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COMPARATIVE MINERALOGICAL-PETROGRAPHICAL CHARACTERISTICS OF METAGABBRO FROM BOREHOLE KV-3 NEAR ROCHOVCE AND OF AMPHIBOLITES OF HLADOMORNÁ VALLEY FORMATION (SLOVENSKÉ RUDOHORIE MTS.)

(Figs. 11, Tabs. 6)

Abstract: In the presented paper, comparative petrographical features and the mineralogy of Hladomorná Valley Formation amphibolites and of metagabbros from the borehole KV-3 near Rochovce are investigated. Metamorphic parageneses of both basite types are of the same type and they are represented by greenish or colourless hornblende, biotite, clinozoisite, chlorite and oligoclase. On the basis of microprobe analyses we have studied the evolution of the composition of hornblendes and biotites in the process of substitution of magmatic minerals by metamorphic ones A permanent interruption in the miscibility of metamorphic Ca-amphiboles (actinolite and aluminous hornblende) has been determined as well as their coexistence in homoaxial intergrowths The similarity of mineral composition and parageneses in amphibolites and metagabbros point to a coincidence of P—T parameters of their metamorphism.

Резюме: Изучены сравнительные петрографические особенности и минералогия амфиболитов из серии Хладоморной долины, и метагаббро из скважины KV-3 близ Роховце. Метаморфические парагенезисы обеих типов базитов однотипны, и представлены зеленоватой или бесцветной роговой обманкой, биотитом, клиноцоизитом, хлоритом и олигоклазом. На основе микрозондовых анализов прослежена эволюция составов роговых обманок и биотитов метагаббро при замещении магматических минералов метаморфическими. Реликтовые магматические амфиболы и биотиты значительно богаче Ti и Al, чем метаморфические. Обнаружен устойчивый разрыв смесимости метаморфических Ca-амфиболов (актинолита и глиноземистой роговой обманки), и их сосуществование в гомоосевых прорастаниях. Близость составов и парагенезисов минералов в амфиболитах и метагаббро указывает на единство P—T параметров их метаморфизма.

Introduction

The studied metabasites come from the contact zone of two tectonic units — Veporicum and Gemericum — in the central part of the Slovenské rudohorie Mts., between the localities Chyžné, Slavošovce and Rochovce (Fig. 1). The me-

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tabasites are considered to be a member of metamorphic rocks of the Hladomorná Valley Formation (Klinec, 1966) occuring at the eastern and southeastern boundary of the Veporicum crystalline formed by granitoids, migmatites and paragneisses.

A predominant part of the Hladomorná Valley Formation rocks is formed by metapelites and metapsammites of originally graywack composition, with lower contents of graphitic and quartzitic members. Metabasites occur in the form of smaller hypabyssal bodies and dykes of magmatic origin — ortoamphibolites, or they form unsharply limited beds of volcanosedimentary character — paraamphibolites — in the surrounding metasediments. They have been studied in the past above all by Mišík (1953) and Vrána (1964) and in the last years by Ivanov (1981, 1983). Stratigraphic classification of the Hladomorná Valley Formation on the basis of palynology corresponds to Lower Paleozoic—Devo-

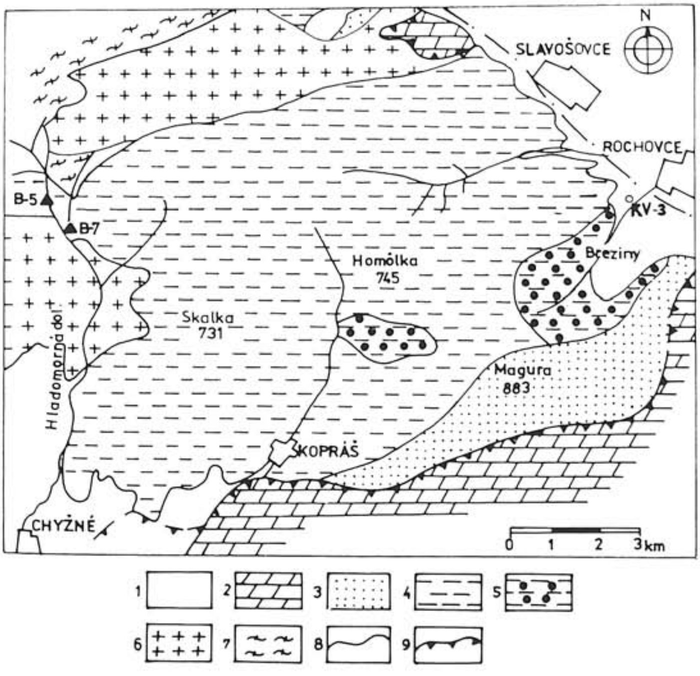

Fig. 1. Geological sketch of the region on the contact zone of Veporicum and Gemericum between Rochovce and Chyžné, elaborated on the basis of geological maps of Klinec, 1976 and Bajaník et al., 1984.

Explanations: 1 — Quarternary rocks; 2 — Gemericum — Dobšiná Group (Carboniferous); 3—7 — Veporicum: 3 — metamorphosed sandstones and slates — Rimava Formation (Permian); 4 — metapelites and metapsammites with bodies of metabasites — Hladomorná Valley Formation and Slatvina Formation (Devonian — Upper Carboniferous); 5 — contact hornfelses with cordierite; 6 — granitoid rocks of Rimavica type (Carboniferous? Cretaceous?); 7 — granitoids, migmatites and paragneisses of the Veporicum crystalline (Lower Paleozoic — Proterozoic?); 8 — geological boundaries; 9 — nappe lines.

Symbols mark the locations of samples analysed by microprobe.

nian (Klinec—Planderová, 1981). A part of the rocks is recently classified as Upper Paleozoic—Upper Carboniferous (Planderová—Vozárová, 1978; Vozárová—Vozár, 1982).

Metamorphism of the studied region was most probably a result of the effects of Hercynian and Alpine orogenies. The earlier — Hercynian regional metamorphism reached the conditions of garnet zone of epidote-amphibolite facies of medium-pressure type (Vrána, 1964; Korikovsky et al., 1986). The most frequent mineral assemblage in metapelites is garnet + biotite + plagioclase + + chlorite + muscovite ± epidote, zoisite + quartz. The later – Alpine regional metamorphism reached probably only the conditions of chlorite to biotite zone the proof of which is also the mineral assemblage chlorite + muscovite (sericite) + quartz ± biotite in Permian metapsammites.

Contact metamorphism is in the studied region connected with metamorphic effects of granitoid intrusions on surrounding rocks and it became evident especially in the formation of contact hornfelses with cordierite in the thermal aureole of the Rochovce granite which does not emerge on the surface (Fig. 1).

Profile of the borehole KV-3

The borehole KV-3 near Rochovce represents a profile across the rocks of this region. The geological structure is formed by complicated fold and nappe structures of Alpine age developed especially in the region of Markušovský Hill (Zoubek—Snopko, 1964; Klinec, 1966; Plašienka, 1980). As it follows from the profile of the borehole (Fig. 2), granitoid rocks occur in the depth of 702—1563 m; they are porphyric granites to granodiorites with pink megacrystals of K-feldspars (Klinec et al., 1980). They are noted for their high contents of REE and magnetic minerals in contrast to other granitoids of West Carpathians. Geochronological data obtained by K/Ar method point to Alpine age of the granites — i.e. 88—75 million years (Kantor—Rybár, 1979). The metabasite–metagabbro - forms a body in the depth 607–702 m. As it follows from its mineralogical-petrographical characteristics and chemical composition, mentioned in greater detail in our next paper, the metabasite represents an originally sub-alkali biotite-pyroxene-amphibole gabbro metamorphosed in the conditions of garnet zone of epidote-amphibolite facies; this corresponds to the conditions of regional metamorphism of Hladomorná Valley Formation (Fig. 2). Fine-grained aplitic granites can be found above the metabasite body. The contact of the metagabbro with the underlying porphyric granites as well as with the overlying aplitic granites is complicated by tectonic dislocations with signs of cataclasis and mylonitization leading us to the assumption of allochthonous, tectonic position of the metagabbro body in the profile; this conclusion is supported also by the absence of contact metamorphic effects of the granite on the body.

Aplitic granite in the form of sporadic pegmatite veins penetrates into the metapelites and metapsammites of Hladomorná Valley Formation in the upper part the profile. On immediate contact the rocks are of hybride character (contact migmatites–hybride granites) with relatively large plagioclase porphyroblasts. Towards the surface the rocks become polymetamorphic with well identifiable structures of earlier regional metamorphism and younger contact effects of the granite. On the basis of variable quartz, plagioclase and phyllosilicate contents the rocks can be classified as phyllites, schists and gneisses with signs of hornfels textures. The age of these rocks is on the basis of palynology Early Paleozoic—Devonian (Klinec—Planderová, 1981). The mineral assemblage of the earlier — Hercynian — metamorphism is garnet ± biotite$_1$ + plagioclase + muscovite + chlorite + quartz ± epidote, zoisite, with a

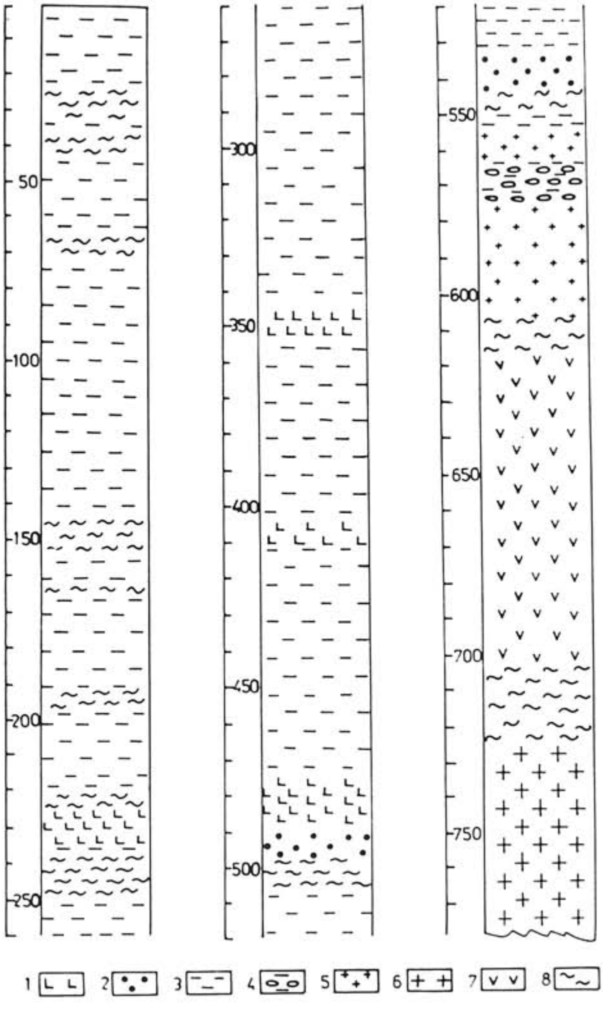

Fig. 2. Geological profile of the borehole KV-3.
Explanations: 1 — metamorphosed lamprophyres, microdiorites and diorite porphyrites; 2 — contact hornfelses with andalusite (andalusite + biotite$_2$ ± cordierite); 3 — regionally metamorphosed metapelites and metapsammites of the garnet zone with manifestations of contact metamorphism (origination of cordierite and biotite$_2$); 4 — hybride granites — contact migmatites with plagioclase porphyroblasts; 5 — aplitic granite; 6 — porphyric granite; 7 — metagabbro; 8 — cataclasites, mylonites and blastomylonites.

relatively well preserved preferred orientation on the planes s_1. Metamorphic conditions of this regional metamorphism reached the temperature 420—450 °C at the pressure 400—450 MPa (Korikovsky et al., 1986). Contact effects of the Rochovce granite were reflected in the change of PTX phase equilibria, with the formation of higher-thermal assemblage cordierite + $biotite_2$, with andalusite in the proximity of the granite (Fig. 1). Rock textures acquire spotted and hornfels character with cordierite porphyroblasts enclosing relics of lower-thermal regional-metamorphic minerals. The P—T conditions of contact metamorphism reached the temperatures 450—490 °C at the pressure of 100—150 MPa (Korikovsky et al., 1986). Both similar structures and hornfels-like mineral parageneses are completely absent in the metagabbro of the borehole.

The metasediments are in the upper part of the borehole penetrated by veins (0.1 m—m) of metamorphosed diorite porphyrites, microdiorites and lamprophyres with preserved ophitic and porphyric textures; they do not have any contact effects on the surrounding metasediments.

Zones of relatively intensive cataclasis and mylonitization are developed in the whole profile of the borehole, especially on the contact of granites with the metagabbro, but also in metasediments; this is a reflection of a complicated Alpine tectonics in this region.

In the presented paper, the results of a comparative mineralogical and petrographical study of metagabbros from the borehole KV-3 and of small metabasite (amphibolite) bodies in para-rocks of Hladomorná Valley Formation are discussed. The comagmatic character of the later mentioned rocks with gabbros according to geochemical criteria was pointed out by Ivanov (1983). Our investigations led to the discovery of another important feature — the indentity of their regional-metamorphic grade, suggesting their recrystallization in the conditions of one metamorphic cycle. We present in the following microprobe analyses of neogenic metamorphic minerals from both basite types as well as of magmatic mineral relics from the metagabbro, and we study the change in composition of primary-magmatic hornblendes and biotites in the course of metamorphism. All mineral analyses have been carried out on the microanalyser CAMECA MS-46 in IGEM, Academy of Sciences of the USSR, by V. A. Boronikhin.

The reconstruction of metamorphic reactions in general, the estimation of facial metamorphic conditions as well as the determination of the primary composition of gabbroids are discussed in the next paper (Korikovsky—Krist—Janák, in press).

Amphibolites of Hladomorná Valley Formation

Petrographical features and parageneses

The amphibolites of Hladomorná Valley have as a rule nematoblastic texture with sub-parallel orientation of hornblendes. However, in spite of a typical metamorphic appearance of amphibolites in many samples, signs of their primary magmatic character have been preserved. According to the grain form of non-regenerated plagioclase phenocrysts in metamorphic mesostasis, the following magmatic texture relics can be distinguished: 1. porphyric (with large plagioclase phenocrysts in recrystallized fine-grained amphibole-epidote-chlorite-plagioclase matrix); 2. gabbroophitic (with clearly idiomorphic tabular plagioclases); gabbroic (with large xenomorphic plagioclase grains alternating with likewise large glomeroblasts of dark minerals — pseudomorphism after magmatic pyroxenes and hornblendes). Textures of the first two types are predominant suggesting hypabyssal, dyke character of the majority of small basite bodies of Hladomorná Valley Formation. In all ortoamphibolites dark magmatic minerals are totally decomposed and plagioclases, in spite of preserving frequently their primary grain contours, are completely substituted by oligoclase.

Principal rock-forming minerals of orthoamphibolites are bluish-green or light-green hornblende, epidote (clinozoisite), chlorite, brown biotite, oligoclase, sphene, ilmenite, sometimes a small amount of quartz. Chlorite porphyroblasts are in complete equilibrium hornblende and all other dark minerals. Noteworthy is the presence of metamorphic biotite in the majority of orthoamphibolites. Its regular distribution in the rock, lack of reactional relations with other phases are a proof that it was formed by the substitution of primary-magmatic biotite and not as a result of potassium metasomatism. It is apparent that the original melt of the basites did not have tholeiite but subalkali composition.

Judging from the assemblage of metamorphic minerals, the primary-magmatic phases of the basites should have been clinopyroxene, hornblende, biotite and possibly hypersthene. To the last one points the abundance of chlorite in orthoamphibolites; it can be a product of hypersthene substitution in metamorphic processes.

As paraamphibolites can be classified thin-banded amphibolites and amphibole schists in which dark (hornblende according to the composition) bands alternate with lighter — quartz-plagioclase or zoisite-muscovite-plogioclase — ones. In some varieties there are carbonate or palmate-garnet grains. Chlorite and biotite are in varying quantities present as well. The primary substrate of such rocks were most probably polymictic, sometimes carbonate tuff-sandstones.

Thus, the following equilibrium parageneses (with sphene, ilmenite or rutile) are characteristic for the amphibolites, irrespective of their primary character:

$\mathrm{Hrb^2 + Clz(Ep) + Chl + Bi^2 + Pl \pm Q^*}$
$\mathrm{Hrb^2 + Clz(Ep) + Chl + Gr + Bi^2 + Pl \pm Q}$
$\mathrm{Hrb^2 + Carb + Chl + Zs + Pl \pm Q}$
$\mathrm{Hrb^2 + Clz(Ep) \pm Bi^2 + Pl \pm Q}$.

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* $\mathrm{Act^2}$ — colourless metamorphic hornblende, An — anortite, Aug — Augite, $\mathrm{Bi^1}$ — primary-magmatic biotite, $\mathrm{Bi^2}$ — metamorphic biotite, Carb — carbonate, Chl — chlorite, Clz — clinozoisite, Ep — epidote, Gr — garnet, $\mathrm{Hrb^1}$ — primary-magmatic hornblende, $\mathrm{Hrb^2}$ — green metamorphic hornblende, Hyp — hypersthene, Ilm — ilmenite, Mgt — magnetite, Olv — olivine, Phl — phlogopite, Pl — plagioclase, Pyr — pyrite, Q — quartz, Sf — sphene, Zs — zoisite. The number in the index of dark mineral ($\mathrm{Bi_{18}}$) is the value of $\mathrm{Fe/Fe + Mg}$, %, in plagioclase index ($\mathrm{Pl_{20}}$) it is the contents of anorthite molecule.

Composition of minerals from amphibolites

Microprobe analyses of hornblendes, biotites, chlorites and plagioclases from two amphibolite types are presented in Tab. 1. The sample B-5-2 is a paraamphibolite with significant quartz contents, B-7^2-1 is othoamphibolite with relics of porphyritic texture in the form of large plagioclase phenocrysts. Hornblende from the sample B-7^2-1 contains in the cores of the grains a "rash" of minute magnetite crystals.

Earlier investigations of parageness and geothermometry of the garnet-mica schists of Hladomorná Valley Formation which contain the amphibolite bodies have shown that their metamorphic grade corresponds according to temperature to garnet zone and according to pressure to kyanite-sillimanite depth of metamorphism (Korikovsky et al., 1986). The critical paragenesis of the schists is $Gr_{88} + Bi_{47} + Clz_{45}$ with permanent presence of chlorite. Chlorites are stable in the amphibolites with a ferruginity limit up to 45 %. The contents of TiO_2 in biotites does not exceed 1.5 wt. %, in aluminous hornblendes it is about 0.3 wt. %. Such compositions of minerals in the presence of the critical paragenesis Hrb + Chl are typical for amphibolites of the garnet zone in the regions of kyanite-sillimanite depth of metamorphism (Korikovsky—Fedorovski, 1980; Laird, 1980, 1982; Laird—Albee, 1981). Thus the determination of metamorphic grade of Hladomorná Valley Formation in this part according to metapelites corresponds to that of metabasites.

Metagabbros in borehole KV-3

Petrographical characteristics

The rocks of the gabbro body in the whole interval 607—702 m underwent metamorphic reworking with the forming of such medium-temperature minerals like greenish and colourless hornblendes, epidote, fine-flaked biotite, chlorite, oligoclase and pyrite. The character of the rock changed from magmatic gabbro to metagabbro — amphibolite. However, the recrystallization was not complete: there have been preserved not only fragments of gabbroid texture and structure but also relics of dark magmatic minerals.

Except medium-temperature alterations, the metagabbro is cross-cut by local younger carbonate and chlorite-epidote-carbonate veinlets.

However, signs of a direct contact effect of the Rochovce granites on the metagabbro have not been found. Micro-grained hornfels textures do not form in the metabasites and subsequent contact minerals comparable with cordierite hornfels assemblages forming in the upper part of granite aureole in place of garnet-mica schists do not occur here. All medium-temperature metamorphic minerals in the metagabbro evidently correspond to a single age generation; no change of paragenesis pointing to an increase of temperature could be distinguished towards the contact with granite. Apart from this, magnesian actinolite-like amphiboles with chlorite and zoisite are stable in the depth 690.3 m in cumulate metagabbros, especially on the contact with granites (sample 690^{30-40}, Tab. 3). All this, as pointed out earlier, is a proof in favour of allochthonous position of the metagabbro in the rock succession penetrated by the borehole KV-3.

Table 1

Composition of minerals (wt. %) from regional-metamorphic amphibolites

No. of sample	B–5–2				B–7^2–1			
Mineral	Hrb[2]	Bi[2]	Chl	Pl	Hrb[2]	Bi[2]	Chl	Pl
Analysis No.	1	2	3	4	5	6	7	8
Oxides								
SiO_2	43.25	38.14	27.46	60.30	48.04	39.99	28.96	63.67
TiO_2	0.33	1.52	0.03		0.28	1.54	0.02	
Al_2O_3	17.33	18.52	24.36	23.47	11.84	17.61	23.28	23.01
FeO	16.13	18.69	23.69		11.16	13.24	15.60	
MnO	0.06	0.04	0.09		0.31	0.14	0.15	
MgO	8.49	11.36	16.58		13.59	15.25	21.26	
CaO	10.18	–	–	5.34	11.01	–		4.11
Na_2O	2.41	0.30	0.22	8.95	1.65	0.32	0.05	9.20
K_2O	0.43	9.36	0.06	0.10	0.30	8.98	0.01	0.08
Total	98.61	97.93	92.49	98.16	98.18	96.07	89.33	100.07
Fe/Fe + Mg, % An % in Pl	51.6	48	44.5	25	31.5	32.7	29.2	20

Relics of magmatic textures and minerals in the metagabbro and their recrystallization

In the majority of samples, remnants of coarse- and medium-grained gabbroid, sometimes cumulate texture are preserved, with mutual xenomorphism of plagioclase and dark minerals. At the same time, glomeroblastic accumulations of large pseudomorphoses of metamorphic amphiboles and biotite usually follow the contours of magmatic phases and oligoclase monocrystals form complete pseudomorphoses after primary plagioclase. Such preservation of magmatic textures in depth-metamorphism is evidently connected with the great compactness of large basite bodies as a result of which they are only to a lesser extent affected by the schist-forming process in the course of synmetamorphic folding.

From dark magmatic minerals, monoclinic pyroxene, brownish-green hornblende and biotite have been found. According to the data of Ivanov (1983), olivine occurs in one of the samples. Hypersthene has not been found; even if it should have been present, then only very infrequently, since cummingtonite, which substitutes hypersthene in metamorphic processes, (Mongkoltip—Ashworth, 1986), has not been observed in the metagabbro from the borehole KV-3. It is possible that a small quantity of hypersthene and olivine crystallized in cumulate varieties of gabbro, since chlorite, forming also as a result of hypersthene (olivine) decomposition, is stable only in the products of their metamorphism (sample 690^{30-40}, Tab. 2).

Clinopyroxene relics, as a result of intensive recrystallization, are preserved infrequently and only in some thin section its small, corroded remnants occur inside metamorphic amphibole. Judging from optical attributes, pyroxene is represented by magnesian augite.

An important feature of the studied gabbros, connected with their subalkali character, is the crystallization of primary-magmatic hornblendes and biotites (phlogopites) together with augite. Their magmatic character can be proved by their grain-form, by specific features of their composition and by the fact that together with augite they are substituted by secondary metamorphic micas and amphiboles.

Primary hornblende (Hrb^1) has the brownish-green colour characteristic for basic magmatic rocks — it is connected with an increase of Ti contents — and short-prismatic crystal forms as a result of crystallization from melt in depth. The contents of TiO_2 (1.9—2.0 wt. %) in magmatic amphiboles are several times higher than in metamorphic hornblendes (see Tabs. 2—4).

The substitution of magmatic amphiboles can take place in different ways. Homoaxial pseudomorphism of green to colourless amphibole with small inclusions of sphene grains can sometimes form in their place. In this case, relics of magmatic hornblendes are preserved as brownish-green cores inside green or colourless amphiboles with gradual or abrupt change of colours between them. All differently coloured parts of the grain have the same angle of extinction. In other cases magmatic hornblendes are substituted from the rims by an aggregate of fine grains of low-titanium green or colourless amphiboles and the titanium surplus is exsoluted in the form of sphene.

Primary-magmatic biotites are represented by two generations. The first one are large-flaked plates of orange-brown biotites or slightly coloured phlogopi-

Table 2

Composition of primary-magmatic and metamorphic minerals (wt. %) from sub-alkali metagabbro, sample No. 690$^{30-40}$

Mineral	Hrb^1	Bi^1	Hrb^2 +	Act^2	Phl-	Chl^2	Mgt	Pyr
Analysis No.	9	10	11	12	13	14	15	16
Oxides								
SiO_2	43.08	40.85	54.19	57.28	42.82	30.91	0.96	
TiO_2	1.92	2.09	0.14	0.07	1.70	0.12	0.73	
Al_2O_3	11.81	15.65	7.57	1.40	14.82	19.37	0.34	0.08
FeO	8.79	8.39	5.40	3.94	5.56	10.93	*Fe_2O_3 = 95.55	Fe = 44.16
MnO	0.19	0.05	0.22	0.18	0.06	0.14	0.36	
MgO	15.68	21.07	18.77	21.84	21.11	26.64	1.06	
CaO	12.02	0.01	10.95	12.76	0.17	0.03		
Na_2O	2.24	0.07	1.42	0.47	0.26	—		
K_2O	1.37	10.27	0.48	0.11	10.03	0.04		
								S 53.31
								Ni 1.98
								Co 0.18
Total	97.10	98.45	99.14	98.05	96.53	88.18	99.00	99.71
Fe/Fe + Mg, %	23.8	18.2	13.9	9.1	12.9	18.7		

* All Fe calculated to Fe_2O_3.

Table 3

Composition of primary-magmatic and metamorphic minerals (wt. %) from sub-alkali metagabbro, sample No. 653^{40-50}

Mineral	Hrb^1	Bi^1	Hrb^2 +	[Act^2 +	Act^2]	Pl
Analysis No.	17	18	19	20	21	22
Oxides						
SiO_2	42.81	39.17	43.74	53.73	53.37	61.13
TiO_2	2.02	3.30	0.88	0.28	0.48	—
Al_2O_3	12.99	16.25	13.17	4.55	4.52	24.15
FeO	9.24	9.86	11.08	6.11	6.28	—
MnO	0.18	0.12	0.23	0.19	0.14	—
MgO	15.67	18.64	14.72	20.31	18.93	—
CaO	11.28	—	11.75	12.51	12.33	5.89
Na_2O	2.02	0.23	2.24	0.88	0.92	8.06
K_2O	1.24	9.47	0.92	0.18	0.20	0.39
Total	97.45	97.04	98.73	98.74	97.17	99.62
Fe/Fe + Mg, %	24.8	22.9	29.7	14.4	15.7	
An % in Pl						28.7

tes of the same size as magmatic hornblendes and in equilibrium with them (anal. 23, Tab. 4). The second generation are accumulations of small, idiomorphic randomly oriented flakes in inclusions inside brownish-green hornblende crystals (an. 18, Tab. 3). Both biotite generations (Bi_I) have the same colour and very high TiO_2 contents (3.3—4.0 wt. %), typical for magmatic micas, 2 to 4 times higher than Ti-contents of metamorphic micas (see Tabs. 2—4). Apparently, biotite grain forms reflects the different stages in the crystallization of melt: small flakes the earlier one, large flakes the later one simultaneous with the exsolution of hornblende.

Analoguously with amphiboles, all stages of the substitution of magmatic biotite by metamorphic varieties — with lower Ti-contents and lighter colour — (Bi^2) can be observed in thin sections.

Only the grain form is preserved from magmatic plagioclases, since they are pseudomorphically substituted by oligoclase. In connection with this process, their primary character remains unclear.

Table 4

Composition of primary-magmatic and metamorphic minerals (wt. %) from sub-alkali metagabbros (samples No. 634^{00-10} and 640^{00-10})

	Sample No. 634^{00-10}							Sample No. 640^{00-10}	
Mineral	Bi^1	→ Bi^{2a}	→ Bi^{2b}	$Hrb^2 + Act^2$		Bi^2	Pl	$Hrb^2 + Act^2$	
Analysis No.	23	24	25	26	27	28	29	30	31
Oxides									
SiO_2	40.45	41.80	42.40	46.67	56.15	39.98	63.44	46.98	56.48
TiO_2	4.04	1.96	0.68	0.54	—	1.62	—	0.48	0.03
Al_2O_3	16.84	16.73	16.68	12.49	2.02	16.27	22.09	10.14	2.17
FeO	9.05	8.52	7.97	8.76	5.77	9.31	—	9.01	5.84
MnO	0.09	0.07	0.09	0.16	0.18	0.05	—	0.21	0.22
MgO	17.60	18.77	19.48	15.53	20.54	19.65	—	16.52	20.39
CaO	—	—	—	11.58	12.45	—	3.48	12.22	12.70
Na_2O	0.43	0.20	0.05	2.01	0.46	0.23	9.95	1.78	0.42
K_2O	8.53	9.08	9.43	0.92	0.05	10.27	0.26	0.63	0.05
Total	97.03	97.13	96.78	98.66	97.62	97.38	99.22	97.97	98.30
Fe Fe + Mg, %	22.4	20.1	18.7	24.0	13.6	21.0		23.4	13.8
An % in Pl							16.2		

Local low-temperature alterations of the metagabbro

Besides medium-temperature regional metamorphism, local low-temperature alterations, mostly of hydrothermal character, can be also observed in the metagabbro.

To these belong several mm or cm thick carbonate, quartz-carbonate-epidote and tremolite-calcite epidote veinlets cross-cutting the metagabbro. In the proximity of these veinlets, saussuritization or pelitization of plagioclases can be observed as well as forming of metasomatic clusters of carbonate, chlorite-carbonate and sometimes serpentine-carbonate composition. Hydrothermal alterations are not accompanied by any schist forming in the metagabbro and the extent of the process is not very large.

The low-temperature phenomenons are most probably connected with Alpine tectonogenesis and disjunctive dislocations accompanying the allochthonous displacement of the metagabbro massif.

Low-temperature alterations are not considered in the present paper.

Metamorphic minerals of the metagabbro

Hornblendes

A specific feature of metamorphism of the gabbro from the borehole KV-3 is the fact that augite and brownish-green magmatic hornblende are most frequently substituted not only by one, but simultaneously by two coexisting Ca-amphiboles — green and colourless. This phenomenon has been known in the study of basite metamorphism for a long time (Spear, 1982) and it is connected with a break in the miscibility of potassium amphiboles in the low- and medium-temperature interval. In our case, the colourless amphibole is similar to actinolite and the coexisting green one is a common aluminous hornblende. Such a break in miscibility can be found also in andalusite-sillimanite and kyanite-sillimanite complexes of depth-metamorphism, in a well defined thermal interval — in biotite zone, garnet zone and in the low-temperature part of staurolite zone (Cooper—Lovering, 1970; Brady, 1974; Misch—Rice, 1975; Graham, 1974; Sampson—Fawsett, 1977; Mongkoltip—Ashworth, 1986). The break in the miscibility of actinolite and hornblende has been confirmed also experimentally (Oba—Yagi, 1987). However, in spite of a general agreement about the existence of this phenomenon and about simultaneous forming of both amphiboles in the stage of progressive metamorphism, the cause of immiscibility is so far not completely clear. A number of investigators opine that this is a case of real immiscibility, i.e. the amphiboles are in equilibrium with each other like two independent minerals. Others assume that the break in miscibility is not in equilibrium and the coexistence of two Ca-amphiboles is only an intermediate kinetic stage on the way to the forming of a completely homogeneous metamorphic hornblende (Mongkoltip—Ashworth, 1986). At the same time, the occurence of both gradual as well as sharp boundaries between differently coloured Ca-amphiboles in the same sample should be pointed out.

In natural metabasites, the ferruginity of amphiboles with the break in their miscibility encompasses the interval from 10 to 60 % (Spear, 1982), which corresponds to magnesian and medium-ferruginous compositions. However, the concrete difference in Al, Na contents and in the interruption of the values of Fe/Fe + Mg between coexisting Ca-amphiboles differs strongly in every pair not only for individual complexes, but also for individual samples; it is evidently determined not only by the differences in pressure and temperature, but also by individual variations in the relations of Na, Ca, Al, Mg and Fe in the samples.

The coexistence of two Ca-amphiboles is in the metagabbros from the borehole KV-3 displayed in the same manner as in metabasites of other regions. Colourless and green parts are usually clearly separated inside individual neogenic amphibole grains, with a sharp or gradual change of colour intensity. The colourless part of a grain can form the outer margin and the green part the core of crystal (Fig. 3); the opposite case occurs as well: colourless parts form the centre of grain (Fig. 4), or they alternate irregularly with greenish parts (Fig. 5). The common feature in all cases is the simultaneous extinction of the colourless and coloured parts of each monocrystal. This amphiboles frequently contain small amoeba-like inclusions of neogenic oligoclase.

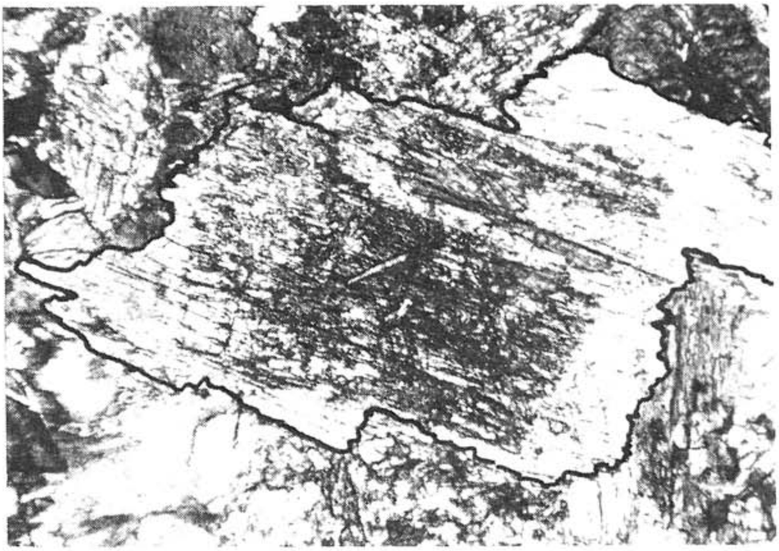

Fig. 3. Zonal pseudomorphs after magmatic hornblende.
Explanations: centre – green amphibole (Hrb^2), outer rim – colourless (Act^2). Metagabbro, thin sect. 634^{00-10}, magnif. 90x.

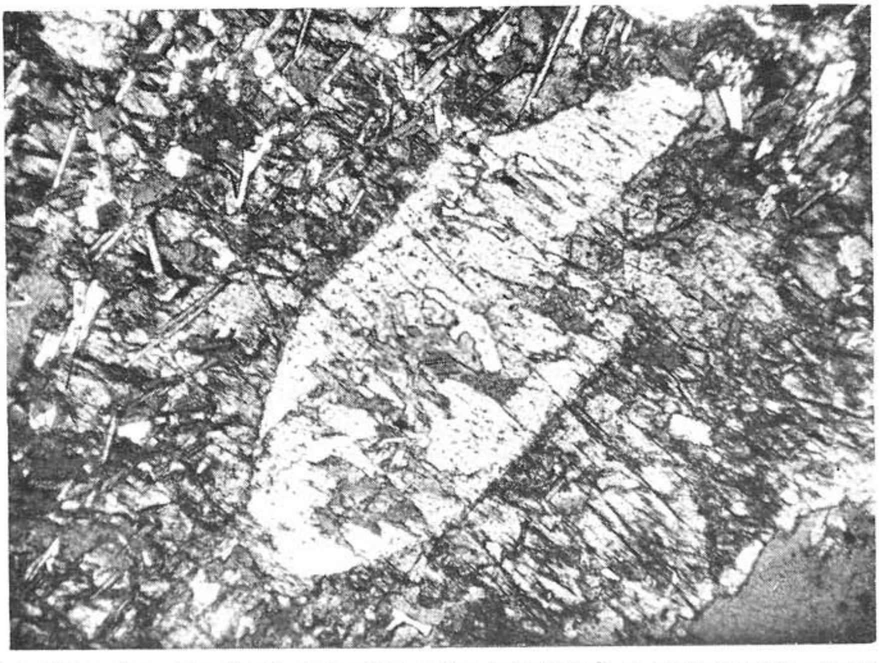

Fig. 4. Colourless core (Act^2) and green outer part (Hrb^2) in metamorphic amphibole containing numerous inclusions of fine biotite. A sharp boundary between differently coloured parts of the crystal is well visible.
Explanations: Metagabbro, thin sect. 634^{00-10}, magnif. 45x.

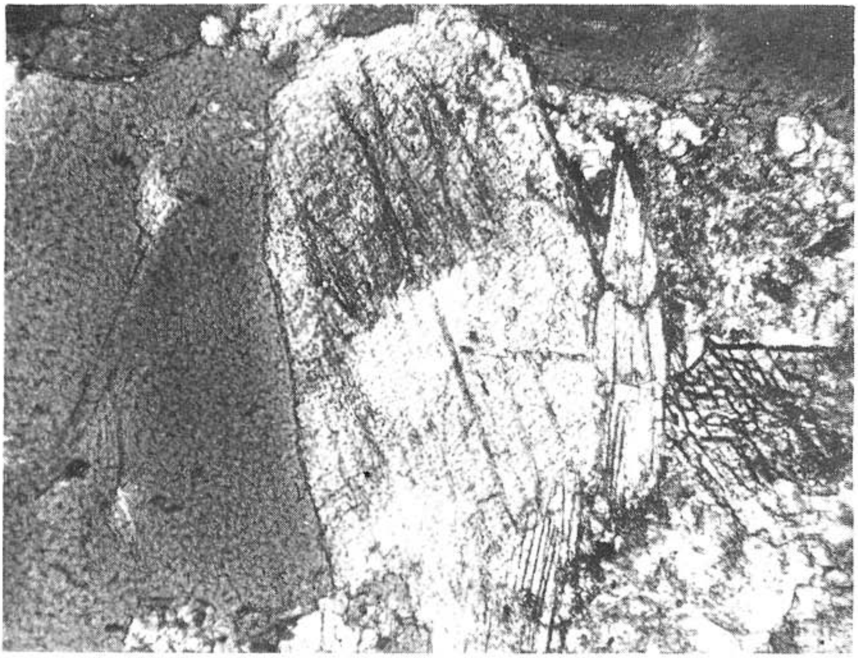

Fig. 5. Different colouring of metamorphic amphibole crystal; the unity of cleavage system is well visible.
Explanations: Metagabbro, thin sect. 624^{20-30}, magnif. 63x.

It is necessary to point out that colourless amphibole is not, as it can be seen on photos and drawings of thin sections (Figs. 3—6), a secondary thin-acicular actinolite variety of a later origin substituting hornblendes, but it is occuring in homoaxial intergrowths with them.

The boundary between colourless and green amphiboles in an intergrowth has been investigated in the sample 640^{00-10} with the help of microprobe. It is a not-twinned monocrystal, with one cleavage system, where colourless and coloured parts alternate randomly and have optically sharp boundaries (Fig. 6). A transversal profile has been made across such a contact marked on Fig. 6 by a line, confirming that the change in the composition from colourless to green amphibole does not occur gradually but with a distinct jump. At the same time (Fig. 5 and Tab. 4), the contents of Al_2O_3, for example, increase suddenly from 2.17 to 10.14 wt. %, and the values of Fe/Fe + Mg from 13.8 to 23.4 %. This is a proof of the occurence of two independent phases of Ca-amphiboles in the crystallographical intergrowth. Their complete analyses are presented in Tab. 4.

In the presented paper, microprobe analyses of four pairs of coexisting metamorphic amphiboles ($Hrb^2 + Act^2$) are available (Tabs. 2—4). Among them, the sample 690^{30-40} represents an exetremly magnesian cumulate gabbro with 15—20 % of plagioclase, and the samples 653^{40-50}, 640^{00-10} and 634^{00-10} are common plagioclase-containing grabbro which forms a large part of the body. In all four pairs, green (or greenish) amphibole is higher ferruginous, with higher natrium and aluminium contents; the colourless one is lower-ferruginous and low-aluminous.

Crystallochemical formulas of the amphiboles are presented in Tab. 5.

On Fig. 7 are shown the differences in the values of Fe/Fe + Mg and in the contents of Na + K and Al_{IV+VI} in coexisting pairs of Ca-amphiboles. In the same figure, the points of composition of magmatic hornblendes are marked; according to these parameters, they proved to be related to green metamorphic amphiboles. At the same time, although hornblendes from the amphibolites of Hladomorná Valley Formation are related to green amphiboles from the metagabbro according to their alkalinity and aluminity (Fig. 7), they are more ferruginous, which is connected with the higher ferruginity of the amphibolites in comparison with the metagabbros. It is interesting that hornblendes are usually homogeneous in amphibolites and simultaneous presence of two Ca-amphiboles is for them not typical. Since the grade of metamorphism of the metagabbros and amphibolites is the same (see the following text), it should be concluded that with the given P—T parameters, the break in hornblende miscibility in the metabasites of Hladomorná Valley Formation occurs only in the interval of ferruginity 10—30 %. In amphiboles with higher ferruginity the miscibility is apparently complete. In connection with this, a very similar analogy can be cited, e.g. with Ca-amphiboles in garnet zone from the region Haast River in New Zealand (Cooper—Lovering, 1970).

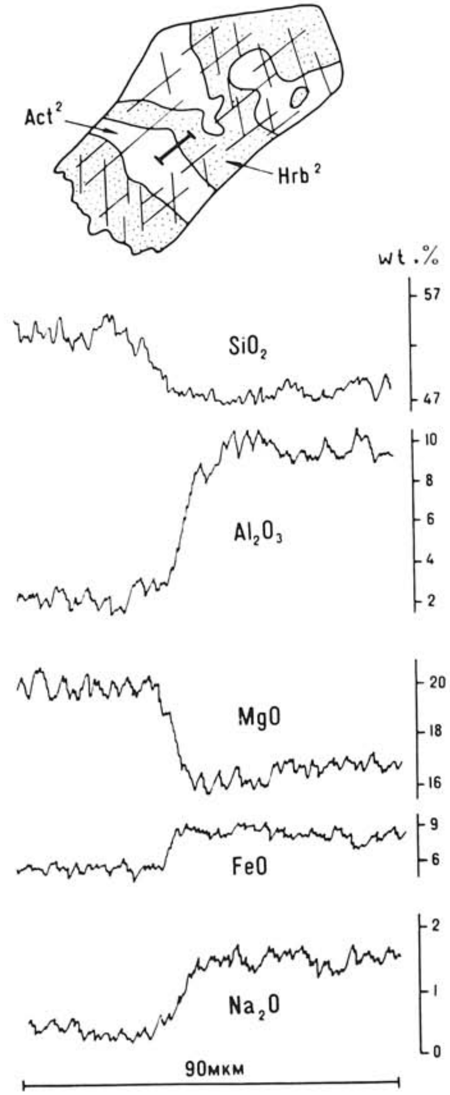

Fig. 6. Changes in the contents of SiO_2, Al_2O_3, FeO and Na_2O on the contact of green and colourless part of a Ca-amphibole monocrystal, on the line of microprobe profile in the studied grain (see drawing on top).

Explanations: Metagabbro from the borehole KV-3, sample 640^{00-10}. Complete analyses of the contacting amphiboles — see Tab. 4.

Table 5

Crystallographic formulas of hornblendes from regional-metamorphic amphibolites (1, 5) and metagabbros (9—31) on the basis of 13 cations of the groups Y and Z

Analysis No.		1	5	9[1]	11	12	17[1]	19	20	21	26	27	30	31
$Z = 8$	Si	6.240	6.784	6.270	7.346	7.840	6.124	6.226	7.364	7.489	6.566	7.755	6.665	7.768
	Al_{IV}	1.760	1.216	1.730	0.654	0.160	1.875	1.774	0.636	0.510	1.433	0.244	1.334	0.231
$Y = 5$	Al_{VI}	1.135	0.754	0.295	0.555	0.066	0.314	0.436	0.099	0.236	0.636	0.084	0.361	0.120
	Ti	0.035	0.029	0.210	0.014	0.007	0.217	0.094	0.028	0.050	0.057	—	0.051	0.003
	Fe	1.945	1.317	1.069	0.612	0.450	1.105	1.318	0.700	0.736	1.030	0.666	1.068	0.671
	Mn	0.007	0.037	0.023	0.025	0.020	0.021	0.027	0.022	0.016	0.019	0.021	0.025	0.025
	Mg	1.825	2.860	3.401	3.792	4.454	3.341	3.122	4.148	3.958	3.256	4.228	3.493	4.179
X	Ca	1.573	1.665	1.874	1.590	1.870	1.728	1.791	1.836	1.853	1.745	1.842	1.857	1.871
	Na	0.674	0.451	0.632	0.373	0.124	0.560	0.618	0.233	0.250	0.543	0.123	0.489	0.111
	K	0.079	0.054	0.254	0.082	0.019	0.226	0.167	0.031	0.035	0.165	0.008	0.114	0.008
ΣX		2.326	2.170	2.760	2.045	2.013	2.514	2.580	2.100	2.140	2.458	1.973	2.460	1.990

[1] Primary-magmatic hornblendes.

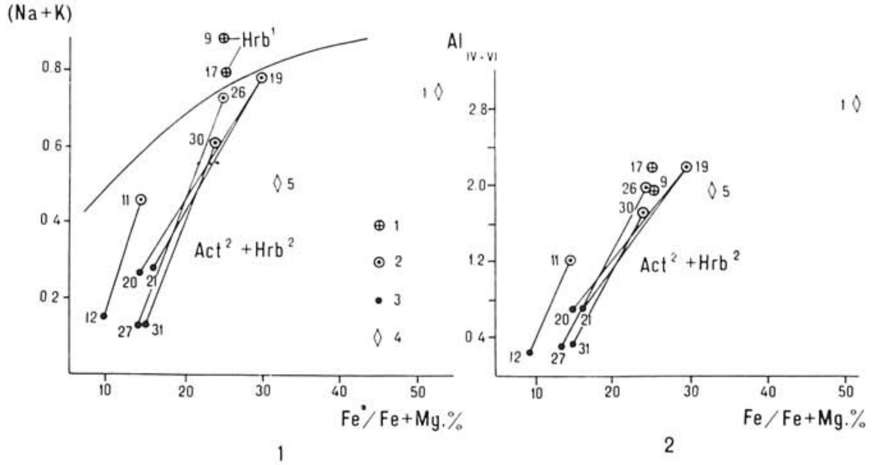

Fig. 7. Crystallographic features of amphiboles from metagabbros and amphibolites: relations of ferruginity and alkali contents (1) and aluminium contents (2).
Explanations: Amphiboles: 1 — primary-magmatic from metagabbros, 2—3 — metamorphic from metagabbros (2 — green, 3 — colourless), 4 — metamorphic from amphibolites of Hladomorná Valley Formation. By lines are connected the compositions of coexisting amphiboles from metagabbros. The numbers are analyses of minerals from Tabs. 1—4.

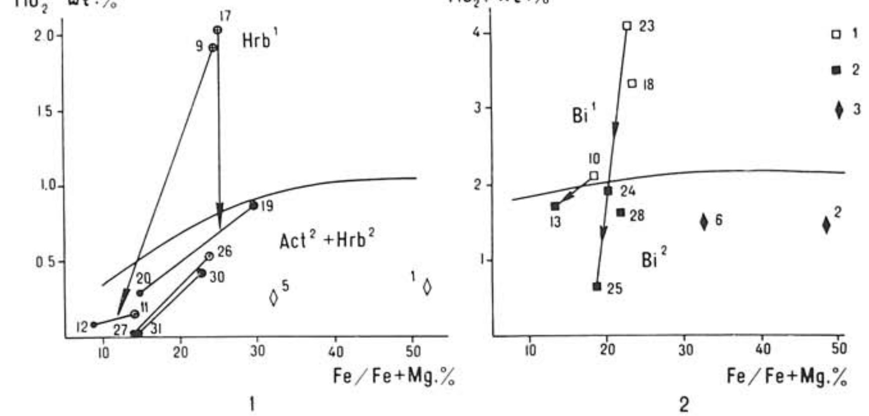

Fig. 8. Relations of ferruginity and titanium contents of amphiboles (1) and biotites (2).
Explanations: Denotation of amphiboles is the same as in Fig. 7. Biotites: 1 — primary-magmatic from metagabbros, 2 — metamorphic from metagabbros, 3 — metamorphic from amphibolites of Hladomorná Valley Formation. Arrows reflect the change of compositions during recrystallization of magmatic minerals into metamorphic ones.

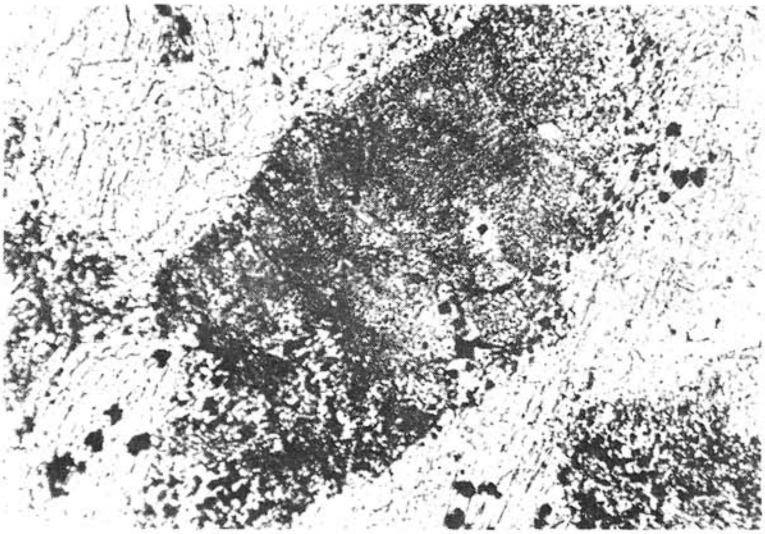

Fig. 9. Pseudomorph of weakly coloured metamorphic amphibole (Act^2) after primary-magmatic hornblende, with "rash" of minute magnetite grains.
Explanations: Cumulate metagabbro, thin sect. 690^{30-40}, magnif. 160x. Analyses of the minerals are in Tab. 2.

What is the difference in the composition of magmatic hornblende and the substituting pair of Ca-amphiboles? There is a certain depletion in Na and Al which becomes stronger with the increase of actinolite contents in the products of the substitution (see Fig. 7). Simultaneously the contents of TiO_2 several times decrease (Tabs. 2 and 3, Figs. 8,1), its surplus is exsoluted in the form of small inclusions of sphene. In this process, in some cases the total ferruginity of neogenic amphiboles does not change (anal. 17, 19 and 20, sample 653^{40-50}), in others it decreases (anal. 9, 11 and 12, sample 690^{30-40}). However, in the latter case the substitution of magmatic hornblende by amphiboles is accompanied by the exsolution of a large quantity of minute magnetite crystals (Fig. 9) and consequently the total Fe balance in metamorphic reactions is preserved.

Biotites

As mentioned earlier, large-flaked orange-brown primary-magmatic biotites are substitued from the rims by an aggregate of small flakes of metamorphic biotite (Fig. 10). The alteration of biotite shown on this photo has been investigated with the help of microprobe (Tab. 4, sample 634^{00-10}). In the central part of the magmatic biotite grain TiO_2 contents is 4.04 wt. % (anal. 23). Towards the rims this grain becomes noticeably lighter in colour, loosing its orange shade, along with a decrease of TiO_2 contents up to 1.96 wt. % (anal. 24). Peripheral part of the biotite is completely substituted by an accumulation of light-brown small biotite flakes with TiO_2 contents of 0.68 wt. % (anal. 25);

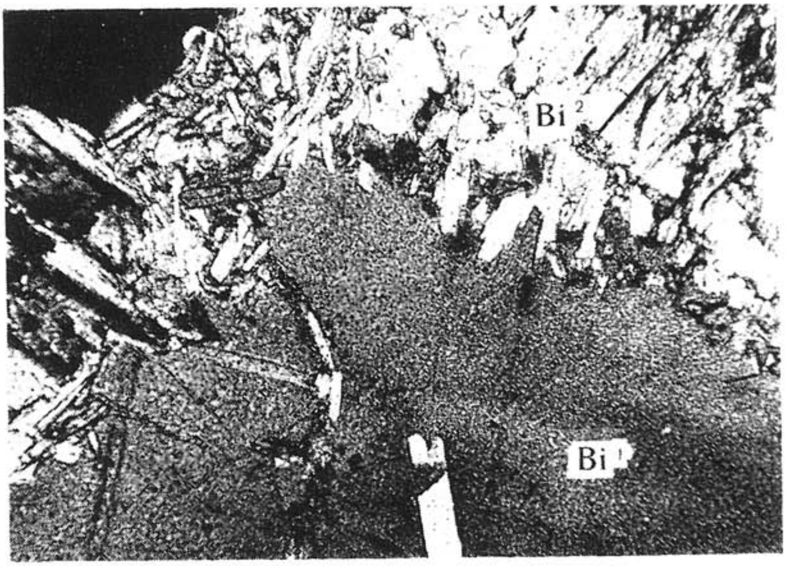

Fig. 10. Substitution of a large magmatic biotite flake (Bi^1) by an aggregate of lighter-coloured, fine-flaked metamorphic biotites (Bi^2).
Explanations: Metagabbro, thin sect. 634^{00-10}, magnif. 100x. Analyses of the biotites – see Tab. 4.

among them are many sphene grains and micro-inclusions of an ore mineral (magnetite or ilmenite).

Alteration of magmatic biotites frequently takes place even without their substitution by a new, fine-grained mica. Primary biotites, while completely preserving their large habit, frequently undergo complete or partial bleaching and change into metamorphic, less Ti-containing and a little less ferruginous mica, in equilibrium with secondary greenish and colourless amphiboles. The beginning of such an alteration is difficult to notice by optical methods. Thus, for example, it is possible that the large mica in sample 690^{30-40} (anal. 10, Tab. 2) with 2.09 wt. % TiO_2, in thin section appearing to be primary-magmatic, in reality reflects already an intermediate stage of recrystallization.

The evolution of the composition of biotites from the metagabbros in the course of crystallization is on Fig. 8 marked by two arrows. Biotites from amphibolites of Hladomorná Valley Formation are according to their TiO_2 contents identical with metamorphic micas from the metagabbros, but they are more ferruginous.

Crystallochemical formulas of micas have been calculated with the purpose of a complete evaluation of the general alteration of their chemistry in metamorphic processes (Tab. 6). It was established that metamorphic biotites from all rock types have not only lower Ti-contents than magmatic ones, but they also contain significantly more Al_{VI} in octahedrons (Fig. 11).

Thus, the general trend of recrystallization of magmatic biotites is following: They are either substituted by a neogenic aggregate, or they undergo internal

Table 6

Crystallochemical formulas of biotites from regional-metamorphic amphibolites (2, 6) and metagabbros (10–28) on the basis of 7 cations of the groups Y and Z

		2	6	10[1]	13	18[1]	23[1]	24	25	28
Z	Si	2.849	2.921	2.879	3.067	2.828	2.912	2.981	3.018	2.870
	Al_{IV}	1.150	1.078	1.120	0.932	1.171	1.087	1.018	0.981	1.129
Y	Al_{VI}	0.479	0.437	0.178	0.318	0.211	0.341	0.387	0.417	0.247
	Ti	0.085	0.084	0.110	0.091	0.179	0.218	0.105	0.036	0.087
	Fe	1.167	0.808	0.494	0.333	0.595	0.544	0.508	0.474	0.559
	Mn	0.002	0.008	0.002	0.003	0.007	0.005	0.004	0.005	0.003
	Mg	1.264	1.660	2.213	2.253	2.006	1.883	1.995	2.066	2.102
X	Ca	—	—	—	0.013	—	—	—	—	—
	Na	0.043	0.045	0.009	0.036	0.032	0.060	0.027	0.006	0.032
	K	0.891	0.836	0.923	0.916	0.872	0.783	0.825	0.856	0.940
Σ X		0.934	0.881	0.932	0.952	0.904	0.843	0.852	0.862	0.972

[1] Primary-magmatic biotites.

recrystallization, loosing a significant quantity of Ti in the process and in its place they are enriched in octahedral Al_{VI}. Their total ferruginity decreases a little. In this process, Ti and Fe are exsoluted along the cleavage of the recrystallized biotite in the form of sphene as well as a small amount of magnetite or ilmenite.

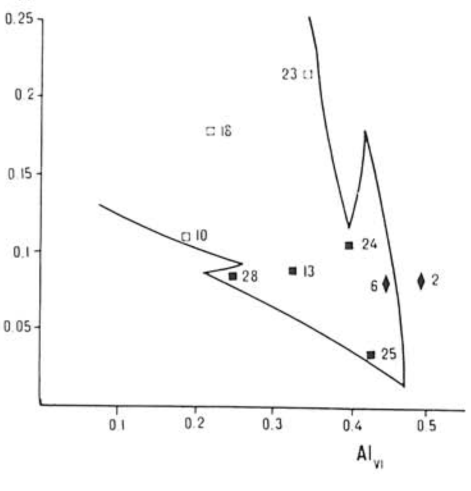

Fig. 11. Relations of Ti–Al_{VI} in different biotite types according to data from Tab. 7.

Explanations: Arrow marks a general trend of change in the composition during recrystallization of magmatic biotites into metamorphic.

Chlorites

Medium-temperature chlorites in equilibrium with two Ca-amphiboles are in the metagabbros present as well. They form large flakes of the same size as amphiboles, without any signs of reactional relations between them. Morphologically they are easily distinguished from fine-grained low-temperature chlorites occuring in thin hydrothermal chlorite-carbonate veinlets or around them.

The analysis of low-temperature chlorite from amphibole-biotite-zoisite metagabbro (sample 690^{30-40}) are presented in Tab. 2. It was found to be more magnesian than the one in amphibolites of Hladomorná Valley Formation (compare with data in Tab. 1), which can be explained by high magnesium contents of the metagabbros in comparison with the amphibolites.

Clinozoisite and zoisite

Low-ferruginous clinozoisites and zoisites are common minerals of the metagabbros. They form separate crystals, mostly intergrown with amphiboles.

Ore minerals

Ore mineralization of the metagabbros has been studied by Ivanov (1981, 1983) and therefore we have not studied this problem in greater detail. We have analysed only magnetite and pyrite; the first one being of undoubtedly metamorphic and the second one probably of metamorphic origin.

Magnetite occurs in the form of a fine "ore rash" enclosed in metamorphic amphibole (Fig. 9) or biotite crystals. Magnetites like the one analysed in Tab. 2 contain a low amount of Mg and Ti and they form after the decomposition of magmatic silicates — hornblende, biotites and possibly augites. Its occurence is fixing the Fe surplus formed only in the cases when metamorphic silicate is higher-magnesian than the magmatic one which it is substituting.

In contrast to magnetite, pyrites occur as comparatively large idiomorphic crystals and apparently they are formed by the substitution of magmatogenic pyrrhotite. This is supported by their significant contents of Ni — 1.98 wt. %, and an admixture of Co — 0.18 wt. % (anal. 16, Tab. 2).

Except pyrite, chalcopyrite grains occur sporadically as well.

Conclusions

We have studied comparative mineralogical-petrographical features of metabasite bodies (amphibolites) in the rocks of Hladomorná Valley Formation, and metagabbros discovered in the borehole KV-3 near Rochovce, in the interval 607—702 m. The gabbros, as a result of Alpine tectonogenesis, were found to be in allochthonous position in the profile and having tectonic contact with the underlying Rochovce granites, this being the cause of the absence of contact effects of the granites on the metagabbros.

The basites of Hladomorná Valley Formation as well as the gabbroid body proved to be recrystallized in the same depth, in the same conditions of medium-temperature regional metamorphism, thus having very similar parageneses and compositions of neogenic minerals. The amphibolites contain remnants of porphyritic or gabbro-ophitic texture and the gabbros the remnants of gabbroic texture. Relics of magmatic minerals have not been preserved in the amphibolites; in the gabbros they are represented by augite (rarely), brownish-green hornblende and reddish-brown biotite. Magmatic hornblendes contain 1.9—2 wt. % TiO_2 and it has high Al contents. In the course of metamorphism it is substituted either by the paragenesis actinolite + hornblende, or by one low-titanium hornblende with TiO_2 contents 0.1—0.8 wt. %. Microprobe investigations revealed a break in the miscibility of metamorphic Ca-amphiboles and equilibrium coexistence of actinolite and low-titanium hornblende in homoaxial intergrowths, as it is characteristic for medium-temperature metabasites of other regions.

Magmatic biotites contain 3.3—4 wt. % of TiO_2. In metamorphic processes they are substituted by lighter-coloured, fine-flaked biotite in which TiO_2 contents are 2—4 times lower and Al_{VI} contents are decreased. The evolution of chemistry of biotites and amphiboles in the course of metamorphism has been studied on a series of diagrams. The similarity of compositions and mineral parageneses of the metagabbros and amphibolites suggests a coincidence of P-T conditions of the process.

Translated by K. Janáková

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