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METAMORPHIC EVOLUTION OF GABBROIC ROCKS OF THE BÓDVA VALLEY OPHIOLITE COMPLEX, NE HUNGARY

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Abstract: The Alpine polyphase metamorphic evolution path of the Bódva Valley Ophiolite Complex was reconstructed using mineral paragenetic observations, mineral chemical and thermobarometric data obtained on metagabbroic samples from boreholes in the Rudabánya Mts., NE Hungary. The dismembered ophiolite complex forms part of the Meliata Unit of the Inner Western Carpathians. The recognizable, first blueschist facies event (min. 700–800 MPa, 350–500 °C) was followed by a nearly isothermal decompression to 400–600 MPa in the greenschist facies. The following metamorphic event was characterized by temperature increase up to 500–600 °C in isobaric conditions to the albite-epidote-amphibolite facies. The P-T path is best explained by subduction, which was followed by uplift without any significant change in the temperature conditions. The late temperature increase might be caused by thermal relaxation following subduction.

Key words: Inner Western Carpathians, Rudabánya Mts., ophiolite complex, gabbro, metamorphism.

Introduction

Metamorphic features of ophiolites provide an effective tool for reconstructing the tectonic conditions of closure of paleoceanic branches. Rocks of mafic composition predominate in ophiolite suites, and their intrusive members (mainly gabbros) may form huge sequences up to a few hundred of meters in thickness. Blueschists and other high-pressure metamorphic rocks — described as features of subduction zones — occur within two tectonic zones of the Western Carpathians: south of the Pieniny Klippen Belt as pebbles in Cretaceous conglomerates (e.g. Dal Piaz et al. 1995 and Faryad 1997) and in the Meliata Unit (e.g. Kamenický 1957; Faryad 1995 and Mello et al. 1998). Recent studies revealed that the metabasic rocks occurring in the Meliata Unit in NE Hungary also show blueschist facies metamorphism and a greenschist facies overprint (Horváth 1997).

The aim of the present paper is to characterize the petrology and the metamorphic P-T conditions of the gabbroic rocks of the Bódva Valley Ophiolite Complex (BVOC), on the basis of the metamorphic petrological results obtained from representative sections of these rocks cored by the boreholes Bódvarákó Br-4, Komjáti Ko-11 and Szögliget Szö-4. These boreholes are located in the Rudabánya Mountains along the Darnó Fault Zone, NE Hungary (Fig. 1).

Geological outline

The dismembered BVOC is related to the Meliata Unit (Fig. 1), which is supposed to represent an oceanic suture zone of the Vardar (s.l.)-Meliata ocean of Triassic–Jurassic age in the Neotethyan realm, in the southern part of the Inner Western Carpathians (Maheľ 1986). Apart from the blueschist facies metabasic and metasedimentary rocks, the Meliata Unit consists of low grade, very low grade and unmetamorphosed limestones, sandstones, phyllites, slates and shales, which were mapped as a single tectonic unit (Mock 1978). Structural investigations indicate that the variously metamorphosed rocks are in tectonic contact within the unit (Neubauer et al. 1992). Recently, Mock et al. (1998) described the type locality of the Meliata Unit, near the village of Meliata, as a tectonic half-window with repeated discontinous tectonic slices. These slices are composed of Jurassic deep-water shales with various large blocks of older (mainly) Triassic rocks. The shales were most likely accumulated in an accretionary wedge.

The oceanic slivers of the Meliata Unit in NE Hungary represent slices and small (from dm to 100 m in scale) fragments embedded in the ductile Upper Permian Perkupa Evaporite Formation found in the basal part of the nonmetamorphic Silica Nappe that forms the uppermost nappe in the area studied (Fig. 1). The Silica Nappe is underlain by the intermediate-high pressure/low temperature metamorphic Torna Nappe (Árkai & Kovács 1986 and Kovács et al. 1996–97) and the Paleozoic rocks of the Gemeric Superunit. The Silica and Torna Nappes and the Meliata Unit built up the South Gemer nappe system of the Gemer-Bükk units of the Pelsonia composite terrane (Kovács et al. 1996-97), also known as the North Pannonian or ALCAPA (Alpine-Carpathian-Pannonian) Unit (Balla 1982; Csontos et al. 1992 and Csontos 1995) which was assembled with other West-Carpathian units during the Miocene (Csontos 1995). Plašienka et al. (1997) infer that these nappes form the Meliata Belt of the Inner Western Carpathians.

On the basis of sporadic biostratigraphic data from radiolarites synchronous with pillow basalts the age of the magmatism in the BVOC is thought to be Middle Triassic (Dosztály & Józsa 1992). The main concern with the K/Ar data from the BVOC (256 ± 26 Ma on amphibole, 233 ± 10 Ma on biotite, 115 ± 5 Ma on feldspar and 210 ± 12 Ma on whole rock, Árva-Sós et al. 1987) is that the mineral chemical compositions (and consequently, the eventual magmatic or metamorphic nature) of the analyzed phases were not checked before the measurements, so this may be the reason why there is a large scatter between the results (from 110 Ma to 270 Ma). The blueschist facies metamorphism occurred in middle Jurassic times (150–165 Ma, K/Ar and $^{40}Ar/^{39}Ar$ ages on phengite from the Slovak part of the Meliata Unit, see Maluski et al. 1993 and Faryad & Henjes-Kunst 1997). Such middle Jurassic data have not been obtained from the BVOC rocks so far, notwithstanding that a comparison between the Alpine metamorphic evolution of the two areas is assumed (Horváth 1997).

The boreholes studied are located in the Rudabánya Mountains along the Darnó Fault Zone in NE Hungary. The profiles of the boreholes where samples were collected are shown in Fig. 2. Major element analyses are given in Table 1. Comprehensive studies of the geochemical character of the BVOC rocks were performed by Réti (1985), Harangi et al. (1996) and Horváth (1997), who all confirmed the MORB character of the ophiolite complex in question, therefore we do not discuss this problem in detail in this paper.

Under a ca. 150 m thick Tertiary and Quaternary cover the borehole **Komjáti Ko-11** cut through an approximately 200 m thick metamafic complex which is built up predominantly of metagabbro and its finer-grained variant (metadol-

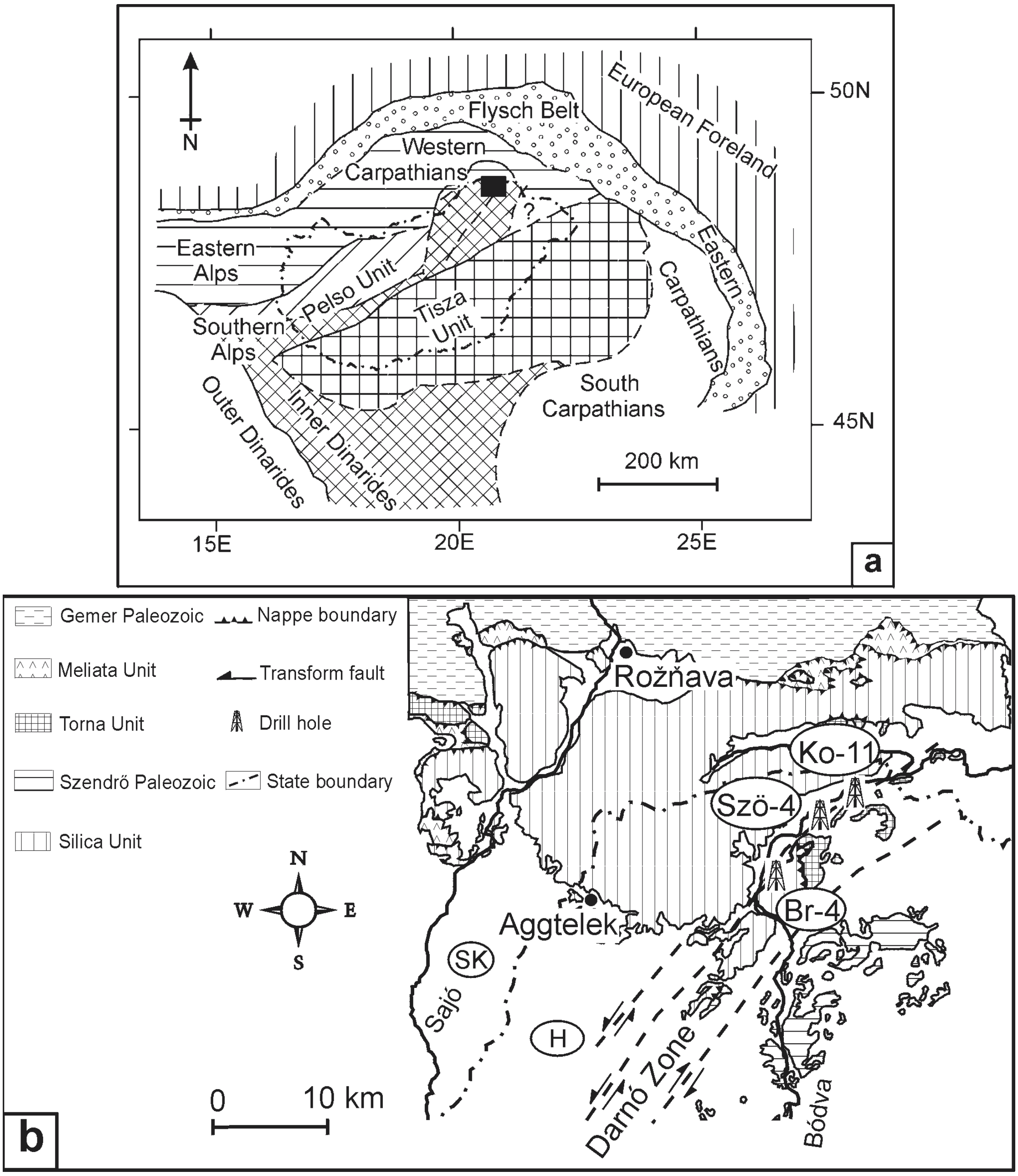


Fig. 1. a — Tectonic sketch map of the Alpine-Carpathian area. Box indicates the investigated area. **b** — Geological map of the Aggtelek-Rudabánya Mts. and adjacent areas with the localition of the boreholes investigated.

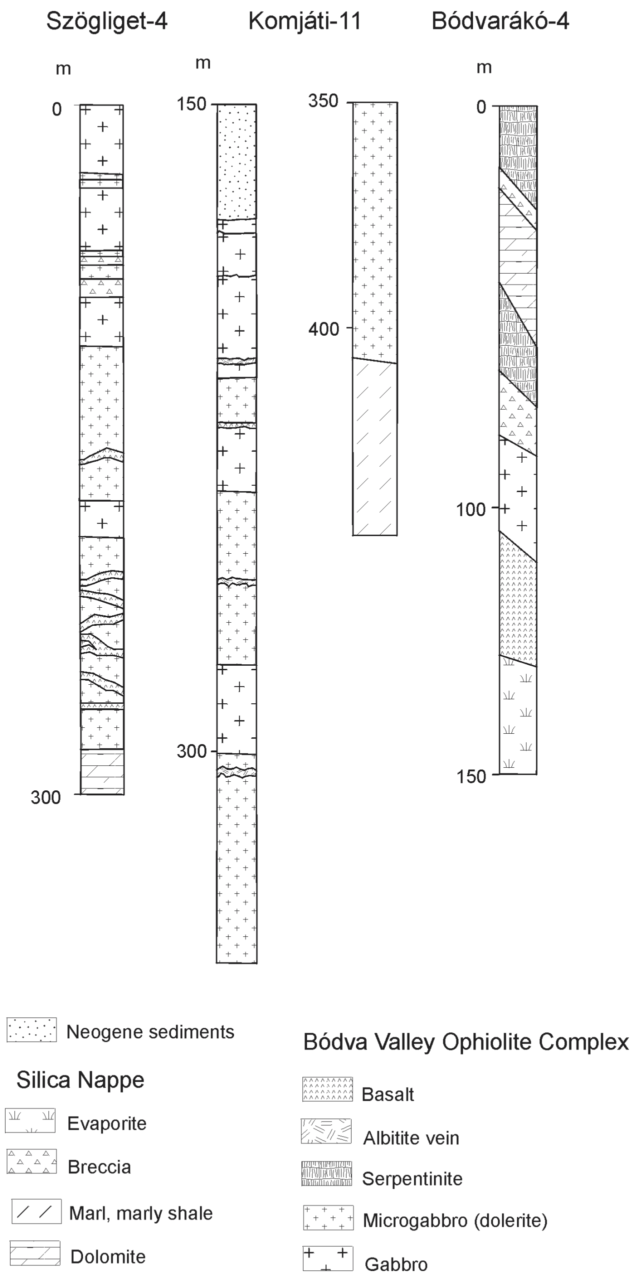


Fig. 2. Geological profiles of the studied boreholes Bódvarákó Br-4, Komjáti Ko-11 and Szögliget Szö-4.

erite), described earlier by Réti (1985) as albite-gabbro and -dolerite. The contact between this complex and the underlying Upper Permian Perkupa Evaporite Formation belonging to the Silica Nappe is tectonic. The metamafic complex is cut by several, thin (ca. 30–50 cm thick) albitite veins and a 50 cm thick metabasalt vein. Albitites represent metamorphosed intermediate-acidic rocks which form small portion in complete ophiolite sequences (see e.g. Coleman 1977).

The borehole **Szögliget Szö-4** is located close to the only surface exposure of the BVOC, at the Tilalmas-tető (-hill), where Vitális (1909) described a strongly weathered metagabbro believed to be occurring as diorite dyke. The upper portion of the metamafic complex is composed of mainly

Table 1: Representative bulk rock compositions from the BVOC gabbros.

Borehole	Sző-4			Br-4	Ko-11		
Depth (m)	190	202	209	94	204	235	318
SiO_2	45.46	46.37	44.81	45.72	46.35	45.46	43.71
TiO_2	2.25	2.34	3.69	4.13	3.22	4.28	4.81
Al_2O_3	14.78	15.29	13.41	14.40	12.78	12.80	10.41
Fe_2O_3	4.82	5.99	7.54	6.82	8.59	7.74	7.63
FeO	5.82	4.64	3.61	5.80	6.05	6.56	7.49
MnO	0.17	0.17	0.14	0.21	0.19	0.32	0.36
MgO	7.26	6.98	6.12	3.88	6.10	4.88	7.08
CaO	10.90	9.62	11.11	8.87	9.20	8.67	11.21
Na_2O	2.77	3.22	3.02	4.86	3.70	4.31	2.88
K_2O	0.57	0.75	0.50	1.29	0.68	0.70	0.25
P_2O_5	0.34	0.37	0.32	0.55	0.36	1.19	0.52
H_2O^+	2.74	2.66	2.28	1.59	2.23	2.17	2.12
H_2O^-	0.38	0.33	0.64	0.27	0.09	0.11	0.14
CO_2	0.93	0.86	1.95	0.62	0.27	0.29	0.54
Total	99.19	99.59	99.14	99.01	99.81	99.48	99.15

metagabbros and metadolerites, the latter being present in a smaller proportion, while the lower part is dominated by metadolerites cut by several metabasalt veins. After a tectonic contact at a depth of ca. 280 m, dolomite and evaporite represent the Silica Nappe.

Among the boreholes studied, the borehole **Bódvarákó Br-4** displays the most complex geological profile. In the upper part, two serpentinite slices separated by thin (ca. 30 m) dolomite and dolomitic marl layers are found. Below the serpentinites, coarse-grained metagabbro and metabasalt occur. The lower part of the section consists of sedimentary rocks of the Silica Nappe, with 200 meters of Upper Permian evaporite and a few tens of meters of Anisian Gutenstein Dolomite.

Summarizing the comprehensive description of the boreholes we can say that the metamafic rocks of the BVOC do not form a single tectonic unit at present, as they are imbricated with the unmetamorphosed sedimentary sequences of the Silica Nappe, and the profiles of the studied boreholes are quite different from each other.

Analytical methods

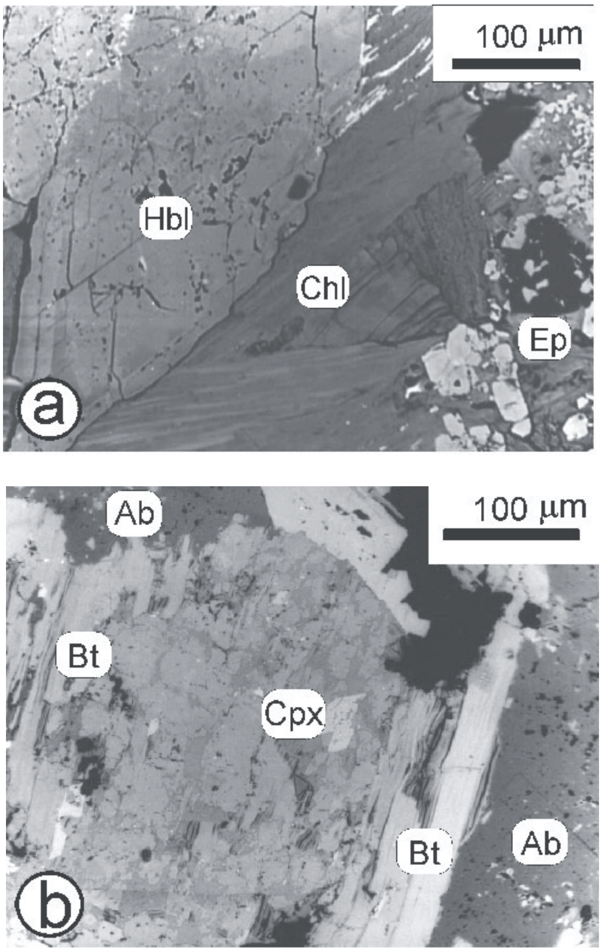
In addition to macro- and microscopic investigations bulk chemical and electron microprobe analyses were performed to check the chemical composition of the major rock-forming minerals and the eventual effects of the whole-rock chemistry on them.

The major element chemical analyses were done by a Perkin-Elmer 5000 AAS, using lithium metaborate digestion in the Laboratory for Geochemical Research, Hungarian Academy of Sciences. Other methods such as gravimetric for SiO_2 and H_2O, permanganometric for FeO and volumetric for CO_2 were also applied.

Qualitative and quantitative chemical analyses of minerals were carried out by a JEOL JXCA-733 electron microprobe equipped with 3 WDS, using the measuring program of Nagy (1984) in the Laboratory for Geochemical Research, Hungarian Academy of Sciences. The measuring conditions were 15 kV, 40 nA, defocused electron beam with a diameter of 5–10 μm, measuring time 5 s. Matrix effects were corrected by using the method of Bence & Albee (1968). The following standards were used for quantitative analysis: orthoclase (K, Al, Si), synthetic glass (Fe, Mg, Ca), spessartine (Mn), rutile (Ti) and albite (Na). Statistical (absolute) errors expressed as 1 σ are as follows: SiO_2 — ±0.3, TiO_2 — ±0.05, Al_2O_3 — ±0.05, FeO — ±0.2, MgO — ±0.1, MnO — ±0.05, CaO — ±0.1, Na_2O — ±0.03, and K_2O — ±0.02 %. Some analyses were done at the Department of Petrology and Geochemistry of the Eötvös University, Budapest, using an AMRAY 1830 I/T6 scanning electron microscope, under operating conditions of 15 kV accelerating voltage and 1–2 nA specimen current. In order to avoid the effects of the different measuring systems, repeated analyses of the same measuring points of some of the samples were performed by both electron microprobe analysers. The calculations of cation numbers for amphiboles follow the scheme of Robinson et al. (1982).

Petrography

Thin section studies reveal that despite the strong metamorphic effects most of the investigated metagabbro samples preserved their original magmatic textures. Neither schistosity nor lineation could be observed. The investigated samples can be divided into three main types, namely: metagabbros (and -dolerites), metabasalts and albitites.



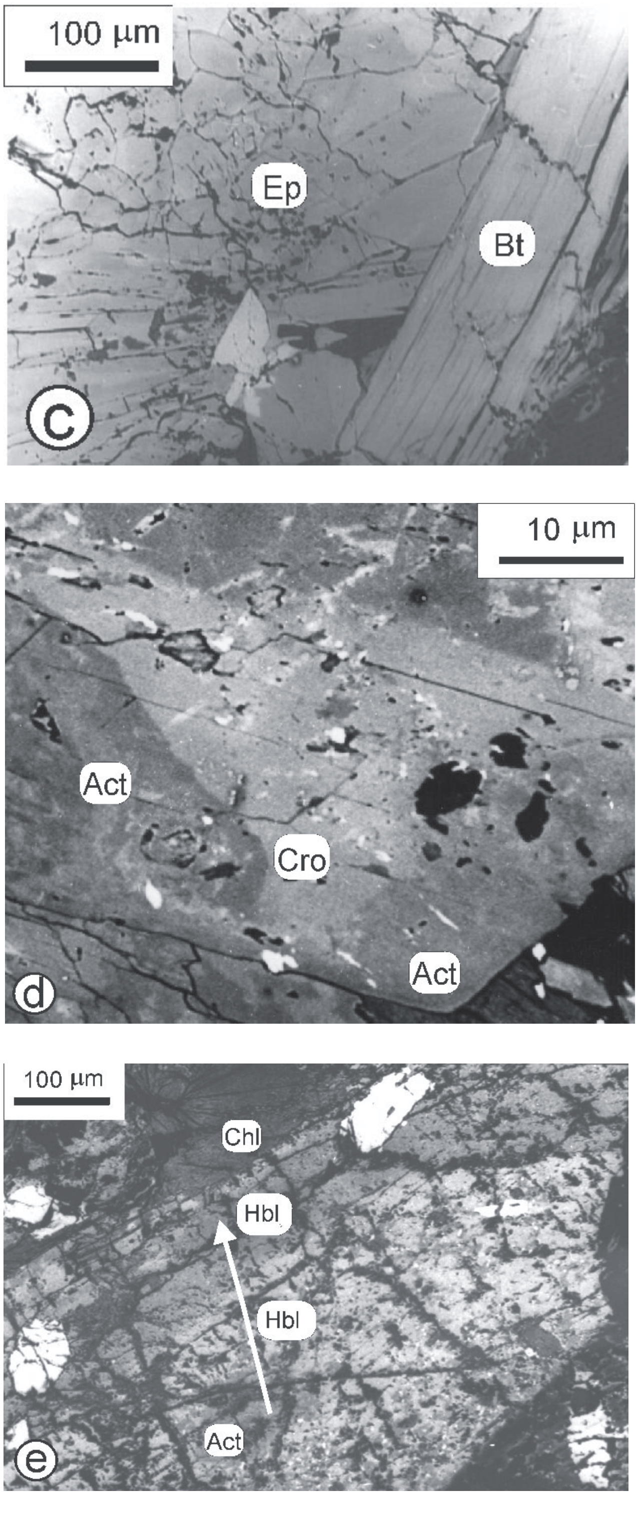


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Fig. 3. BSE images of textural features in the BVOC samples. Abbrevations are after Bucher & Frey (1994). **a** — The stable association of hornblende-chlorite-epidote in metagabbro, **b** — relic magmatic clinopyroxene rimmed by biotite and albite, **c** — biotite-epidote assemblage in metagabbro, **d** — relic crossite in actinolite, **e** — actinolite core rimmed by zoned hornblende (Hbl_1 and Hbl_2) with chlorite (arrow marks the chemical compositions presented in Fig. 4a).

The dominant rock type of the studied boreholes is coarse-grained (>5 mm) *metagabbro*. Its variants exhibit ophitic to subophitic texture, and sometimes grade into finer-grained (1–3 mm) *metadolerite*. Metagabbros and metadolerites consist of actinolite, hornblende, epidote, albite, chlorite, quartz ± clinopyroxene, blue amphibole, biotite, titanite, Fe-Ti-oxides, apatite and zircon. In these rocks the association actinolite and/or hornblende, epidote, chlorite, albite and quartz is the dominant mineral assemblage (Fig. 3a). Clinopyroxene is a relic magmatic mineral in the Szögliget and Bódvarákó gabbros. It shows pinkish pleochroism and is rimmed by amphibole or biotite (Fig. 3b). Blue amphibole shows blue-violet pleochroism, usually rims the brownish hornblende and occurs also as fissure fillings. Actinolite with pale brown-green or green pleochroism is abundant and rims both the hornblende and the blue amphibole and contains them as relics as well (Fig. 3d) or is rimmed by hornblende (Fig. 3e). Actinolite is sometimes sprinkled with an aggregate of small, green euhedral biotites. The other type of occurrence of biotite is brown flakes together with epidote rimming clinopyroxene (Fig. 3b and 3c). Biotite was found only in the Szögliget and Bódvarákó gabbroic bodies, where relic clinopyroxene was preserved as well. Epidote is also abundant and shows euhedral and subhedral forms. Two types of epidote can be seen: big (up to 5 mm) crystals and smaller crystal aggregates, which sometimes rim the bigger ones. Albite commonly displays subhedral forms and is twinned occasionally. Chlorite is found in the matrix and forms pseudomorphs after clinopyroxene. Apatite, titanite, zircon and Fe-Ti-oxides were found as accessory minerals. In some cases apatite and titanite form cm large crystals.

Metabasalts show intergranular or intersertal texture, with matrix consisting of chlorite, albite, epidote and opaque minerals. Replacing phenocrysts and filling amygdules we can find abundant actinolite, chlorite, calcite, minor albite, epidote and biotite. The metabasalts are cut by numerous veins filled usually by actinolite, calcite, and rarely calcite-epidote-chlorite assemblage is found as well. The metabasalt complex sometimes grade into metadolerites or cut them.

Albitites are present only in the Komjáti-11 borehole. Phengite and chloritoid were found with apatite as an accessory phase in the albitite veins additionally to albite and chlorite (Horváth 1997). Aggregates of chloritoid and matrix phengite seem to be in equilibrium with each other, while chlorite was found in the albite-rich matrix. Albite and apatite contain varying amounts of fluid inclusions, which may be the target of future investigations.

Mineral chemistry

Results only from the gabbros and their diagnostic metamorphic mineral assemblages containing amphibole, biotite, chlorite and epidote, are presented in this paper. The mineral chemistry of preserved magmatic phases and the other metamorphic rocks (metabasalts and albitites) and their role in the magmatic and/or metamorphic evolution of the BVOC will be discussed separately. Cation numbers are calculated for 23 oxygens for amphibole, 22 for biotite, 20 for chlorite and 12.5 for epidote.

Table 2: Representative chemical compositions of amphiboles from the BVOC.

	Na-amphibole		Na-Ca-amphibole		Actinolite		Hornblende	
SiO_2	54.24	53.81	48.20	48.36	55.14	52.98	46.47	51.17
TiO_2	0.00	0.00	2.63	2.86	0.31	0.53	0.33	1.09
Al_2O_3	4.48	4.14	4.33	4.40	1.18	1.79	7.61	4.76
FeO^*	23.42	23.65	17.72	17.71	11.33	14.21	14.71	10.62
MnO	0.00	0.00	0.32	0.36	0.18	0.29	0.19	0.23
MgO	7.34	7.40	12.06	12.05	17.26	14.05	13.96	16.93
CaO	2.39	2.68	8.10	8.32	11.92	11.45	12.05	11.47
Na_2O	5.46	5.18	2.89	2.99	0.57	1.04	2.10	1.93
K_2O	0.00	0.00	0.59	0.65	0.05	0.15	0.45	0.15
Total	97.33	96.86	96.84	97.70	97.94	96.49	97.87	98.35
Si	7.831	7.816	7.093	7.082	7.782	7.777	6.791	7.238
Al^{IV}	0.169	0.184	0.751	0.759	0.196	0.223	1.209	0.762
Al^{VI}	0.593	0.525	0.000	0.000	0.000	0.087	0.102	0.031
Ti	0.000	0.000	0.291	0.315	0.033	0.058	0.036	0.116
Fe^{3+}	1.308	1.365	0.992	0.865	0.404	0.093	0.582	0.466
Mg	1.579	1.602	2.645	2.630	3.631	3.074	3.041	3.569
Fe^{2+}	1.519	1.508	1.189	1.304	0.933	1.652	1.216	0.791
Mn	0.000	0.000	0.040	0.045	0.022	0.036	0.023	0.028
Ca	0.370	0.417	1.277	1.305	1.802	1.801	1.887	1.738
Na	1.528	1.459	0.825	0.849	0.156	0.296	0.595	0.529
K	0.000	0.000	0.111	0.121	0.009	0.028	0.084	0.027
Total	14.897	14.876	15.214	15.275	14.968	15.155	15.566	15.451

Amphibole shows a wide range of chemical compositions even in the same sample, and it looks heterogeneous locally in some BSE images with varying Fe/Mg (Fig. 3a,d). Representative analyses of amphiboles are given in Table 2. Horváth (1997) found evidence for the existence of several generations of amphiboles: namely a magmatic, and two metamorphic ones. The subdivision of Ca-amphiboles is based on the fact that magmatic Ca-amphiboles are enriched in Ti, Al and Na, and depleted in Si as compared to metamorphic amphiboles (Mével 1988 and Sadek Ghabrial et al. 1996). Relic Na-amphiboles [riebeckite, according to the nomenclature of Leake et al. (1997), Fig. 4c] and Ca-Na-amphiboles (winchite) together with actinolite and magnesiohornblende were found, which formed the first evidence of polyphase metamorphism in the BVOC (Horváth 1997). The preservation of relic magmatic or metamorphic amphiboles is a common phenomenon in metabasic rocks. However we have to emphasize that magmatic amphiboles were not found in the Szögliget and Bódvarákó samples. Beside these data new mineral chemical data published in this paper reveals a systematic change in the mineral chemistry of metamorphic Ca-amphiboles depending on the various P-T conditions experienced by the rock samples. The metamorphic Ca-amphiboles from the Szögliget samples are edenite-pargasite or magnesiohornblende according to the nomenclature of Leake et al. (1997), while the Komjáti amphiboles fall into the actinolite or magnesiohornblende field (Fig. 4a,b). Some relic barroisite and winchite (Na-Ca-amphiboles), with intermediate Na_{M4} (around 0.7) and Al^{IV} (0.8–0.9) compared relatively to Na-amphiboles and hornblendes, were also found (Fig. 5) in the Komjáti and Szögliget samples. Two generations of metamorphic Ca-amphiboles were found in the Komjáti samples, as was also shown by Horváth (1997). This fact could also be the result of differences in the bulk

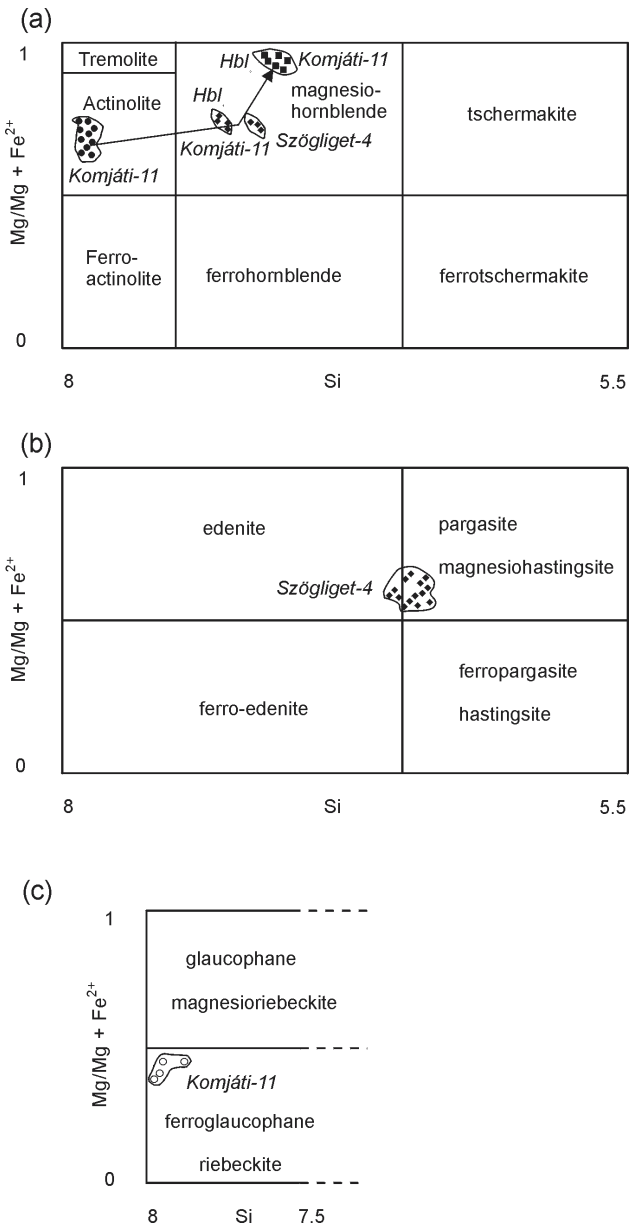

Fig. 4. Chemical compositions of Ca-amphiboles **(a, b)** and Na-amphiboles **(c)**. The arrow indicates the change in chemical composition observed in the Komjáti samples (Fig. 3e).

chemistry of the samples occurring on the microdomain scale. Taking into account that we found zoned Ca-amphiboles with an actinolitic core rimmed by magnesiohornblende (Fig. 3e and 4a) this interpretation is not supported by the author. We think that the systematic change from actinolite to magnesiohornblende (Fig. 4a) is a result of changing P-T conditions and can be used for geothermobarometric calculations. Hornblendes are usually richer in Al and poorer in Si compared to actinolites (Table 2), while their Na_{M4} content is almost the same (Fig. 5). These changes are reflected in the chemistry of chlorites as well, but in the opposite order, as chlorites found in equilibrium with hornblende have lower Al and higher Si content than chlorites in equilibrium with actinolite (Table 3).

Table 3: Representative chemical compositions of minerals from the BVOC.

	Biotite		Chlorite		Epidote	
SiO_2	36.49	39.22	23.96	25.38	37.94	37.21
TiO_2	4.36	3.28	0.08	0.17	0.07	0.04
Al_2O_3	13.75	14.31	17.8	16.68	24.27	26.03
FeO^*	22.56	15.66	22.14	20.96	12.22	9.59
MnO	0.26	0.29	0.37	0.49	0.07	0.03
MgO	10.5	16.03	18.13	19.67	0.09	0.06
CaO	0.04	0.01	0.03	0.04	23.26	23.92
Na_2O	0.36	0.25	0.02	0.01	0.00	0.02
K_2O	8.73	9.94	0.37	0.44	0.01	0.01
Total	97.05	98.99	82.90	83.84	97.93	96.91
Si	5.554	5.658	5.339	5.548	3.198	3.079
Ti	0.499	0.356	0.013	0.028	0.004	0.002
Al	2.467	2.433	4.675	4.297	2.411	2.539
Fe^{2+}	2.872	1.889	4.126	3.831	0.000	0.000
Mg	0.034	3.447	6.022	6.408	0.011	0.007
Fe^{3+}	0.000	0.000	0.000	0.000	0.861	0.597
Mn	2.382	0.035	0.070	0.091	0.005	0.002
Ca	0.007	0.002	0.007	0.009	2.101	2.121
Na	0.106	0.070	0.009	0.004	0.000	0.003
K	1.695	1.829	0.105	0.123	0.001	0.001
Total	15.614	15.719	20.366	20.339	8.592	8.352

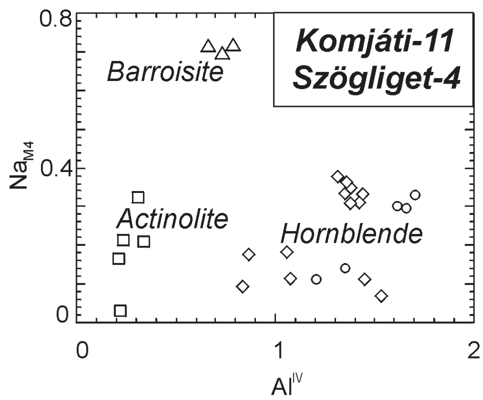

Fig. 5. Al^{IV}-Na_{M4} diagram for Na-Ca- (triangles) and Ca-amphiboles from Komjáti-11 (squares and circles) and Szögliget-4 (diamonds). Note that actinolites have lower Al^{IV}, but relatively the same Na_{M4} content compared to hornblendes.

Biotite is the dominant mafic mineral in the Bódvarákó gabbros and it occurs in the Szögliget rocks as well. X_{Mg} ranges from 0.45 to 0.65 while the Ti content is up to 0.73 p.f.u. in some analyses (average Ti content is between 0.5 and 0.6). There is no chemical difference between the various textural occurrences of biotite. *Chlorite* is a common mineral in the studied rocks. It has X_{Mg} values between 0.58 to 0.65 in all rock samples. *Epidote* has a restricted chemical composition with the pistacite content ranging from 20 % to 30 %. *Plagioclase* was found as pure albite. Representative analyses of biotite, chlorite and epidote are listed in Table 3.

Thermobarometry

Amphibole-bearing assemblages have often been proposed as potential geothermobarometers, because the paragenesis of amphibole-plagioclase is very common in metabasic rocks, and is stable over a very wide P-T range (e.g. Spear 1993). There are several potential geothermobarometers used in metamorphic petrology involving various Ca-amphiboles and Ca-bearing plagioclase (e.g. Plyusnina 1982 and Holland & Blundy 1994). However, only a few can be applied to albite-bearing metabasic rocks. Albite may be in equilibrium with Ca-amphibole even at 600 °C at low pressures as shown by Spear (1993).

In this study the empirically calibrated (Na,Ca)-amphibole-albite-chlorite-epidote-quartz geothermobarometer of Triboulet (1992) was used in the system SiO_2–Al_2O_3–FeO–MgO–CaO–Na_2O–H_2O. It considers two equilibria with tremolite-edenite and tremolite-(pargasite, hastingsite) end members, respectively. The results of mineral chemical analyses obtained from amphiboles and coexisting epidote and chlorite give way to the calculation of two arrays of $\ln K_D$ (distribution coefficience) isopleths. The calculation procedure of $\ln K_D$ values follows the scheme described by Triboulet (1992). The isopleths for these equilibria intersect at high angles and define a P-T value for the end-member compositions of amphibole in the above mentioned assemblage. Additionally the geothermobarometer of Gerya et al. (1997) was also used. It requires only the chemical compositions of amphiboles in P-T calculations using the isopleths of the Al and the Si contents of amphiboles.

The P-T conditions for the earliest blueschist facies event is poorly constrained, because the assemblage Na-amphibole + epidote + albite + quartz is stable over a wide range in the P-T field. Minimum pressure of 700–800 MPa at temperatures around 350–500 °C were obtained using the experimental work of Maruyama et al. (1986) for the blueschist-greenschist transition. For actinolites from the Komjáti-11 samples we obtained pressures of 400–600 MPa from the Na_{M4} content of the actinolites (0.4–0.7) which is an empirical geobarometer proposed by Brown (1977), and temperatures between 350 and 400 °C with the same pressure range using the geothermobarometer of Triboulet (1992). This is in good agreement with the results of Horváth (1997). The Na_{M4} content of the metamorphic hornblende is between 0.4 and 0.7 for the Szögliget and Komjáti amphiboles. For these assemblages the P-T conditions are 400–600 MPa and 500–600 °C for Komjáti-11, and 500–700 MPa and 550–600 °C for the Szögliget-4 gabbros. In the Szögliget samples there is only a trace for the earlier blueschist and greenschist facies event observed and better preserved in the Komjáti-11 gabbros. For the Bódvarákó samples the P-T conditions are poorly constrained. The occurrence of biotite-epidote assemblage replacing magmatic clinopyroxene implies temperatures around 400–450 °C at 400–600 MPa (Bucher & Frey 1994). In some samples small, green biotite can be seen on large actinolite crystals as a newly formed phase which confirms the results stated above. The results of the thermobarometric calculations and the inferred P-T path for the BVOC gabbros are given in Fig. 6.

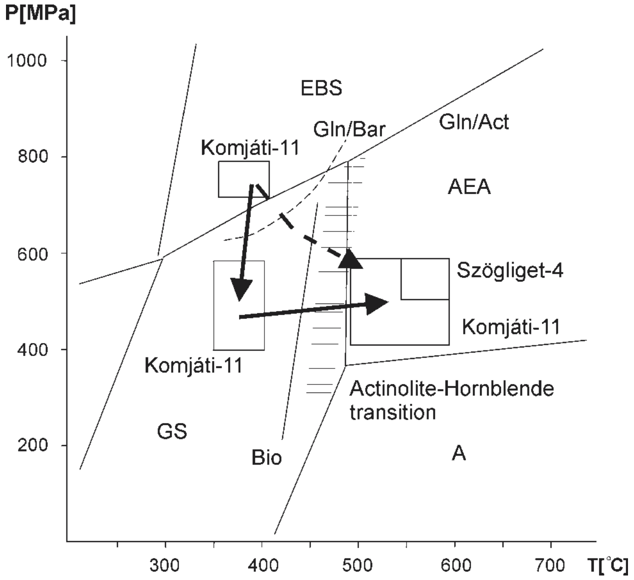

Fig. 6. Inferred P-T path of metamorphosed gabbroic rocks from the BVOC (broken arrow represents an alternative P-T path). **A**: amphibolite facies, **AEA**: albite-epidote-amphibolite facies, **EBS**: epidote-blueschist facies, **GS**: greenschist facies (facies boundaries after Evans 1990), **Gln/Act**: glaucophane-actinolite transition after Maruyama et al. (1986), **Gln/Bar**: glaucophane-barroisite transition after Ernst (1979), **Bio**: biotite-in reaction after Bucher & Frey (1994), **Actinolite-hornblende transition** after Spear (1993).

Discussion

The metamorphic evolutionary path and the petrological features of the BVOC gabbros were determined using representative samples from 3 boreholes from the Rudabánya Mountains, NE Hungary. The obtained metamorphic petrological results are partly in good agreement with the earlier statements of Horváth (1997), and in some places amplify them. The first part of the P-T path (Fig. 5) shows clockwise shape and is a general feature of P-T paths from subduction zones with a high-medium pressure low-temperature blueschist facies event followed by greenschist facies with nearly isothermal decompression. This fact is supported by the occurrence of some Na-Ca-amphiboles, which formed after the Na-amphiboles, but before the greenschist facies overprint. The temperature increase from greenschist facies to albite-epidote-amphibolite facies (according to Evans 1990), well documented by the continous chemical changes in Ca-amphiboles (from actinolite to magnesiohornblende), can be explained by two solutions: *1* — a separate metamorphic event caused by intrusion of a hot magmatic body, or *2* — a thermal relaxation following subduction. There is no evidence for a major magmatic event after subduction which could have caused contact metamorphism in this area, so the first solution is thought to be inappropriate. The second solution is heavily favoured by the author, because various rates of uplift for different portions of the downgoing slab even in the same subduction zone seem to be a reasonable feature. This interpretation is supported by the continuous change in amphibole chemistry from the Komjáti samples and the microtextural observation of hornblende replacing actinolite in various samples. Similar changes in amphibole chemistry were reported by Dobmeier (1998) from the western Alps, where actinolite was found in the cores of some amphiboles which were replaced at the rims by hornblende. In that case the temperature increase was accompanied by a pressure increase as well, which was not observed in the BVOC.

The timing of the metamorphic events outlined above are slightly controversial in the BVOC. Sporadic K/Ar measurements (Árva-Sós et al. 1987) yield widely scattered ages between 270 and 110 Ma. The main concern with the K/Ar data is that the mineral chemical compositions of the analyzed phases were not checked before the measurements, and the formation conditions of the minerals were not cleared (magmatic, metamorphic events or even weathering). The oldest ages were obtained on amphiboles from the Szögliget Szö-4 borehole (256 ± 26 Ma) or on whole rock specimens (200–225 Ma) from the Bódvarákó gabbros. Biotite K/Ar age from a sample from the Bódvarákó Br-4 borehole yields 233 ± 10 Ma, and Ar/Ar data from the same sample shows 240 ± 2 Ma (Balogh, pers. comm.). This age data provides evidence for an Late Permian-Early Triassic metamorphic event in the BVOC, which is in contradiction to the Middle Triassic opening of the Meliata ocean proposed by various authors (e.g. Kovács et al. 1996–97 and Plašienka et al. 1998) and the Middle-Late Jurassic subduction of the Meliata oceanic basin (Maluski et al. 1993; Faryad & Henjes-Kunst 1997). Further isotope geochronological data on minerals, the magmatic or metamorphic origin of which is well constrained, are needed to solve this controversy. The other major question is the exact timing of the imbrication of the BVOC into the basal part of the Silica Nappe. It is certain that this event took place after the complex metamorphic evolution of the BVOC, because the Silica Nappe is not effected by regional metamorphic events (Árkai & Kovács 1986). The author believes that the new metamorphic petrological data presented in this paper will help to clarify some parts of the tectonic evolution of the North Hungarian area still in obscurity, even though that it raises more questions about the affinity of the BVOC nowadays related to the Meliata Unit.

Conclusions

The Alpine polyphase metamorphic evolution path of the Bódva Valley Ophiolite Complex was reconstructed using mineral paragenetic, mineral chemical and thermobarometric results obtained on metagabbroic samples from boreholes in the Rudabánya Mts., NE Hungary. The first recognizable, blueschist facies event (min. 700–800 MPa, 350–500 °C) was followed by nearly isothermal decompression to 400–600 MPa in the greenschist facies. The following metamorphic event was characterized by temperature increase up to 500–600 °C in isobaric conditions. This means that the metamorphism reached even the albite-epidote-amphibolite facies of Evans (1990). The P-T path outlined above can be best described by a subduction to at least 25 km of crustal depth, which was followed by an uplift without any significant change in the temperature conditions. The late temperature increase was caused by thermal relaxation following subduction.

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