same body with amphibolite is in good agreement with the common geotectonic background of their primary andesite-basalt magma and primary HT-peridotite–komatiite magma. Gabbro crystallized in the depth of the rift zone, but the HT-peridotite–komatiite magma (serpentinite) and basalt of the GAC (amphibolite) were solidified on the sea floor. So these rocks are members of the Paleozoic

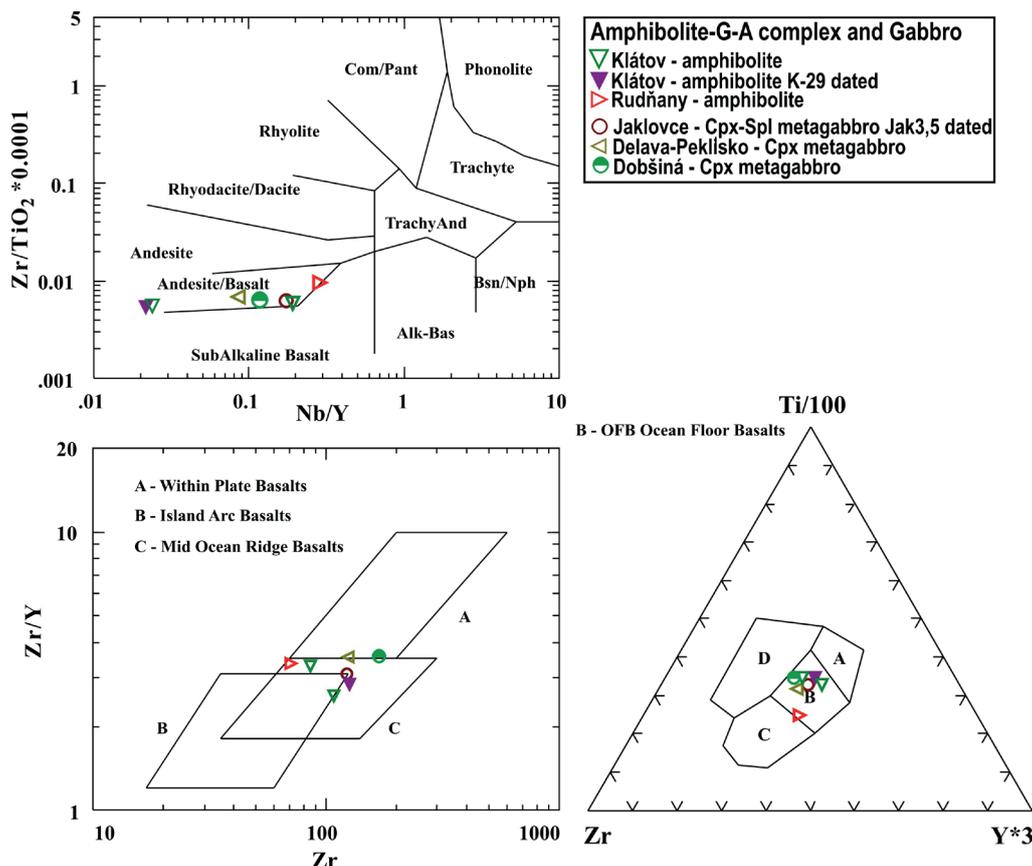


Fig. 49. Classification of the whole-rock analyses of amphibolites from GAC and metagabbros from the Devonian-Early Carboniferous ophiolite suite of Gemic unit. The protolith of amphibolites and gabbros was represented by the melt of basalt-andesite composition, generated in various depths of mid-ocean rift.

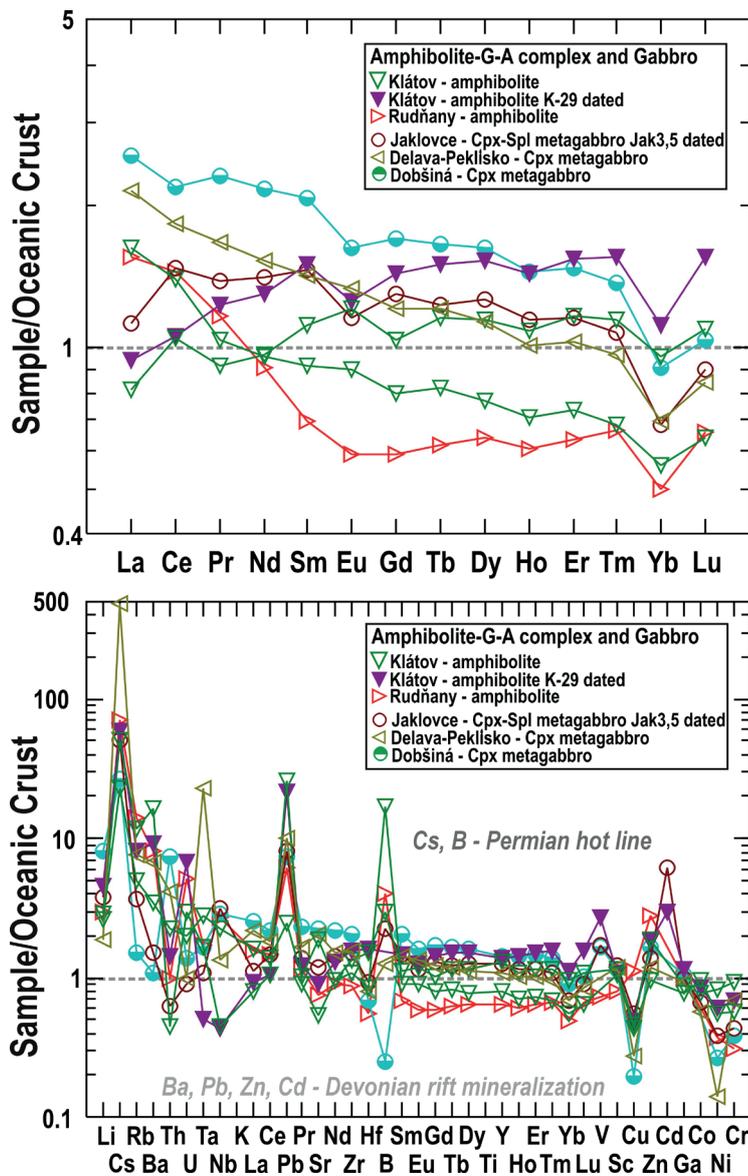


Fig. 50. The REE contents and model of immobile elements (IE) are normalized on the contents of the oceanic crust according to Boynton (1984) as well as Sun and McDonough (1989). Amphibolites from GAC and metagabbros belong to the Early Paleozoic ophiolite suite of Gemic unit. Anomalous Ba, Pb, Zn and Cd contents indicate the influence of crystallization of the stratabound sulphidic mineralization of the Smolnik type from the dark and light chimneys in the Devonian-Early Carboniferous oceanic rift. The Cs and B anomalies indicate the metamorphism on the hot line, producing **M1b** recrystallization of amphibolite and metagabbro in Permian.

metamorphism **M0** of oceanic floor is documented by the hornblende cooling age 362 Ma (Fig. 54). Later metamorphic recrystallization of the pumpellyite-actinolite facies is related to compressional Variscan orogenic stage **M1a** individualizing tectonic blocks of metaophiolite suite in Late Carboniferous (around 300 Ma). During Permian metamorphism **M1b** (275-258 Ma) the tectonic blocks underwent recrystallization in the epidote-amphibolite facies to amphibolite facies at medium pressure (Fig. 52). This metamorphism on the hot line was accompanied with the origin of anatectic granite of S-type and corresponding volcanism on the surface (Radvanec et al., 2009, 2010; Radvanec and Grecula, 2016). The youngest metamorphic overprint **M2** in the greenschist facies is the result of Alpine orogenic processes (Fig. 54).

The Cpx-metagabbro is a part of metaophiolite suite and according to mineral assemblages and ACF diagrams it was metamorphosed gradually and correspondingly with metapelite/metasediment to amphibolite (Fig. 54). The metagabbro has preserved the primary magmatic diopside, augite and other minerals (cf. Ch. 3).

Serpentinite - former peridotite with Cr-spinel and ilmenite, being a part of the metaophiolite suite, has also underwent the polyphase metamorphism correspondingly with Cpx-gabbro and metapelite/metasediment to amphibolite. During the polyphase metamorphism the original Mg silicates of peridotite (olivine and pyroxenes) were as the first changed to talc and Mg chlorite. In this earlier metamorphism there crystallized tremolite and later at the margin of tremolite there crystallized actinolite (cf. Ch. 4). The hydration or metamorphism of peridotite took part gradually and correspondingly as in metapelite/metasediment to amphibolite and Cpx-gabbro. At the earliest stage it was at P-T conditions of the sub-facies to facies of greenschists and later in the equivalent of the epidote-amphibolite facies (cf. Spear, 1995). Assemblage of the greenschists facies minerals originated in the metaperidotite/

ophiolite suite of Gemic unit, having their origin in the mantle and reaching the surface of the mid-oceanic rift in the period of Upper Devonian to Lower Carboniferous (Figs. 51 and 52, Ch. 7).

6 Metamorphic P-T-t path of the ophiolite suite of Gemic unit and its relation with tectonics

The P-T-t path summarizes the results of mineralogical-petrological investigation of polyphase metamorphism of the protolith of ophiolite suite (Fig. 54; cf. Chs. 1-5). According to found mineral assemblages and CFA diagrams, the metapelite/metasediment to amphibolite (GAC) was metamorphosed gradually. First - Late Devonian to Early Carboniferous low-pressure amphibolite facies me-

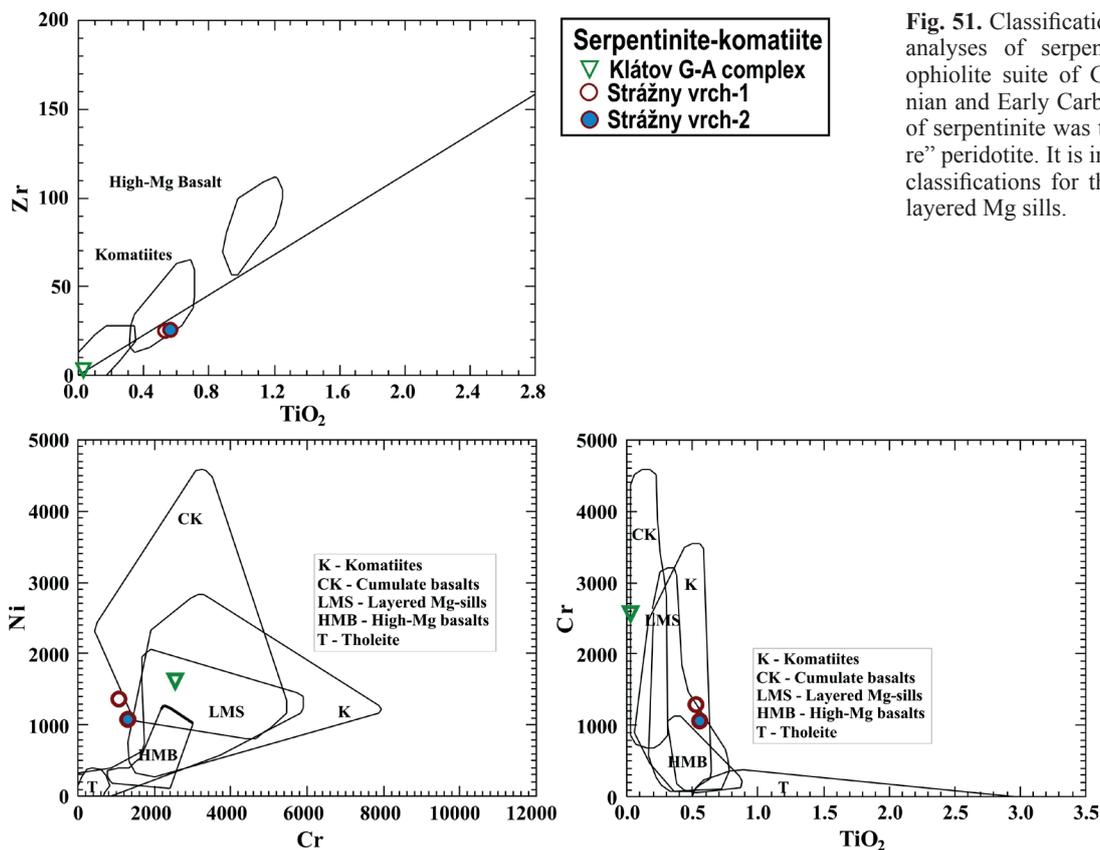
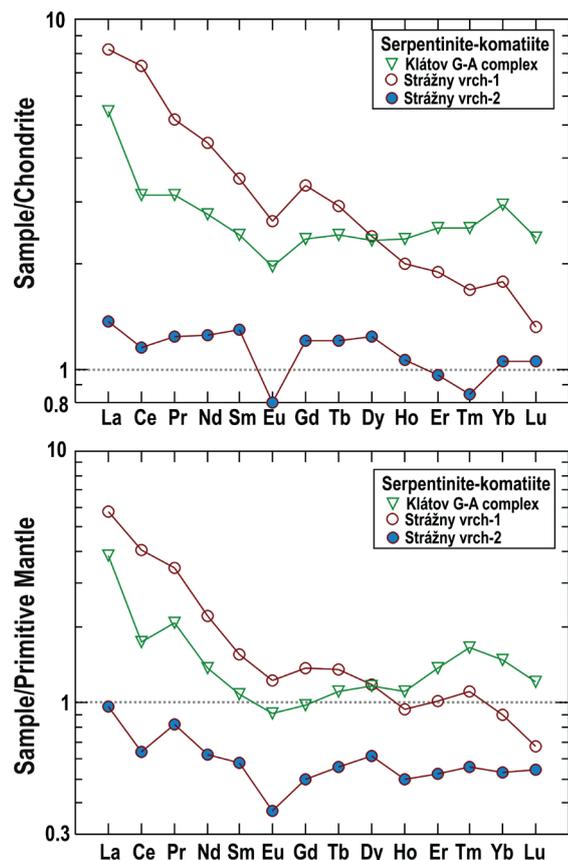


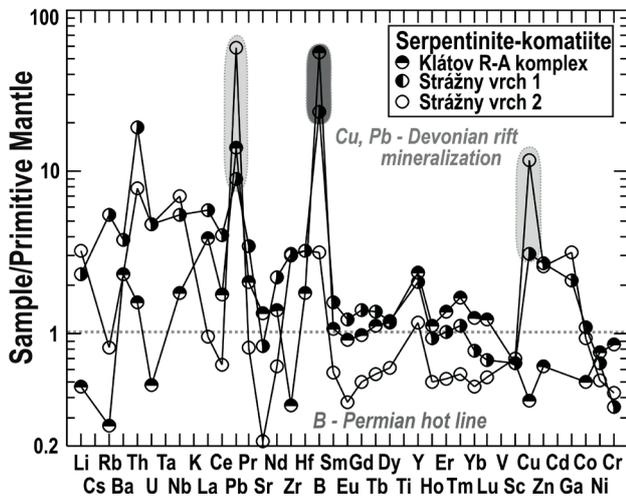
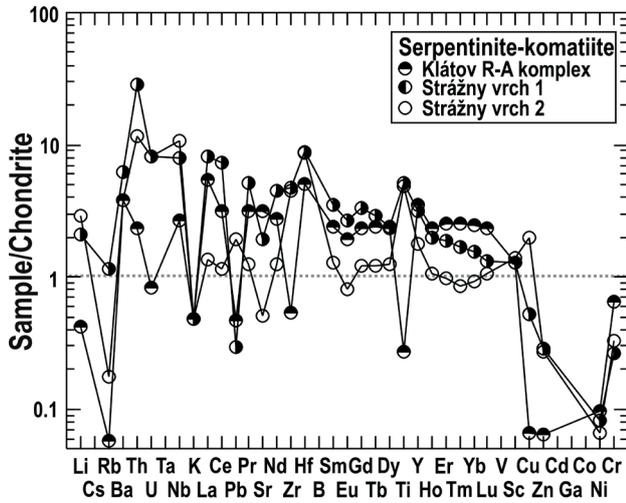
Fig. 51. Classification of the whole-rock analyses of serpentinite of Paleozoic ophiolite suite of Gemic unit (Devonian and Early Carboniferous). Protolith of serpentinite was the “high-temperature” peridotite. It is indicated by chemical classifications for the komatiite field or layered Mg sills.



serpentinite at **M0** metamorphic conditions and the equivalent of the epidote-amphibolite facies at P-T conditions of the **M1b** metamorphism. The equivalent of pumpellyite-actinolite facies metamorphism **M1a** was not revealed in metaperidotite/serpentinite. The reason is in stability of talc and Mg chlorite from **M0** in P-T conditions of pumpellyite-actinolite facies **M1a**. The gradual peridotite hydration or metamorphism took part correspondingly as in the case of further rocks of the metaophiolite suite (Fig. 54).

In the meso-scale (Fig. 55), correspondingly with the microtectonic results (cf. Fig. 18d), the Variscan tectogenesis is represented with **VD_{1a}** deformation stage, representing in the Klátov body thrusting towards the SW in P-T conditions of the **M1a** metamorphic stage. Unroofing kinematics to NE during **VD_{1b}** (**M1b**) stage was later switched to SW-trending ductile sliding (**VD₂** close to the end of **M1b** stage). Because numerous rock blocks, incl. outcrops were mainly during the Alpine **AD₃** stage rotated, but described overprinting relations were preserved - though in rotated azimuth orientation - we completed them in the tectonogram **VD_{1-2 rot.}** Additionally we must emphasize that the primary Paleozoic rifting stage (**VD₀** - **M0**) was

Fig. 52. Contents of REEs are normalized to chondrite and primitive mantle according to Boynton (1984), as well as Sun and McDonough (1989).



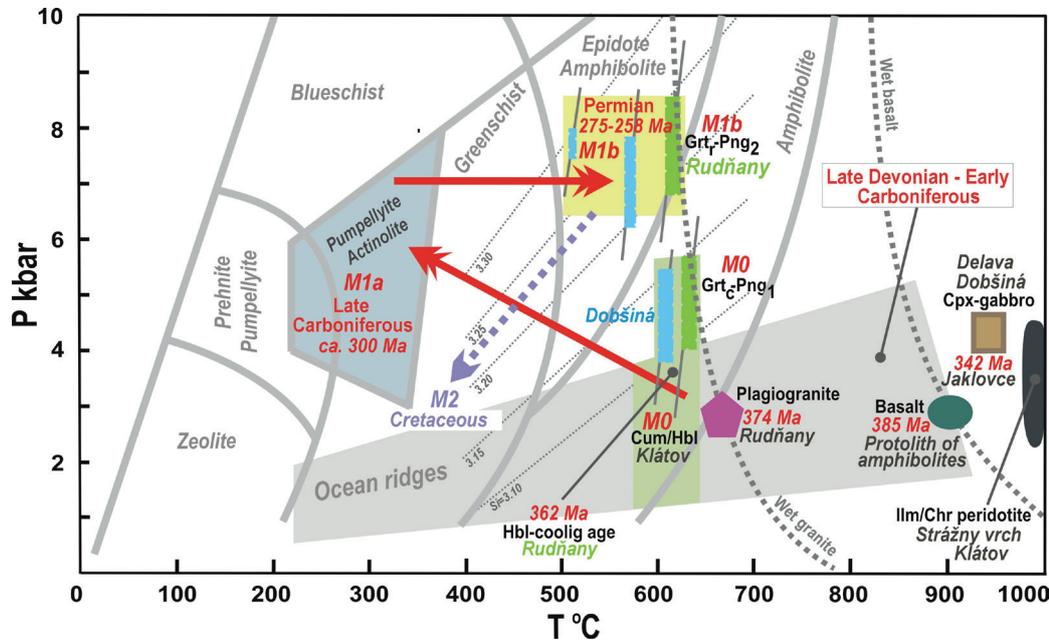
not reliably documented by relevant planar or linear structures (mainly due to later overprint in VD_{1b} - $M1b$), so we did not visualize it in Fig. 55.

The Alpine deformation stages in the *Klátov* body encompass NE-vergent thrusting (AD_1), subsequent Alpine SW-SSW-vergent unroofing (AD_2) and AD_3 subhorizontal shearing along the conjugate system of shear zones trending NW-SE (dextral; dominating in the *Klátov* body) and NE-SW (sinistral). Recently there was distinguished a new deformation phase AD_4 , encompassing the pure shear faults with vertical trend of displacement (uplifts, subsidences).

The geotectonic background of processes producing the successive metamorphic events $M0$, $M1a$, $M1b$, $M2$, as well as deformation events VD_0 , VD_{1a} , VD_{1b} , VD_2 , AD_1 , AD_2 , AD_3 and AD_4 is described in details in papers by Radvanec and Grecula (2016) so we will not treat with it in this study.

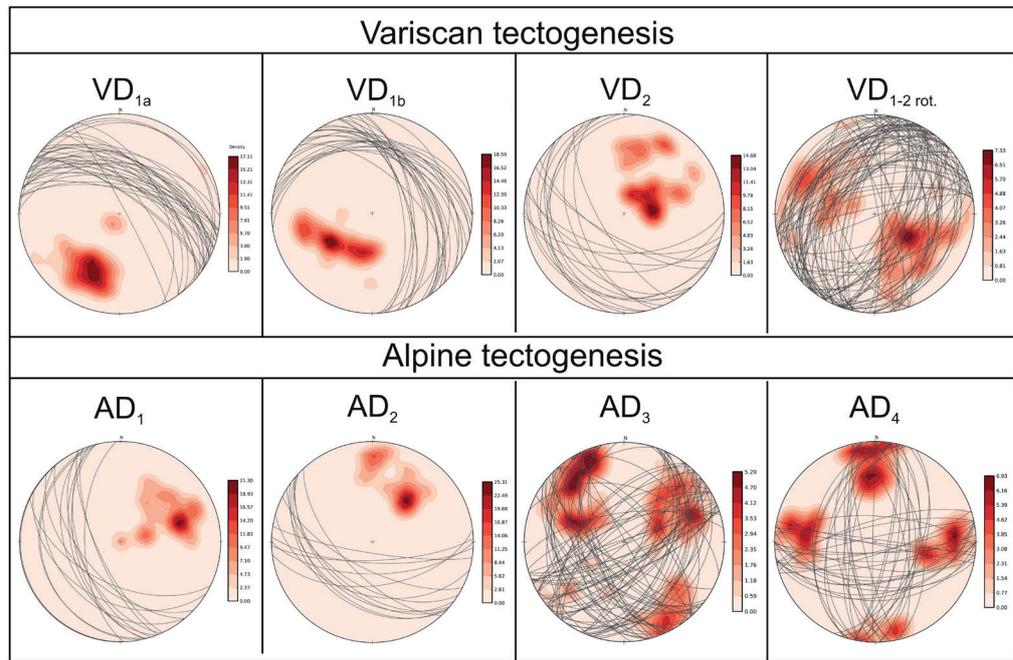
Fig. 53. Contents of REEs and model of immobile elements (IE) are normalized to chondrite and primitive mantle according to Boynton (1984), as well as Sun and McDonough (1989).

Fig. 54. P-T-t path of the polyphase metamorphism of the rocks of ophiolite suite (amphibolite, Cpx-gabbro, plagiogranite, peridotite) and metapelite/metasediment in investigated localities. The ages of plagiogranite, basalt and Cpx-gabbro represent the ages of magmatic zircon from magmatic pre-metamorphic protoliths from the Upper Devonian to Lower Carboniferous (Putiš et al., 2009a). $M0$ – the ocean floor metamorphism in amphibolite facies with the cooling age of the hornblende 362 Ma. Grt_c-Png₁-garnet (core) vs. phengite-1 – phengite thermometer (Green and Hellman, 1982) in combination with the phengite barometer ($Si = XX$, isolines, Massone and Schreyer, 1987); Cum/Hbl – cumingtonite-hornblende thermometer.



$M1a$ – pumpellyite-actinolite facies with interpreted emplacement of metaophiolite suite around 300 Ma, Late Carboniferous. $M1b$ – epidote-amphibolite facies to amphibolite facies 275-258 Ma, Permian. Grt_r-Png₂ - garnet (rim) vs. phengite-2 – phengite thermometer in combination with phengite barometer. $M2$ – greenschists facies of the Alpine orogeny, Cretaceous. Ilm – ilmenite, Chr – chromite. Metamorphic facies according to Spear (1995), cf. Chs. 1-5.

Fig. 55. Spatial orientation of the outcrop scale planar structures from the *Klátov* metaophiolite block, divided according to overprinting relation and the ductility of deformation. Each tectonogram shows great circles of the planes of individual deformation stages (Variscan VD_{1a} , VD_{1b} , VD_2 and those from rotated outcrops $VD_{1-2\text{ rot.}}$; as well as Alpine AD_1 , AD_2 , AD_3 and AD_4 ; Schmidt projection), as well as contours of poles of these planes (red girdles). For further details see text.



7 Conclusions

The presented study manifested the existence of Variscan dismembered ophiolite suite in the northern zone of Gemeric unit of the Western Carpathians (in so-called North Gemeric zone). This ophiolite-bearing zone is interpreted as one segment of elongated Paleozoic branch of Paleo-Tethys ocean within the disintegrating Paleozoic supercontinent. This former segment of Paleozoic mid-ocean ridge of Paleo-Tethys consists of variegated lithology, occurring now in three principal localities of the gneiss-amphibolite complex (GAC) in the Gemeric unit (Western Carpathians) - the *Dobšiná*, *Rudňany* and *Klátov* localities. Additional smaller occurrences at *Jaklovce*, *Delava* and *Dobšiná* (Cpx metagabbro) and the *Strážny vrch* hill (serpentinite) were recently also added to this suite.

The Paleozoic ophiolite suite in Gemeric unit is built of six polymetamorphosed principal rock types: (1) gneiss with garnet (Alm+Pl+Bt+Ms+Qtz+Act+Chl) and graphite (occurrences at *Dobšiná* and *Rudňany*), (2) plagiogranite (Kfs+Ab+Pl+Ms+Bt+Qtz+Zo+Cal; $^{87}\text{Sr}/^{86}\text{Sr} = 0.7033$; age 374 Ma; *Rudňany*), (3) gneiss with amphibole porphyroclasts (Cum-Hbl/Prg-Act) and graphite (*Klátov*), (4) amphibolite (Pl+Hbl+Tnt+Ap+Pmp+Ilm+Act+Ep+Chl; *Klátov*, *Rudňany*, *Dobšiná*); (5) serpentinite (Chl+Dol+Ctl+CrSpl+Hem; *Klátov*, *Strážny vrch* hill); (6) metagabbro (Di+Aug+CrSpl+Pl+Hbl/Prg-KPrg-Act+Ep+Qtz+Tnt+Chl+MnIlm+Tnt+Ap+Zrn+Png+Ab+Hyl, *Jaklovce*, *Delava*, *Dobšiná*).

The suite of above listed rocks underwent a multi-stadial tectono-metamorphic overprint. First - Late Devonian

to Early Carboniferous low-pressure amphibolite facies metamorphism **M0** (deformation stage VD_0) of ocean floor is documented by the hornblende cooling age 362 Ma. Later metamorphic recrystallization of the pumpellyite-actinolite facies is related to compressional Variscan orogenic stage **M1a** (VD_{1a}) affecting the metaophiolite suite in Late Carboniferous (around 300 Ma). During Permian metamorphism **M1b** (VD_{1b}), the tectonic blocks of metaophiolite suite underwent recrystallization in the epidote-amphibolite facies to amphibolite facies by the input of heat at medium pressure. This metamorphism on the hot line was accompanied with the origin of anatectic granite of S-type and corresponding volcanism on the surface. The youngest metamorphic overprinting **M2** (AD_2) in the greenschist facies is the result of Alpine orogenic processes.

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Supplement 1. Whole-rock analyses of principal rock types of the Paleozoic metaophiolite suite in Gemic unit. The whole-rock analyses were done by the Geoanalytical laboratories of the State Geological Institute of Dionýz Štúr, Spišská Nová Ves.

Rock	Amphibolite	Amphibolite	Amphibolite	Amphibolite	Gabbro	Gabbro	Gabbro	Serpentinite	Serpentinite	Serpentinite	Plagiogramite
Locality	Klátov	Klátov	Klátov	Rudňany	Dobšiná	Jaklovce	Delava	Strážny vrch1	Strážny vrch2	Klátov	Rudňany
SiO ₂	49.75	48.60	46.50	58.00	47.10	48.70	51.10	38.70	47.50	34.70	75.70
TiO ₂	2.32	1.92	1.45	0.74	2.76	1.99	1.79	0.56	0.53	0.03	0.07
Al ₂ O ₃	12.22	13.30	14.80	14.00	13.80	13.90	15.50	5.01	5.65	1.78	13.00
Fe ₂ O ₃	15.70	13.60	12.80	8.72	14.50	12.60	10.30	15.40	11.60	8.65	0.86
MnO	0.28	0.23	0.17	0.17	0.18	0.02	0.17	0.20	0.15	0.18	0.02
MgO	7.32	9.03	7.81	5.29	6.20	6.63	6.89	27.80	25.10	28.80	0.35
CaO	7.55	7.13	11.10	5.25	8.88	8.77	7.42	1.68	2.66	7.33	1.51
Na ₂ O	2.26	2.80	2.30	4.00	3.20	3.90	4.60	0.20	0.20	0.20	5.10
K ₂ O	0.33	0.73	0.47	0.85	0.08	0.34	0.60	0.05	0.05	0.05	1.85
P ₂ O ₅	0.22	0.19	0.19	0.08	0.24	0.20	0.20	0.06	0.07	0.07	0.01
LOI		2.26	2.11	2.71	2.62	4.17	1.23	10.10	6.27	17.90	1.28
Ba	226	406	86	202	27	38	167	21	13	13	561
Rb	18	26	11	30.6	3.3	8	17	4	0.6	0.2	87.17
Sr	119	71	248	97	295	157	267	23	6	37	91
Cs	1.75	1.52	0.68	2.11	0.8	1.52	14.6	0.64	0.15	0.19	5.81
Li	45	29	26	30	82	38	19	5	7	1	6
Ga	20	15	13	17	18	17	16	8	12		16
Tl	0.11	-	-	-	-	-	-	-	-	-	0.49
Ta	0.15	0.5	0.84	0.52	0.5	0.33	6.96	0.92	0.7	0.31	1.01
Nb	1	1	5	6	6.3	7	3	3	4	1	4
Hf	4.09	3.8	2.1	1.37	1.7	2.36	2	0.9	0.9	0.5	2.32
Zr	127	108	86	71	167	123	124	26	25	3	61
Y	45	42	26	21	45.7	40	35	7	4	8	4.36
Th	0.31	0.1	0.5	0.22	1.61	0.14	0.9	1.2	0.5	0.1	1.62
U	0.68	0.3	0.2	0.51	0.14	0.09	0.1	0.1	0.1	0.01	2.77
Cr	186	251	155	84	103	116	183	1064	1292	2559	16
Ni	82	112	74	51	36	52	19	1368	1078	1611	10
Co	40	36	45	25	28	31	27	114	98	52	12
Sc	42	44	40	30.32	44.3	46.7	45	11	12	11	0.12
V	667	433	341	185	415	427	309	71	72	53	11
Cu	43	40	37	95	17	48	24	88	334	11	27
Pb	17	20.6	2	5	6	6.49	8.1	1.8	7	0.98	12
Zn	156	161	82	237	140	118	102	132	125	30	26
B		12	68	16	1	9	5	14	1.9	33	36
La	3.47	3.00	6.00	5.74	9.45	4.17	8.00	3.00	0.50	2.00	1.30
Ce	12.16	12.00	16.00	16.71	25.30	17.00	21.00	7.00	1.10	3.00	1.78
Pr	2.21	1.64	1.86	2.09	4.18	2.50	3.01	0.71	0.17	0.43	0.18
Nd	12.95	9.61	9.56	9.02	21.70	14.10	15.30	3.16	0.89	1.97	0.68
Sm	4.93	3.68	3.01	2.30	6.83	4.84	4.71	0.81	0.30	0.56	0.21
Eu	1.63	1.57	1.17	0.77	2.12	1.50	1.74	0.23	0.07	0.17	0.30
Gd	6.61	4.77	3.68	2.72	7.84	5.95	5.57	1.02	0.37	0.72	0.31
Tb	1.31	1.00	0.71	0.54	1.44	1.07	1.05	0.17	0.07	0.14	0.07
Dy	8.72	6.54	4.40	3.64	9.32	7.20	6.46	0.91	0.47	0.89	0.58
Ho	1.87	1.41	0.92	0.79	1.88	1.49	1.31	0.17	0.09	0.20	0.13
Er	5.69	4.31	2.72	2.36	5.45	4.29	3.81	0.47	0.24	0.63	0.51
Tm	0.84	0.62	0.37	0.36	0.74	0.58	0.52	0.06	0.03	0.09	0.09
Yb	5.66	4.88	2.86	2.54	4.62	3.50	3.55	0.44	0.26	0.73	0.91
Lu	0.87	0.61	0.36	0.37	0.58	0.50	0.47	0.05	0.04	0.09	0.15

Supplement 2. Representative microprobe analyses of minerals of the Paleozoic metaophiolite suite in Gemic unit related to individual metamorphic stages.

Locality	Rock	Mineral	Met. event	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	Total
Dobšiná	GAC	Grt-core	M0	36.99	0.00	21.45	0.01	32.18	4.06	4.56	1.27	0.02	0.00	100.53
Dobšiná	GAC	Grt-rim1	M0	37.78	0.00	21.29	0.00	26.63	7.30	2.85	4.36	0.00	0.00	100.21
Dobšiná	GAC	Grt-rim2	M1b	37.43	0.00	20.59	0.00	19.45	11.31	0.92	9.89	0.00	0.00	99.59
Rudňany	GAC	Grt-core	M0	37.22	0.08	21.36	0.00	30.13	4.68	4.95	1.56	0.00	0.00	99.98
Rudňany	GAC	Grt-rim1	M0	37.38	0.30	20.48	0.00	29.33	1.58	3.62	6.92	0.00	0.00	99.61
Rudňany	GAC	Grt-rim2	M1b	37.42	0.17	21.11	0.00	23.32	6.69	1.28	10.08	0.00	0.00	100.07
Dobšiná	GAC	Bt	M1b	35.16	1.94	17.69	0.00	21.73	0.30	9.36	0.03	0.23	9.06	95.50
Rudňany	GAC	Bt	M1b	36.36	2.05	17.09	0.00	20.26	0.16	10.41	0.00	0.25	9.74	96.32
Rudňany	Granite	Bt	M1b	46.54	0.04	24.65	0.02	8.68	0.10	4.07	0.04	0.08	10.76	94.98
Delava	GAC	Bt	M1a	37.43	1.38	16.49	0.03	13.15	0.07	16.15	0.15	0.03	9.14	94.02
Jaklovec	Gabro	Cpx1	M0	50.37	1.24	2.49	0.00	12.94	0.42	12.88	18.42	0.41	0.00	99.17
Jaklovec	Gabro	Cpx2	M1b	48.54	1.75	2.23	0.07	19.73	0.49	6.12	20.78	0.50	0.00	100.21
Delava	Gabro	Cpx1	M0	51.72	0.76	2.36	0.43	6.24	0.14	16.45	21.24	0.27	0.01	99.62
Delava	Gabro	Cpx2	M1b	52.26	0.05	0.20	0.00	12.42	0.88	10.42	23.46	0.27	0.00	99.96
Dobšiná	Gabro	Cpx1	M0	51.14	0.12	0.97	0.00	13.23	0.32	9.95	23.35	0.32	0.01	99.41
Dobšiná	Gabro	Cpx2	M1b	50.80	0.14	0.57	0.00	18.41	0.45	6.31	22.33	0.00	0.00	99.01
Dobšiná	GAC	Pmp	M1a	38.23	0.06	25.54	0.00	3.14	0.12	2.81	23.46	0.08	0.00	93.44
Jaklovec	Gabro	Pmp	M1a	36.99	0.04	23.87	0.00	6.37	0.15	1.85	22.01	0.11	0.02	91.41
Delava	Gabro	Pmp	M1a	38.25	0.08	24.56	2.87	0.03	0.18	4.34	22.56	0.05	0.08	93.00
Klátov	GAC	Png1	M0	47.73	0.01	35.79	0.00	0.63	0.00	0.93	0.02	0.13	10.57	95.81
Klátov	GAC	Png2	M1b	49.72	0.02	30.84	0.00	1.71	0.04	2.33	0.03	0.28	10.08	95.05
Rudňany	GAC	Png1	M0	47.20	0.13	34.93	0.00	0.55	0.00	0.33	0.00	0.98	10.31	94.43
Rudňany	GAC	Png2	M1b	49.43	0.18	26.71	0.00	4.45	0.09	2.88	0.00	0.07	10.14	93.95
Rudňany	Granite	Png1	M0	45.52	0.04	32.56	0.00	5.27	0.02	0.35	0.01	0.25	10.66	94.68
Rudňany	Granite	Png2	M0	45.94	0.05	35.00	0.00	2.67	0.05	0.23	0.02	0.23	10.79	94.98
Dobšiná	GAC	Png1	M0	46.94	0.64	33.59	0.00	1.46	0.00	1.41	0.00	0.95	10.11	95.10
Dobšiná	GAC	Png2	M1b	47.06	0.33	26.02	0.00	5.67	0.11	4.33	0.22	0.23	10.71	94.68

Fragmenty variskej metaofiolitovej suity Paleotetýdy v gemeriku

Do metaofiolitovej suity staršieho paleozoika gemerika patria amfibolity, ktoré sa striedajú s rulami (metapelit-metasepilit s grafitom) na severnom okraji gemerika v pruhu od Dobšinej cez Rudňany po Klátov (obr. 1 až 4). Na týchto troch lokalitách je rulovo-amfibolitový komplex v samostatných tektonických blokoch (Popreňák et al., 1973; Grecula a Dianiška, 1977; Dianiška a Grecula, 1979; Grecula, 1982; Grecula a Kucharič, 1985, 1989; Grecula et al., 2009; Spišiak et al., 1985; Hovorka et al., 1979, 1984; Faryad, 1986; Radvanec, 1992, 1994a, 1994b; Hovorka a Spišiak, 1981; Spišiak a Hovorka, 1985; Hovorka a Spišiak in Cambel et al., 1985; Hovorka et al. in Hurný, 1982; Pramuka, 1985, 1985b, 1986; Rozložník, 1965; Bajanič a Hovorka, 1981; Hovorka a Ivan, 1985). Okrem týchto tradičných lokalít sa do metaofiolitovej suity zaradili nové lokality klinopyroxenických (Cpx-) gabier a serpentinitov (obr. 1).

Vzorky z metaofiolitovej suity (rulovo-amfibolitový komplex; R-A komplex) na lokalitách Dobšiná, Rudňany, Klátov, Strážny vrch, Jaklovce a Delava sa odobrali z odkryvov, vrtovej a banských diel. Z týchto vzoriek sa robili leštené výbrusy a vyseparoval sa z nich zirkón na jeho datovanie v rámci spolupráce s PriF UK v Bratislave (prof. M. Putiš). Zo vzoriek sa urobili objemové chemické analýzy v geoanalytických laboratóriách ŠGÚDŠ v Spišskej Novej Vsi. Minerály sa študovali v odrazených elektrónoch (BSE) a chemické analýzy minerálov sa robili mikroanalýzatorom CAMECA SX 100 v Geologickom ústave Dionýza Štúra v Bratislave (tab. 1 a 2).

Postupné metamorfogénne minerálne asociácie M0 – metamorfóza oceánskeho dna, M1a – pumpellyitovo-aktinolitová fácia a M1b – epidotovo-amfibolitová až amfibolitová fácia s chemickými klasifikáciami minerálov R-A komplexu sú na obrázkoch 5 až 18 a 18b. Vzťah mikroštruktúrnej vnútornej stavby R-A komplexu v postupnom štruktúrnom vývoji je na obr. 18c. Duktilná deformácia metamorfózneho štádia M0 je zmenená na deformáciu s nižším stupňom duktility v štádiu M1a a následne opäť na duktilnú deformáciu M1b v úplnej zhode a s postupným metamorfogénnym vývojom R-A komplexu. Rovnaká postupnosť minerálnych asociácií a rovnaké metamorfózne fácie sa zistili v Cpx-metagabrách na lokalitách Jaklovce, Delava a Dobšiná (obr. 26 až 42). Serpentinity metaofiolitovej suity sa zistili na lokalitách Suchý vrch a Klátov (obr. 1). Rovnako ako horniny R-A komplexu a Cpx-gabrá sú polyfázovo metamorfované (obr. 43 až 46). Serpentinit obsahuje postupné asociácie tremolit – talk a mladšiu asociáciu chryzotil – Mg-chlorit – aktinolit. Serpentinity majú

celohorninové komatiitové charakteristiky (obr. 51 až 53). Protolity R-A komplexu a metagabrá sú klasifikované ako horniny stredoocéánskych chrvtov (obr. 49 až 51).

V R-A komplexe na lokalite Rudňany sa zistil plagiogranit. Vznikol anatektickým tavením MORB-protolitu blízko eutektického bodu 650 °C a bol odtavený z hornín (bazalt, peridotit) plášťa. Izotopový pomer plagiogranitu $^{87}\text{Sr}/^{86}\text{Sr} = 0,7033$ a jeho vek je $374,5 \pm 4$ mil. rokov (obr. 20). Granitová tavenina nebola úplne ekvilibrovaná s okolitým hornblendom (amfibolitom), čo indikuje $^{87}\text{Sr}/^{86}\text{Sr} = 0,7051$, keď sa hornblend v Rb-Sr minerálnej izochróne zahrnie do hodnôt lineárnej regresie minerálov granitu (plagioklas – K-živec1 – K-živec2 – biotit). Podľa izotopových pomerov $^{40}\text{Ar}/^{39}\text{Ar}$ hornblend v amfibolite obklopujúcom plagiogranit zaznamenal jeho chladnutie pri teplote okolo 550 °C v období $362,5 \pm 5$ mil. rokov. Tieto údaje dobre charakterizujú metamorfózne podmienky nízkotlakovej a vysokoteplotnej amfibolitovej fácie M0 oceánskeho dna v staropaleozoickom rifte (Radvanec a Grecula, 2016).

Polyfázová metamorfóza metaofiolitovej suity staršieho paleozoika najprv prebiehala v P-T podmienkach nízkotlakovej amfibolitovej fácie a anatektickým tavením M0 v oceánskom rifte v období devón až spodný karbón. Potom boli tieto horniny vo vrchnom karbone obdukované a metamorfované v pumpellyitovo-aktinolitovej fáci M1a a v perme variského orogénu dosiahla polymetamorfóza podmienky strednotlakovej epidotovo-amfibolitovej až amfibolitovej fácie M1b. Permské preteplenie zaznamenal hornblend v bezprostrednom okolí plagiogranitu (obr. 20e a 54). Alpínsky orogén je zaznamenaný vznikom chloritu, pričom časť odkryvov R-A komplexu, a to predovšetkým v klátovskej oblasti, bola postihnutá rotáciou v pravostrannej strižnej zóne deformačného štádia AD₃ (obr. 55).

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