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SERGEI PETROVICH KORIKOVSKY* — ERNEST KRIST** — MARIAN JANÁK**

METAMORPHIC PHASE EQUILIBRIA AND PRIMARY CHARACTER OF METAGABBROS FROM BOREHOLE KV-3 NEAR ROCHOVCE AND OF AMPHIBOLITES OF HLADOMORNÁ VALLEY FORMATION (SLOVENSKÉ RUDOHORIE MTS.)

(2 Figs., 1 Tab.)

A b s t r a c t: The studied metagabbros correspond, according to their chemical composition to the type of melanocratic magnesian subalkali gabbroids. Critical parageneses of the amphibolites and metagabbros, according to their position in the metapelites of the Hladomorná Valley Formation, correspond to the garnet zone of metamorphism, with T = 440—450 °C. Paragenetical analysis determined two types of metamorphic reactions in all basite varieties. Augite-hornblende gabbros are replaced by the paragenesis hornblende + actinolite + epidote + oligoclase + sphene, without chlorite; in gabbros with olivine (hypersthene) occured the paragenesis hornblende ± actinolite + chlorite + epidote + oligoclase + sphene. Some of the differences in the metamorphic assemblages of the amphibolites and metagabbros are connected with the difference in their primary ferruginity.

Р е з ю м е: Метагаббро по хим. анализам отвечают типу меланократовых магнезиальных субщелочных габброидов. Критические парагенезисы амфиболитов и метагаббро, по сопоставлению с метапелитами серии Гладоморной долины, отвечают гранатовой зоне метаморфизма, с T = 440—450 °C. Парагенетический анализ установил 2 типа метаморфических реакций во всех видах базитов. За счет авгит-роговообманковых габбро образуется парагенезис [роговая обманка + актинолит] + эпидот + олигоклаз + сфен без хлорита, а в габбро с оливином (гиперстеном) -парагенезис [роговая обманка ± актинолит] + хлорит + эпидот + олигоклаз + сфен. Некоторые различия метаморфишеских ассоциаций амфиболитов и метагаббро связаны с разницей в их первичной железистости.

In an earlier work (K r i s t — K o r i k o v s k y — J a n á k — B o r o n i k h i n, 1988) we have discussed the geological position of metagabbros from the borehole KV-3 and of metabasites (amphibolites) of the Hladomorná Valley Formation, and we have also presented comparative data on their mineralogy and petrography. It has been shown that basites as well as gabbros underwent deep metamorphic recrystallization with the formation of very similar medium-temperature mineral assemblages including greenish or colourless hornblende, epidote, chlorite, low-titanium biotite and oligoclase. At the same time, a miscibility gap of actinolite and Al-rich hornblende has been determined.

* Dr. S. P. K o r i k o v s k y, Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry, Acad. Sci. USSR, Staromonetny per. 35, 109017 Moscow.

** Prof. RNDr. E. K r i s t, CSc., RNDr. M. J a n á k, Department of Mineralogy and Petrology, Faculty of Natural Sciences, Comenius University, Mlynská dolina G, 842 15 Bratislava.

The difference in the volumes of the basic rock bodies led to a varying intensity of structural re-working of the gabbros and smaller basite bodies from the Hladomorná Valley Formation rocks. If the basites, on one hand, are completely transformed into amphibolites, relics of primary-magmatic minerals — Ti-rich hornblende and Ti-rich biotite and sometimes augite — were preserved in the gabbros. A series of microprobe analyses allowed to determine the trend of composition changes of amphiboles and biotites during metamorphic recrystallization.

In the present paper, the authors are discussing, on the basis of mineral analyses and observations of reaction textures, metamorphic reactions in the metagabbros and amphibolites and are presenting an estimation of regional metamorphic facial conditions which appeared to be identical for all types of metabasites, metagabbros and primarily sedimentary rocks of the Hladomorná Valley Formation.

The authors attempted also a reconstruction of the quite unusuall primary composition of gabbros from the borehole KV-3 which has few analogues.

Primary composition of the studied gabbros

Due to metamorphism, it is difficult to determine the quantitative mineral composition of the primary gabbros. It is nevertheless clear that their magmatic paragenesis was $Aug + Hrb^1 + Bi^1 + Pl \pm Olv$*; apatite was a frequent accessory mineral. Primary ore minerals have not been preserved, the presence of pyrrhotite, completely substituted by pyrite, can be only assumed. Apparently, the content of reached augite 30 %, of magmatic hornblende 20 — —30 % and the content of biotite attained 10 %. The content of plagioclase in gabbros is 40—30 % and in cummulates 10—20 %. However, it has to be stressed that the amount of magmatic plagioclase was probably higher, since a part of it breaks down during metamorphic amphibolization of gabbros, according to the reaction $Aug + Pl + H_2O = Hrb^2 + Ep(Zs)$.

Petrographical study of the gabbros in a profile has shown that a majority of the body corresponds to biotite-amphibole-pyroxene gabbros, with a plagioclase content of 30—40 %.

Cummulate gabbros with plagioclase contents not exceeding 20 % are very rare; it is possible that olivine and hypersthene were present especially in these rocks.

Mineral changes in gabbros from the borehole KV-3 show that their metamorphism was not accompanied by any significant supply of components except H_2O. No signs of K-Na metasomatism or of a loss of Mg, Fe or Ca could be observed. Grain aggregates and monocrystals of metamorphic amphiboles and

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* Act^2 — colourless metamorphic hornblende, An — anorthite, Aug — augite, Bi^1 — primary magmatic biotite, Bi^2 — metamorphic biotite, Carb — carbonate, Chl — chlorite, Clz — clinozoisite, Ep — epidote, Gr — garnet Hrb^1 — primary magmatic hornblende, 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 a dark mineral (Bi_{18}) — the value of Fe/Fe + Mg, %, in the index of plagioclase — (Pl_{20}) — the content of the anorthite molecule.

biotites form pseudomorphs in situ after their magmatic analogues, or in place of augite. Analyses of such metagabbros should correspond to the composition of primary basite.

However, in contrast to isochemical regional metamorphism, low-temperature hydrothermal effects have metasomatic character with a clearcly defined femic trend. The formation of feldspar-free chlorite-carbonate, epidote-tremolite and serpentine-carbonate nests and veinlets cross-cutting plagioclase, amphibole and biotite is accompanied by frequent loss of aluminium and alkalies and enrichment by magnesium, iron and calcium.

Because of this, samples with minimal hydrothermal alterations (Tab. 1) have been collected for chemical analyses. Our analyses are similar to the results mentioned in the work I v a n o v (1983, Tab. 1). A comparison of the results with some standard magmatic basites (Tab. 1) has shown that gabbros from the borehole KV-3 belong to a rare type of mafic rocks.

Their principal specialities are high magnesium contents and high contents of alkalies, especially of K_2O. The amount of MgO is 14.7—16.6 %, the corresponding value of Fe/Fe + Mg is 16—23 %, which is almost twice less than in average gabbros or hornblendites. The total content of alkalies attains 5—5.1 wt. % (samples 630^{00-10} and 624^{20-30}), which is 1.5 times higher than in an average gabbro or hornblendite.

According to their alkali contents, basites from the borehole KV-3 correspond to the group of sub-alkali gabbros (Classification..., 1981). However, the later mentioned rocks are characteristic by their generally higher ferruginity. Thus, the studied basites are comparable only with two magnesian representatives of the group of sub-alkali gabbros — with biotite gabbros from the gabbro-pyroxenite-dunite formation of the Middle Ural Mts. (V o r o b i e v a et al., 1962 — analysis No. 8 in Tab. 1) and with kentallenites — a variety of essexites (T r ö g e r, 1935 — analysis No. 9 in Tab. 1). These and other ones are characteristic by the presence of olivine; olivine relics have not been found in our thin sections from the metagabbros, but I v a n o v (1983) mentiones their sporadic occurrence.

According to formation characteristics, the most correct one is apparently the classification of the basites from the borehole KV-3 with biotite gabbros of a typical eugeosynclinical gabbro-pyroxenite-dunite formation; their high K_2O content is caused only by an admixture of biotite. At the same time, kentallenites are rocks of the post-orogenic stage of evolution; except biotite, augite and olivine they contain potassium feldspar (Z a v a r i t s k i, 1956) which is completely absent in metagabbros from the borehole KV-3.

The most unusual trait of the metagabbros from the borehole KV-3 is their low content of Al_2O_3 - 7—10.4 wt. %, which is almost twice lower than in normal gabbros and lower than in hornblendites, biotite and alkali gabbros (Tab. 1). Considering the mineral composition of the metagabbros, such a low general alumina content cannot be satisfactorily explained. Thus, rock-forming minerals of the metagabbros contain the following quantities of Al_2O_3 (wt. %): magmatic amphiboles 11—13; magmatic biotites 15—16; metamorphic amphiboles: green - 12—13, colourless - 1.4—7; metamorphic biotites - 14—16; chlorites - 19; plagioclases - 22—24; clinozoisite - 27—30 % Al_2O_3. Thus, low Al_2O_3 contents in the rock are possible only if the principal mineral of metagabbros is colourless amphibole (Act^2), which is not always the case: the sum of the amounts

Table 1

Chemical analyses of metagabbros from the borehole KV-3 near Rochovce in comparison with the compositions of typical magmatic basites from other regions

Sample No.	Metagabbros from borehole KV-3*					Examples of other magmatic basites			
	624^{20-30}	630^{00-10}	634^{00-10}	653^{40-50}	696^{00-10}	Average[1] gabbro	Hornblen-dite[1]	Biotite[2] gabbro	Kentalle-nite[3]
Anal. No.	1	2	3	4	5	6	7	8	9
SiO_2	48.26	46.76	47.71	49.93	46.94	48.24	42.80	46.54	48.00
TiO_2	1.74	1.83	1.49	1.24	1.13	0.97	1.62	0.60	0.22
Al_2O_3	9.29	8.39	8.53	6.97	10.43	17.88	10.55	10.39	12.52
Fe_2O_3	1.29	3.42	3.59	3.48	2.57	3.16	6.62	3.01	8.74
FeO	6.29	5.65	4.85	4.63	5.31	5.95	9.16	8.80	—
MnO	0.18	0.30	0.28	0.27	0.22	0.13	0.24	0.06	—
MgO	14.80	16.60	16.06	14.67	16.16	7.51	12.48	14.78	15.26
CaO	9.89	9.25	9.78	12.56	11.17	10.99	11.67	11.29	7.94
Na_2O	2.50	1.87	1.88	2.30	2.00	2.55	1.89	2.21	3.11
K_2O	2.61	3.17	2.48	0.82	1.38	0.89	1.00	1.79	2.68
H_2O^+	2.46	1.75	2.60	2.35	2.00	1.45	1.73	1.34	1.36
H_2O^-	0.10	0.31	0.04	0.10	0.30	—	—	—	—
P_2O_5	0.22	0.36	0.29	0.18	0.19	0.28	0.24	—	—
Total	99.63	99.58	99.58	99.50	99.80	100.00	99.76	100.81	99.83
Fe/Fe+Mg	22.00	20.50	22.00	23.00	16.00	39.00	40.00	30.00	22.00

*Analysed by Ing. K. D u b í k o v á Department of Mineralogy and Petrology of the Comenius University.
[1]D a l y (1933), [2]V o r o b i e v a et al. (1962), [3]T r ö g e r (1935).

of green hornblende, biotite and plagioclase is not lower and sometimes it is significantly higher than the content of actinolite. Because of this, it cannot be excluded that the reason for a certain decrease of the alumina contents in the metagabbros in comparison with the magmatic basite are superimposed hydrothermal phenomena, especially carbonatization. However, since CO_2 contents have not been determined, this suggestion cannot be proved.

Thus, even if we would make a correction to low-temperature hydrothermal alterations, it is apparent that primary magmatic basites from the borehole KV-3 belong to the group of melanocratic magnesian sub-alkali gabbros with biotite-augite-hornblende composition, possibly with some olivine and hypersthene.

At the same time, the low silica contents of the analysed rocks indirectly confirm the primary character of the first-generation amphiboles and biotites. Our consideration was the following: even if a part of amphiboles and biotites were formed later as a result of a supply of K and Na from granites and aplite veins, this would inevitably lead to a simultaneous increase of SiO_2 contents in the metagabbro, since K-Na metasomatism always has not purely alkali, but silica-alkali character. However, the contents of SiO_2 (in average 46—49 wt %) do not exceed the usual values for gabbros, indicating an absence of metasomatism and being as well an evidence in favour of magmatic origin of titanium biotites and hornblendes crystallizing as a result of high K, Na and water-fluid contents in sub-alkali gabbroid melt.

Acording to the opinion of M. I v a n o v, gabbroids from the borehole KV-3 and orthoamphibolites of the Hladomorná Valley Formation are in their geochemical and petrochemical criteria similar and they are comagmatic. The quantity of $K_2O + Na_2O$ in the orthoamphibolites is also high and it forms 4.2—4.8 wt. % (I v a n o v, 1983, Tab. 1); except this, these rocks as well as the metagabbros always contain considerable admixtures of biotite which proves the primary sub-alkali character of the Hladomorná Valley Formation metabasites. However, there is also an essential difference — the ratio Fe/Fe + Mg is in the amphibolites 30—37 % (I v a n o v, 1983, Tab. 1) which is considerably higher than in metagabbros from the borehole KV-3 (22—23 %). This could mean that the Hladomorná Valley Formation metabasites represent late differentiates of a sub-alkali basite melt (an evidence of this is the dyke character of their bodies) and the metagabbros are, according to their composition, more similar to an undifferentiated primary melt.

General mineral equilibria in metagabbros from the borehole KV-3 and in amphibolites of the Hladomorná Valley Formation

Paragenetical and mineralogical studies of sub-alkali gabbros from the borehole KV-3 allowed to determine the following metamorphic parageneses in the studied rocks (with sphene, apatite, pyrite and chalcopyrite):

$[Hrb^2 + Act^2] + Bi^2 + Chl + Clz(Zs) + Pl \pm Mgt(Ilm)$
$[Hrb^2 + Act^2] + Bi^2 + Chl + Pl \pm Mgt(Ilm)$
$[Hrb^2 + Act^2] + Bi^2 + Clz(Zs) + Pl \pm Mgt(Ilm)$
$[Hrb^2 + Act^2] + Clz(Zs) + Pl$

The following parageneses are stable the Hladomorná Valley Formation amphibolites of the garnet zone:

orthoamphibolites (with sphene, apatite, pyrite and chalcopyrite):

$Hrb^2 + Bi^2 + Chl + Clz + Pl \pm Mgt(Ilm)$
$Hrb^2 + Chl + Clz + Pl \pm Mgt(Ilm) \pm Q$

paraamphibolites (with sphene, apatite, sometimes pyrite):

$Hrb^2 + Bi^2 + Chl + Clz + Pl \pm Q$
$Hrb^2 + Chl + Clz \pm Gr + Pl \pm Q$
$Act^2 + Carb + Chl + Zs + Pl \pm Q$

As we can see, the assemblages of the metagabbros and amphibolites are very similar; the same critical paragenesis -Hrb + Chl + Clz - is characteristic for both rock types, indicating the same kind of metamorphism and their belonging to one temperature subfacies - the garnet zone (Korikovsky, 1979; Laird, 1980). Of course, equilibrium chlorite occurs more rarely in the metagabbros than in the amphibolites. At the same time, the latter rocks are not characterized by a simultaneous occurrence of two co-existing Ca-amphiboles; on the other hand, carbonate and garnet occuring in the paraamphibolites are not characteristic for the metagabbros.

Apparently, the abovementioned differences are connected with different chemical compositions, especially magnesium contents, of the metagabbros and amphibolites, as it was already pointed out earlier. We shall study these differences on phase diagrams.

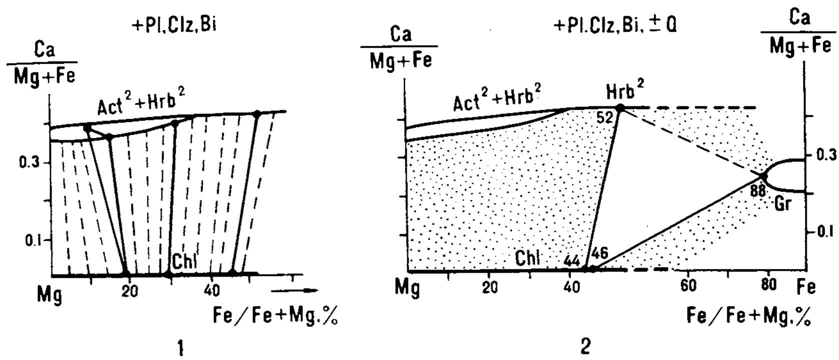

Fig. 1. Equilibria between Ca-amphiboles, chlorite and garnet in metagabbros, amphibolites and clinozoisite-containing schists of the garnet zone in the Hladomorná Valley Formation, on an Mg-Fe-Ca diagram with the Ca-point in infinity.

Explanations: 1 — connodes in the paragenesis [$Hrb^2 + Act^2$] — Chl in metagabbros and amphibolites on the basis of data Tabs. 1—4 in Krist et al. (1938) (magnesian corner of the diagram). 2 — general phase equilibria in the whole interval of ferruginity, including data of Korikovsky et al. (1986, Tab. 1); numbers-ferruginity of minerals in critical parageneses on the basis of microprobe determinations (see text).

On Fig. 1, representing the Mg-corner of the Mg-Fe-Ca diagram with the Ca-point in infinity, there are shown the relations of the ferruginity of coexisting amphiboles and chlorites according to the data of K r i s t et al. (1988, Tabs. 1 and 2): coupled analyses - (1)—(3), (5),—(7), (11 ,12)—(14) - have been used here. As it follows from the diagram, at the value of Fe/Fe + Mg over 30 % hornblende is more ferruginous than the coexisting chlorite, and at Fe/Fe + Mg less than 30 % vice versa. This extreme in the composition of phases is significant because an exactly identical inversion of the relation iron-magnesium in coexisting hornblendes and chlorites can be found in metabasites of other regions in the conditions of garnet zone from kyanite-sillimanite type of aureoles (K o r i k o v s k y — F e d o r o v s k y, 1980; L a i r d, 1980, 1982). The fact that in our case (Fig. 1) the compositions of the minerals of the metagabbros from the borehole KV-3 and of the amphibolites of the Hladomorná Valley Formation can be united in one relationship is another evidence of the identical grade of their metamorphism.

On Fig. 1, 1 we have also shown the immiscibility of hornblende and actionolite in the interval of Fe/Fe + Mg = 0—35 %; however, at Fe/Fe + Mg over 35 % the miscibility gap disappears and Ca-amphibole is represented by a homogeneous bluish-green aluminiferous hornblende.

Thus, the partial difference in the parageneses of the metagabbros and amphibolites reflects only the usual differences in the equilibria of more magnesian rocks (metagabbros) and less magnesian rocks (amphibolites), with equal P-T parameters of metamorphism.

On Fig. 1, 2, on the complete Mg-Fe-Ca diagram with the Ca-point in infinity are shown equilibria of amphiboles, chlorite and garnet in the whole interval of their ferruginity in the rocks of the Hladomorná Valley Formation. The compositions of minerals of higher-magnesian rocks (left side of the diagram) are taken from the paper of K r i s t et al. (1988, Tabs. 1 and 2). The most extreme couple as far as its composition is concerned is Hrb_{52}-Chl_{44} (amphibolite B-5-2, Tab. 1, K r i s t et al., l.c.). Garnet and chlorite compositions of relatively more ferruginous rocks (right side of the diagram; Gr_{88}-Chl_{46}) are taken from garnet-mica schists surrounding the amphibolite (K o r i k o v s k y et al., 1986, Fig. B-10, Tab. 1). Since clinozoisite can be found in this schist, we can assume that the rock, according to its saturation with Ca, resembles amphibolites. Actually, garnet from this rock contains in its peripheral part 20—24 % of grossularite molecule, which is equivalent to the normal calcium content of iron--magnesian garnets from amphibolites of the garnet zone in other regions (K o r i k o v s k y — F e d o r o v s k y, 1980; L a i r d, 1980). The ferruginity of chlorite in the garnet schist B-10 (46 %) practically agrees with the ferruginity of chlorite (44 %) from the amphibolite B-5-2 (K r i s t et al., 1988, Tab. 1). The abovementioned facts justify us to unite all presented equilibria of the Hladomorná Valley Formation rocks in one diagram (Fig. 1, 2) for assemblages saturated with Ca.

Thus, it can be stated that in the garnet-zone rocks of the studied region containing amphibole or clinozoisite and saturated with Ca, the following assemblages are stable:

in higher-magnesian rocks the assemblage
$[Hrb^2 \pm Act^2] + Chl + Clz + Pl$;

in average-ferruginous rocks the assemblage
$Hrb^2 + Chl + Clz + Pl$;
in high-ferruginous rocks the assemblage
$Gr + Chl + Clz \pm Hrb^2 + Pl$.

Garnet-chlorite amphibolites occur very rarely in the Hladomorná Valley Formation and their mineral composition have not been studied yet. Analogically with amphiboles of the garnet zone from other complexes, the ferruginity of hornblende in association with garnet is always high - from 55 to 85 %; these assumed compositions are shown on the diagram by a point.

What is the reason for the rarity of garnet-chlorite ortho and paraamphibolites? The problem is that amphibolites with high-ferruginous garnet (Fe/Fe + + Mg = 88—90 %) and amphibole can originate only as a result of metamorphism of high-ferruginous basites and tuff-sandstones, i.e. rare rock types. Common basites of the studied territory have ferruginity not exceeding 30—35 % (Ivanov, 1983) and garnet cannot originate in them at the temperature of garnet zone.

Metamorphic reactions during basite metamorphism

A comparison of magmatic and metamorphic minerals of metagabbros from the borehole KV-3 has shown the following changes in their compositions during metamorphism (Krist et al., 1988).

Magmatic hornblendes (Hrb^1) are during their substitution by a Ca-amphibole couple depleted in Na, Al and Ti. If the value of Fe/Fe + Mg did not change in this process, the most probable reaction would appear to be the following one:

$$Hrb^1 + H_2O \longrightarrow [Hrb^2 + Act^2] + Pl_{20} + Sf \tag{1}$$

Brownish-green hornblendes were replaced by intergrowths of green and colourless Ca-amphiboles, with small palmated inclusions of oligoclase and numerous fine sphene grains.

If higher-magnesian metamorphic amphiboles were formed by substitutions, the surplus of iron was exsoluted inside the pseudomorphs in the form of numerous micro-inclusions of magnetite (Krist et al., 1988, Fig. 8). Since a part of iron in magnetite is oxidated, it is clear that such a reaction is stimulated by local increase of oxygene activity, indicating oxidative conditions of metamorphism:

$$Hrb^1 + H_2O + O_2 \longrightarrow [Hrb^2 + Act^2] >_{Mg} + Mgt + Pl_{20} + Sf \tag{2}$$

During the substitution of magmatic augite, Ca-amphiboles are formed as a result of a reaction with contacting primary plagioclases:

$$Aug + Pl + H_2O \longrightarrow [Hrb^2 + Act^2] + Clz/Zs \tag{3}$$

Breakdown of magmatic biotite is accompanied by a loss of a significant amount of Ti and increase in the quantity of octahedral aluminium (Al_{VI}) (K r i s t et al., 1988, Fig. 10). A possible source of Ca for the formation of sphene, as well as of additional Al for higher-aluminium biotite, appears to be the participation of an anorthite plagioclase molecule in the reaction:

$$Bi^1{}_{Ti} + An + H_2O \longrightarrow Bi^2 >_{Al} + Sf \qquad (4)$$

The result of the reaction is either bleaching of large orange-brown biotites, or their substitution by an aggregate of light-coloured, low-titanium biotites with ingrowths of sphene (or ilmenite) grains.

As far as the transformation of sulfides is concerned, large pyrite crystals were most probably formed as pseudomorphs after magmatic pyrrhotite. Since the sulfur anion $[S_2]^{2-}$ which enters pyrite represents a more oxidated form than the anion S^{2-} in pyrrhotite (B e t e k h t i n, 1955), such a substitution is stimulated not only by temperature decrease, but also by highly oxidizing character of metamorphic fluids.

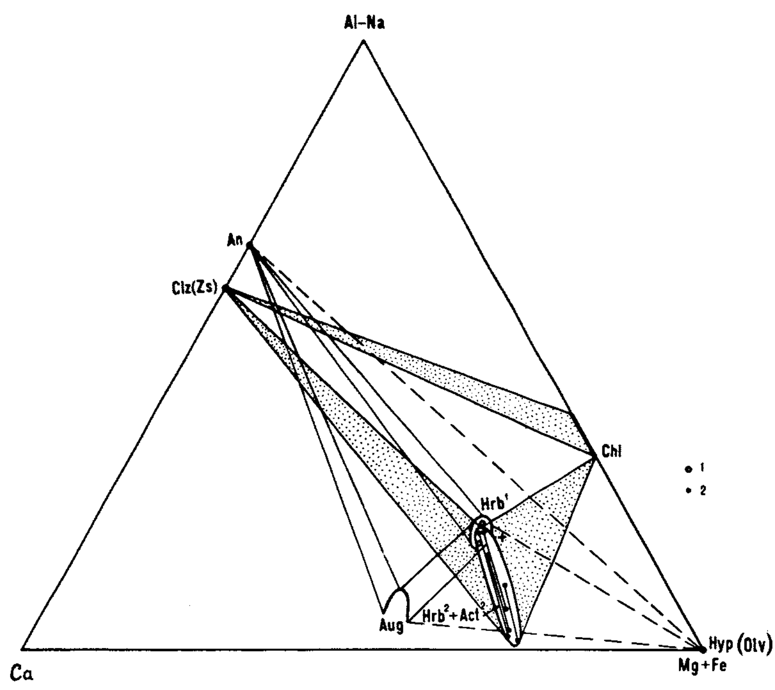

Fig. 2. Primary-magmatic and superimposed metamorphic assemblages of metagabbros and amphibolites of the Hladomorná Valley Formation on a (Mg, Fe)-Ca-Al projection of the diagram (Mg, Fe)-Ca-Al-Na.

Explanations: 1 — magmatic hornblendes; 2 — corresponding metamorphic Ca-amphiboles. Metamorphic assemblages are indicated by dotting.

Common transformations of basites can be illustrated on the diagram (Mg, Fe)-Ca-Al which is a projection of the composition of the analysed magmatic and metamorphic minerals (except biotite) onto this plane from the point of albite in the tetrahedron (Mg, Fe)-Ca-Al-Na (Fig. 2). In such a projection, the variability of plagioclase composition is not reflected on the diagram and only anorthite composition is included. When plotting the composition of hornblendes, the amount of Al proportional to their Na content has been deduced from their formulae. The average composition of augite from gabbros is plotted on the basis of data of Dobretsov et al. (1971).

The usual primary-magmatic paragenesis of sub-alkali gabbros is Aug + + Hrb^1 + Pl(An), with a surplus of biotite. It is assumed that hypersthene and olivine can occur as an additional phase.

As it follows from the intersection of the connodes on the diagram (Fig. 2), the most evident substitute of the magmatic assemblage Aug + Hrb^1 + Pl(An) is the bimineral paragenesis Hrb^2 + Act^2 + Clz(Zs), practically without chlorite. This could explain the relatively rare occurrence of chlorite in the metagabbros in comparison with the amphibolites of the Hladomorná Valley Formation. Therefore, the leading summary reaction is the following one:

$$\mathrm{Aug} + \mathrm{Hrb}^1 + \mathrm{Pl(An)} + \mathrm{H_2O} \longrightarrow [\mathrm{Hrb}^2 + \mathrm{Act}^2] + \mathrm{Clz}\ \mathrm{Pl}_{20} + \mathrm{Sf} \qquad (5)$$

The appearance of another phase - chlorite - and the formation of the tripple paragenesis [Hrb^2 + Act^2] + Clz + Chl is possible, as it follows from Fig. 2, only during metamorphism of hornblende gabbros (i.e. after decomposition of the paragenesis Hrb^1 + An), or of mafic gabbros containing some hypersthene or olivine. Graphically it can be deduced from the fact that the connodes of the assemblage [Hrb^2 + Act^2] + Chl + Clz on Fig. 2 in reality intersect mostly the connodes of the magmatic assemblages Hrb^1 + An and Hrb^1 + Hyp(Olv) + An, i.e. chlorite can originate only after the decomposition of these two parageneses. The relative rarity of chlorite in metagabbros from the borehole KV-3 could indicate that hypersthene (olivine), if it was present at all, played only an extremely unimportant role. Thus, the appearance of chlorite-containing assemblages could be connected with the following reactions of gabbro recrystallization, from which the most probable appears to be the reaction (6):

$$\mathrm{Hrb}^1 + \mathrm{Pl(An)} + \mathrm{H_2O} \longrightarrow [\mathrm{Hrb}^2 + \mathrm{Act}^2] + \mathrm{Clz} + \mathrm{Chl} + \mathrm{Pl}_{20} + \mathrm{Sf} \qquad (6)$$

$$\mathrm{Hrb}^1 + \mathrm{Hyp(Olv)} + \mathrm{Pl(An)} \longrightarrow [\mathrm{Hrb}_2 \pm \mathrm{Act}^2] + \mathrm{Chl} + \mathrm{Clz(Zs)} + \mathrm{Pl}_{20} + \mathrm{Sf} \qquad (7)$$

Analoguous reaction (5)—(7) took apparently place during the metamorphism of small basite bodies in the Hladomorná Valley Formation, as a result of which these rocks were transformed into amphibolites. However, due to higher ferruginity of these rocks, the miscibility of Ca-amphiboles in them is complete, and they are represented by homogeneous light- or brownish-green hornblendes. The wide stability of chlorite in the amphibolites could indicate the primary presence of hypersthene in these basites and therefore the probable model of their metamorphism is the reaction (7) and not (6).

Thus we come to the conclusion that regional metamorphism of metagabbros and amphibolites of the Hladomorná Valley Formation is representing an isochemical process with hydratation and decomposition of magmatic minerals and with a supply of only H_2O. The fluids had oxidizing character indicated by the crystallization of magnetite and the substitution of pyrrhotite by pyrite.

Estimation of the parameters of metamorphism of the basites

The correspondence of mineral assemblages of metagabbros from the borehole KV-3 with orthoamphibolites of the Hladomorná Valley Formation indicates that all these basites as well as the surrounding garnet-mica schists were metamorphosed in the conditions of one-act regional metamorphism with a grade corresponding in the studied territory to the garnet zone. The temperature conditions determined earlier on the basis of biotite-garnet thermometer (Korikovsky et al., 1986) correspond to 440—450 °C. This estimate seems to be wholly reasonable, since chlorite is widely stabile in all rock types and critical parageneses are Gr + Chl (mica schists) and Hrb + Chl (metabasites). At the same time, staurolite and the paragenesis Bi + Al_2SiO_5 are completely missing in the metapelites which indicates metamorphic temperatures bellow the tripple point of aluminium silicates with coordinates corresponding to values about 500 °C (Holdaway, 1971).

These moderate temperatures are confirmed by the pecularities in amphibole and biotite compositions characteristic for the garnet zone in other complexes: low Ti contents, the coexistence of actinolite and hornblende.

It was not possible to determine the value of pressure on the basis of existing mineral parageneses which are not informative from the viewpoint of geobarometry. The suggested variants of the biotite-muscovite-chlorite-quartz and garnet-muscovite-biotite-plagioclase barometers proved to be extremely imprecise, as it was shown also by the study of Dalradian zonal metamorphism in Scotland (Hudson, 1985).

A number of earlier presented indirect mineralogical criteria (Korikovsky et al., 1986) indicates that the regional metamorphism belonged most probably to the kyanite-sillimanite pressure type, i.e. with $P_s = 4—5$ kbar. We should add that its extreme in the equilibrium $Hrb^2 + Act^2 + Chl$ and the limits of miscibility in Ca-amphibole couples are analogous with those observed in the garnet zone, especially in aureoles of the kyanite-sillimanite type (Korikovsky — Fedorovsky, 1980; Cooper — Lovering, 1970; Laird, 1980).

Thus, we accept the following parameters of progressive metamorphism for all Hladomorná Valley Formation basites in the region of Rochovce: T = 440—450 °C, $P_s = 4—5$ kbar. At a geothermal gradient of 15 °C/km usual for Phanerozoic metamorphic belts, this corresponds to a depth of 15—18 km.

The age of the regional metamorphism corresponded to Variscan orogeny. This was proved by the age determination of Rimavica granites by U-Pb method on magmatic zircons, giving the age 350 ± 5 m.y. (Bibikova et al., 1988). The samples were collected in the region of Krokava, from peripheral parts of the massif which breaks through and is injected into garnet-mica schists of the Hladomorná Valley Formation and of the Revúca Group (Vozárová —

V o z á r, 1982), the metamorphic grade of which is the same as in the region of Rochovce. Contact effects of the granites are limited only to alkali metasomatism—muscovitization and biotitization of the surrounding schists. In exocontacts granites frequently form thin concordant injections; thermal cordierite-andalusite hornfelses have not been found on the studied territory. This all indicates syntectonic and synmetamorphic character of the Rimavica granites and, consequently, the age of their crystallization - 350 ± 5 m.y. - can be also considered to be the age of peak regional metamorphism of the Hladomorná Valley Formation rocks, as well as of the enclosed basite bodies.

Conclusions

Chemical analyses of the metagabbros have shown that they belong to a rare type of melanocratic sub-alkali gabbroids with magnesium contents of 77—84 % and with low aluminium contents, they correspond either to kentallenites or to melanocratic biotite gabbros from the gabbro-pyroxenite-dunite formation.

Paragenetical analysis of the Hladomorná Valley Formation metagabbros from the borehole KV-3 has shown that the paragenesis $Hrb^2 \pm Act + Bi + Chl + Ep + Pl \pm Mgt$ is characteristic for both rock types, with chlorite having a ferruginity of 44 %. According to a number of signs parageneses of both metabasite types correspond to the assemblages of regional-metamorphic clinozoisite-containing schists of the Hladomorná Valley Formation (K o r i k o v s k y et al., 1986): this allowed to determine the metamorphic grade common for all studied rocks, with the parameters $T = 440—450$ °C, $P_s = 4—5$ kbar.

A reconstruction of metamorphic reactions during the recrystallization of the basites has shown that reaction of the type

$$Aug + Hrb^1_{Ti} + Pl(An) + H_2O \longrightarrow [Hrb^2 + Act^2] + Ep + Pl_{20} + Sf$$

with the formation of metamorphic assemblages without chlorite is the most probable one for gabbros of primarily augite-hornblende composition.

For primarily hypersthene (olivine) containing gabbros as well as for the Hladomorná Valley Formation basites, reactions of the type

$$Hrb^1_{Ti} + Hyp(Olv) + Pl(An) + H_2O \longrightarrow [Hrb^2 \pm Act^2] + Chl + Ep + Pl + Sf$$

are more probable, resulting in the appearance of chlorite in the metamorphic assemblage along with other minerals. The breakdown of titanium-containing magmatic biotite leading to the formation of low-titanium biotite with sphene intergrowths took place in the presence of an anorthite plagioclase molecule, according to the scheme

$$Bi^1_{Ti} + An + H_2O \longrightarrow Bi^2<_{Al} + Sf.$$

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