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ENCLAVES IN THE ROCHOVCE GRANITE INTRUSION AS INDICATORS OF THE TEMPERATURE AND ORIGIN OF THE MAGMA

ĽUBOMÍR HRAŠKO[1], ALEXANDER B. KOTOV[2], EKATHERINA B. SALNIKOVA[2]
and VIKTOR P. KOVACH[2]

[1]Slovak Geological Survey, Mlynská dolina 1, 817 04 Bratislava, Slovak Republic
[2]Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences, Makarova Emb. 2, 199034 St. Petersburg, Russian Federation

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Abstract: Two boreholes in the Mo-W-bearing porphyric Cretaceous granite, located near the village of Rochovce, Western Carpathians, reveal the existence of two types of enclaves: 1. micaceous enclaves (biotite-plagioclase gneisses without quartz, with highly calcitic plagioclases) and 2. mafic microgranular enclaves (MME), with predominantly dioritic composition. In the first type, corundum, Zn-hercynite and magnetite were produced due to the high temperature melting of biotite. These are considered to be restites. The melting reactions in biotite indicate that the granite magma temperatures exceeded 800 °C at the time of the enclave melting. The mafic microgranular enclaves represent portions of mafic magma incorporated in the granitic magma. Seven types of mineralogical-petrological indicators of magma mixing were found. The chemical and Sm/Nd isotopic characteristics of the host granite and MME show that chemical and isotopic equilibration was achieved within the granite-MME system. The initial ϵNd value in granite (–3.0) indicates that some mafic magmatic material was added to the magma chamber. The apparent crustal residence age (T^*_{DM} = 1100 Ma) indicates an old, Precambrian history of the crustal source material. Thus, the Rochovce magma was derived from a crustal source, with addition of more mafic (probably mantle-derived) magma.

Key words: Western Carpathians, Cretaceous, granite, mafic microgranular enclaves, micaceous enclaves, mixing, Sm/Nd isotopes.

Introduction

The hidden Cretaceous Rochovce granite intrusion in the Western Carpathians has attracted the attention of research workers since seventies because of its geotectonic position, geochemical, petrographic and mineralogical features and Mo-W mineralization potential. The former investigations concern: geological-petrographic and petrological features related to the granite and its host rocks (Klinec & Macek 1979; Klinec et al. 1980; Korikovsky et al. 1986; Krist et al. 1988; Korikovsky et al. 1989; Radvanec 1994); mineralogical-geochemical and metallogenic features (Ivanov 1984; Határ et al. 1989; Gregor 1992); isotopic-geochronological features (Kantor & Rybár 1979; Kovach et al. 1986; Cambel et al. 1989; Repčok et al. 1992; Žák et al. 1994; Hraško et al. 1995) and metallogenetic features (Václav et al. 1988, 1990).

The study of enclaves in the Rochovce intrusion provides a better understanding of the genesis of the granitic magma.

Geological context

The Rochovce type granite intrudes into an area intersected by a major regional tectonic zone (the Lubeník Line), which separates two mega-tectonic blocks, the Veporic and the Gemeric Superunits (Fig. 1). They are bound to a system of shear zones running in an E-W direction, oblique to the strike of the Lubeník Line, which marks a zone formed during the Alpine collision of the two structural mega-blocks.

The following rock types crop out in the area (from NW to SE): porphyritic granitoids of the Vepor type (Variscan), with frequent superimposed Alpine deformation and recrystallization, aplites and aplitic granitoids, migmatitized metasediments, Early Paleozoic metasediments of the Hladomorná dolina Complex, metasediments of the Revúca Group (Vozárová & Vozár 1982), composed of the Slatvina (Stefanian C-D) and Rimava (Permian) Formations.

The Gemeric Superunit, represented in this area by the Ochtiná Formation (Vozárová in Bajaník et al. 1981), was thrusted over the Veporic Superunit, along the Lubeník Line which marks the trace of the thrust plane. The contact between the two megablocks was intruded by an Alpine granite body elongated in an E-W direction (Fig. 1). U-Pb dating, done on abraded zircons, gives to this intrusion a concordant age of 81–82 Ma (Michalko in Hraško et al. 1995).

Description of the Rochovce granitoid

The petrographic features of the Rochovce granitoid have been recorded in the papers of Klinec et al. (1980) and Határ et al. (1989). The latter authors specified two intrusive phases, the younger one being a differentiate, which contains the Mo mineralization.

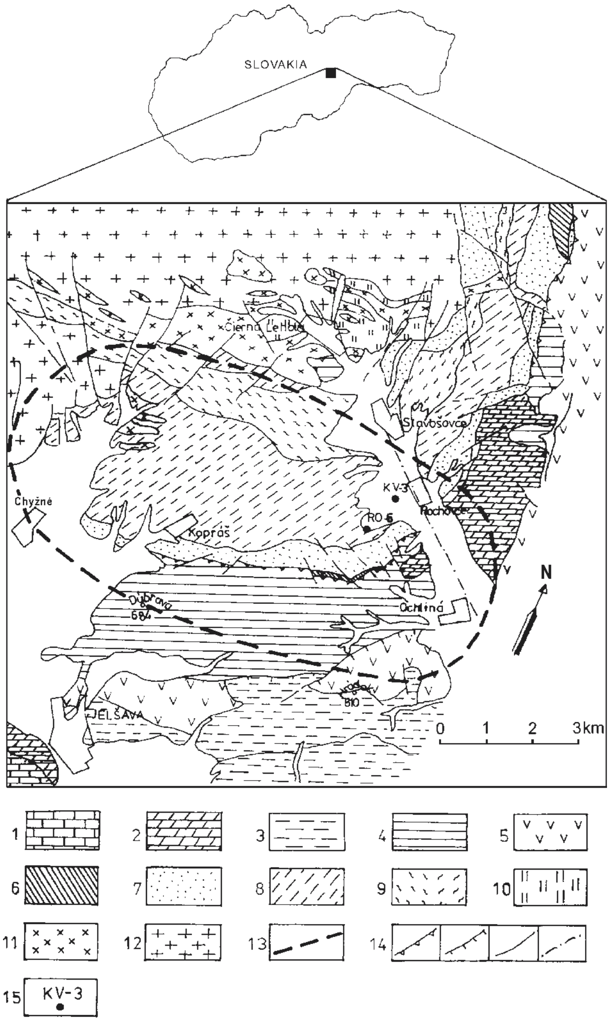


Fig. 1. Simplified geological map of the Rochovce area (modified after Bajaník et al.,1984): 1 — Silica Nappe (Lower Triassic), 2-5 Gemeric Superunit; 2 — Meliata Group (Triassic-Jurassic), 3 — Gočaltovo Group (Permian), 4 — Dobšiná Group (Carboniferous), 5 — Gelnica Group (Cambrian? Silurian); 6 — 12 Veporic Superunit; 6 — Foederata Group (Lower Triassic), 7 — Rimava Formation (Permian), 8 — Slatvina Formation (Stefan C-D) and part of the Hladomorná valley Complex (Lower Paleozoic), 9 — Slatvina Formation, 10 — Kráľová hoľa Complex— migmatites, gneisses (Lower Paleozoic?), 11 — leucocratic aplitoidic granitoids (Upper Carboniferous-Permian?), 12 — predominantly porphyric granitoids (Lower Carboniferous), 13 — geophysically indicated Rochovce granite intrusion, 14 — nappes, strike slips, observed and inferred faults, 15 — drill holes.

The *first phase* of granitoids, which represents the northern part of the body, includes: a) coarse-grained to porphyric granites with phenocrysts of pink potassium feldspars; they predominate at greater depths; b) granite porphyries, locally with parallel fabric, predominating in the marginal parts of the body; c) different varieties of mafic magmatic enclaves. Only this type of granite contains MME and rarely micaceous enclaves. The magmatic accessory mineral association is allanite-titanite-magnetite(+ maghemite)-zircon-apatite-thorite.

Leucogranitoids from the *second phase*, located predominantly in the southern portion of the body, are free of enclaves. Radvanec (1994) has proposed a model, in which the granites of this phase evolved in a process of melting of metasediments, subjected to temperatures of 650 °C and pressures of 9 kbar.

Types of enclaves in the Rochovce intrusion

The studied enclaves come from a coarse grained porphyric monzogranite (first phase) intersected in the borehole KV-3, which reached the deepest part of the granitic body. Three types of enclaves were observed:

1. xenoliths — non melted, irregular, angular small enclaves from the overlying rocks, i.e. mainly contact hornfelses, or metagabbros.
2. micaceous (surmicaceous) enclaves are very scarce, with diffusional or lentiform shape up to 5 cm in diameter, randomly distributed in granite.
3. mafic microgranular enclaves (MME), with predominantly dioritic characteristics.

The sizes of enclaves vary from a few cm. Enclaves up to 20 cm are scarce. The latter two types are important as they can be used to characterize the granitic magma source for the Rochovce intrusion.

Petrographic and mineralogical characteristics

Micaceous enclaves

The enclaves of this type occur locally in the form of diffusional, or lentiform features, up to 3-5 cm in diameter. The fabric is slightly parallel, locally randomly oriented and the

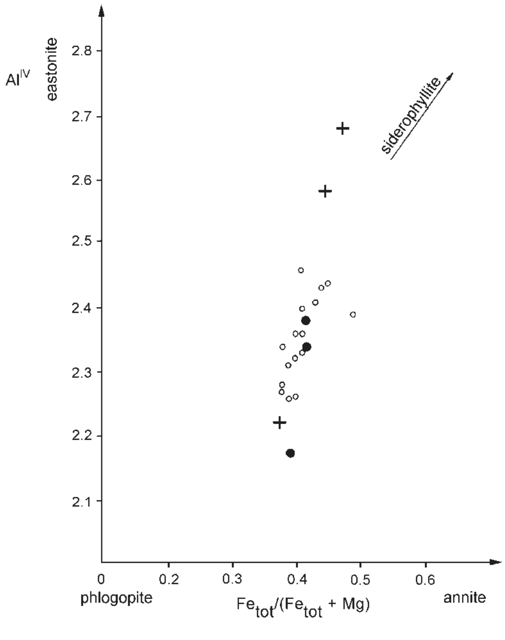


Fig. 2. Al^{IV}- Fe_{TOT}/ (Fe_{TOT}+ Mg) classification of biotites; void circles — granite biotites, full circles — MME biotites, crosses — micaceous enclave biotites.

texture is granolepidoblastic. They were classified as biotitic-plagioclase gneisses (biotite content is more than 40 vol.% and plagioclase content more than 45 vol.%). They do not contain any quartz. Small amounts of the following minerals occur: K-feldspar, amphibole, epidote, magnetite, corundum, spinel with Zn-hercynite composition, apatite, titanite, zircon and allanite. The modal composition of a representative example of these enclaves is given in Table 1.

The composition of *plagioclases* ranges between An_{30} and An_{50}. Rare relics of the calcic labrador (An_{60} or more, Table 2), form patches in less calcic plagioclases (non peristeritic) in the vicinity of the corundum crystals. Even more calcic plagioclases (probably bytownite or anorthite) are present. However, their composition could not be specified, due to their small size.

Compared to the biotites found in the granite and/or mafic microgranular enclaves, these *biotites* are more aluminous (Table 3, Fig. 2). The composition of biotites from the most recrystallized portions resembles that of biotites in the MME and granite (see also Határ et al. 1989).

Corundum forms irregular grains up to 0.5 mm in diameter. The marginal parts may be replaced by white mica. Due to superimposed alterations its relation to the higher-temperature mineral assemblage is problematic. However, it is often included in plagioclase, when biotite is around. Corundum, in a sample from a depth of 899.6 m, contains: Al_2O_3 (97 wt. %) and Fe_2O_3. BEI image (Pl. I: Fig. 1) shows a high temperature mineral association replaced by a lower temperature association (white micas-zoisite). The typical texture of micaceous enclave is shown in Fig. 3.

Spinel occurs in the form of beer-bottle-green grains, grouped in large clusters and associated with tiny magnetite grains. The grain size is less than 0.1 mm. They are considered to represent the ultimate desintegration product of biotite. Its composition corresponds to that of the Zn-Mg bearing hercynite (Table 4). It is frequently associated with the magnetite in a matrix composed of very fine-grained white micas and epidote-zoizite group minerals — products of superimposed alteration.

Alterations: substitution of the corundum by white micas is the most distinct type of subsolidus alteration. Microprobe study revealed that the phyllosilicate minerals are concentrated in an envelope, the margarite being in the internal and the phengite in the ex-

Table 1: Modal compositions of the micaceous enclaves and MME (in vol. %). *Abbreviations:* Pl — plagioclase (in MME — andesine-oligoclase), Ab — in MME oligoclase-albite, Kfs — K-feldspar, Qtz — quartz, Bt — biotite, Hbl — hornblende, Chl — chlorite, Mag — magnetite, Ser — sericite (margarite, phengite), Zrn — zircon, Spn — sphene (titanite), Aln — allanite Ap — apatite Acc — accessories (allanite, zircon, apatite, corundum, hercynite), Cal — calcite, Ep — epidote, Zo — zoizite/clinozoizite, + — present under 0.1 vol.%.

Enclave	Depth (m)	Pl	Ab	Qtz	Kfs	Bt	Hbl	Mag	Ap	Zrn	Spn	Aln	Chl	Ser	Cal	Ep	Czo	Acc
Micaceous	899.6	46.1			+	43.9		4.2					1.5	3.6			+	0.6
	1376.4	52.4			0.2	40.0	0.1	6.5					+	+		+	+	0.8
MME	1036.6	30.8		2.4	44.2	8.2	8.3	2.3	1.1	+	0.4	+	0.6	+	+			
	1084.2	65.1		0.8	0.2	21.1	6.2	2.1	1.7	+	+	+	2.7	+				
	1145.3	63.8				12.8	9.2	0.1	+	+			11.1	+				
	1153.3	59.7		3.8	1.9	27.5	0.4	1.3	3.1	0.1	0.1	0.3	1.3	0.5	+			
	1422.5	5.6	11.4	3.5	70.7	5.4		1.0	0.7		0.4	0.2	0.5	0.5				
	1471.5	53.1	0.8	7.5	14.7	15.1	2.7	1.2	1.0	0.2	0.3	0.2	0.9	+	0.2			
	1471.5	52.2	4.6	2.0	29.0	16.8	2.0	0.9	0.6		0.2	0.2	1.0	+	0.3			

Table 2: Compositions of plagioclases in the MME and in the micaceous enclaves.

Enclave	MME				MME						Micaceous	
Point	1/13	1/11	1/14	A-1/1	1	3	4	2/5	2/4	3/1		
Depth (m)	814.0	814.0	814.0	1153.3	1471.5	1471.5	1471.5	1471.5	1471.5	1471.5	899.6	899.6
SiO_2	56.38	60.80	64.42	63.08	56.27	60.67	64.54	64.16	57.37	62.35	51.93	51.40
Al_2O_3	27.57	24.37	22.73	23.54	26.53	24.22	21.64	22.63	27.45	24.48	30.40	30.43
CaO	9.20	5.56	3.54	4.44	8.42	5.71	3.00	3.74	8.44	5.58	12.46	12.52
Na_2O	5.88	7.78	9.48	8.50	6.45	8.14	9.80	8.39	6.01	7.93	3.85	3.70
K_2O	0.12	0.32	0.19	0.19	0.15	0.33	0.29	0.28	0.19	0.22	0.12	0.07
FeO	0.09	0.20	0.09	0.00	0.02	0.16	0.13	0.13	0.17	0.30	0.26	0.05
Total	99.24	99.03	100.45	99.75	97.84	99.23	99.40	99.33	99.63	100.86	99.02	98.17
	Recalculated to 8 O											
Si	2.545	2.724	2.829	2.790	2.575	2.719	2.863	2.840	2.573	2.740	2.373	2.368
Al	1.467	1.287	1.176	1.227	1.431	1.279	1.131	1.180	1.451	1.268	1.638	1.652
Ca	0.445	0.267	0.166	0.210	0.413	0.274	0.143	0.177	0.405	0.263	0.610	0.618
Na	0.515	0.676	0.807	0.729	0.572	0.707	0.843	0.720	0.523	0.676	0.341	0.330
K	0.007	0.018	0.011	0.011	0.009	0.019	0.016	0.016	0.011	0.012	0.007	0.004
Fe	0.003	0.007	0.003	0.000	0.001	0.006	0.005	0.005	0.006	0.011	0.010	0.002
Total	4.982	4.979	4.992	4.967	5.001	5.004	5.001	4.938	4.969	4.970	4.980	4.974
Type and	xenocryst		matrix		lagthy plagioclase			matrix	lagthy plagioclase		near contact	
position	rim	internal			centre	inter.	rim		center	inter.	biotite-corundum	
Or	0.72	1.90	1.08	1.13	0.88	1.89	1.64	1.73	1.16	1.30	0.73	0.43
Ab	53.25	70.33	82.00	76.73	57.59	70.71	84.14	78.85	55.66	71.07	35.61	34.70
An	46.03	27.77	16.92	22.14	41.53	27.40	14.22	19.42	43.18	27.63	63.66	64.87

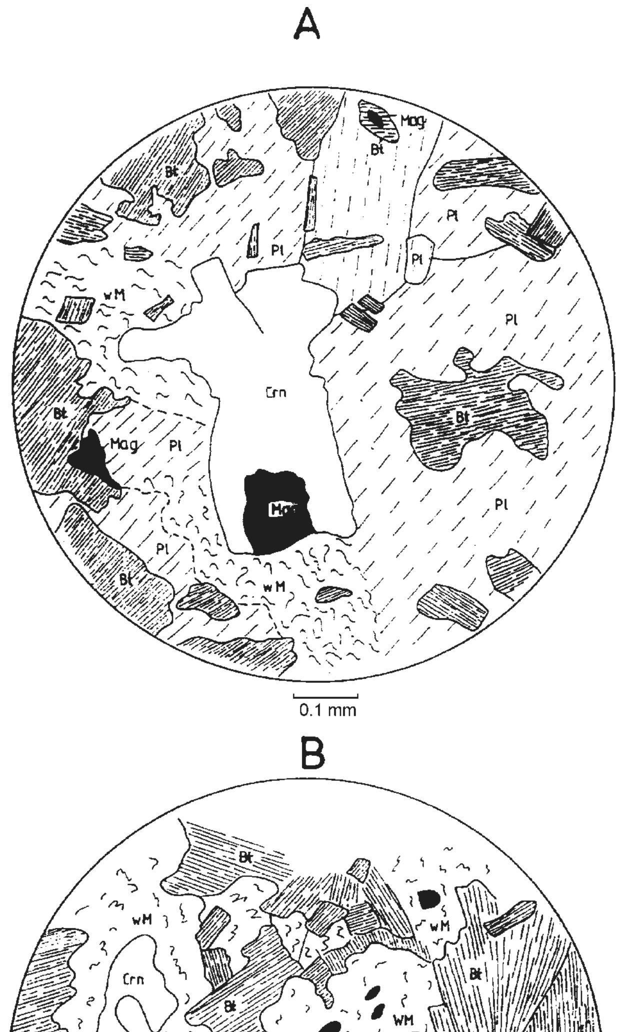


Fig. 3. Mineral associations in micaceous enclaves: **A** — corundum-magnetite-biotite-plagioclase; **B** — corundum-magnetite-biotite-plagioclase, hercynite-magnetite-biotite-plagioclase. *Abbreviations:* Crn — corundum, Mag — magnetite, Hc — hercynite, Bt — biotite, Pl — plagioclase, wM — white micas (phengite, margarite).

ternal zone. Sphalerite, formed on account of Zn-hercynite, has also been identified. Its precipitation occurred during a postmagmatic period and was followed by a fluidization stage, which was locally associated with increasing activity of sulphur and subsequent development of pyrite impregnations.

Table 3: Compositions of the biotites from the micaceous and MME (in w. perc.).

Type	micaceous			MME	MME	MME
Depth (m)	899.6	899.6	1376.6	1145.3	1471.5	1471.5
SiO_2	34.69	33.97	37.78	36.40	38.97	36.26
Al_2O_3	18.86	18.76	14.23	13.06	13.90	13.37
TiO_2	2.45	2.84	2.28	2.99	2.96	3.51
FeO	17.20	18.02	14.76	16.98	15.58	16.60
MgO	11.44	10.91	13.72	13.20	13.70	12.98
MnO	0.49	0.53	0.69	0.62	0.71	0.68
Cr_2O_3	0.04	0.02	0.00	0.00	0.00	0.02
K_2O	9.55	9.32	9.72	10.32	9.28	10.13
Na_2O	0.13	0.13	0.09	0.06	0.11	0.11
Total	94.85	94.50	93.27	93.63	95.21	93.66
	recalculated to 22 oxygens					
Si	5.280	5.220	5.780	5.660	5.830	5.620
Al	3.380	3.390	2.565	2.390	2.451	2.440
Ti	0.280	0.330	0.262	0.350	0.334	0.410
Fe tot 2+	2.190	2.310	1.888	2.210	1.949	2.150
Mg	2.700	2.500	3.127	3.060	3.054	3.000
Mn	0.060	0.070	0.090	0.080	0.090	0.090
Cr	0.000	0.000	0.000	0.000	0.000	0.000
K	1.850	1.830	1.897	2.050	1.771	2.000
Na	0.040	0.040	0.027	0.020	0.032	0.030
Total	15.780	15.690	15.636	15.820	15.511	15.740
Al-IV	2.660	2.780	2.220	2.340	2.170	2.380
Fe/ (Fe+Mg)	0.448	0.476	0.376	0.419	0.390	0.417

Table 4: Compositions of hercynites in the micaceous enclave (depth 899.6 m).

Anal. no	1	2	3	4
	Weight percent			
Al_2O_3	55.97	56.34	56.42	56.26
ZnO	7.05	6.87	13.05	12.75
FeO	31.02	31.45	25.18	25.09
MnO	2.63	2.44	1.96	1.85
MgO	3.22	3.23	3.17	3.05
Cr_2O_3	0.17	0.23	0.56	0.58
Total	99.96	100.56	100.34	99.58
	recalculated to 24 cations			
Al 3+	15.23	15.17	15.26	15.33
Fe 3+	0.77	0.74	0.51	0.43
Cr 3+	0.01	0.09	0.23	0.24
Fe 2+	5.21	5.27	4.32	4.42
Mn 2+	0.49	0.47	0.38	0.36
Mg 2+	1.10	1.10	1.09	1.05
Zn 2+	1.20	1.16	2.21	2.18
Total	24.01	24.00	24.00	24.01

Mafic microgranular enclaves (MME)

These enclaves have a mostly dioritic composition. Their size may reach several cm, rarely more than 15 cm. Their shapes are amoeboidal (Pl. I: Fig. 2), semioval to oval (Pl. I: Fig. 3), which is a typical feature for a hot and a less viscous dioritic magma, trapped within a granitic magma environment. The enclave margins are mostly sharp, or diffusional. In the latter case the tiny minerals of the MME are trapped as poikilitic inclusions in quartz and K-feldspar — the latest products of the granite magma crystallization. They are dark, or pale grey in the presence of quartz, or pinkish, in the pres-

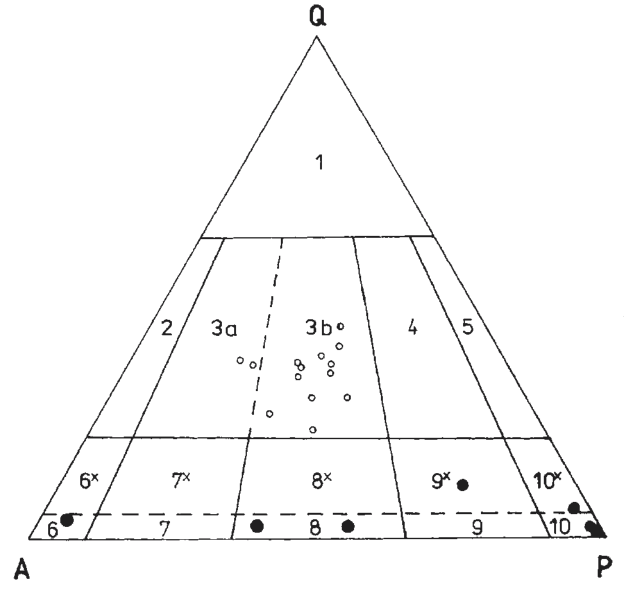


Fig. 4. Q–A–P diagram for modal composition of mafic microgranular enclaves (full circles) and associated granites (open circles). 3a — syenogranites, 3b — monzogranites, 6 — alkali-syenite, 8 — monzonite, 9^x — quartz-monzodiorite, 10 — diorite, 10^x — quartz-diorite.

ence of K-feldspar. The content of alkaline feldspars shifts the MME modal composition into the fields of quartz diorite-monzonite-syenite (Fig. 4). The composition of mafic microgranular enclaves is given in Table 1.

The texture of enclaves is massive, fine-grained and microdioritic. They locally contain larger plagioclase xenocrysts (1–5 mm), with comparable size and the type of zoning, characteristic for the plagioclases present in the granite, but with a typically thin, more calcic fringe (X_{An} ~ 0.46). The xenocrysts are several times larger than the minerals from the matrix (usually <0.1–0.5 mm). Xenocrysts of quartz and locally also amphibole and biotite are present. The plagioclase (X_{An} ~ 0.43–0.14) laths (up to 0.1 × 1 mm) are oriented at random, the spaces between them being filled with a more sodic and younger plagioclase (X_{An} ~ 0.22–0.17). They may also be included in the poikilitic quartz or K-feldspar in the matrix. The poikilitic minerals are more than ten times (more than 15–20 mm across) larger and fluently pass into the granitic matrix. In small enclaves the poikilitic minerals occupy most of the enclave area, which causes shifts of their modal composition to syenitic.

The mafic minerals are biotite (up to 27 %) and amphibole (up to 9 %). The biotite composition is characterized by a predominance of Mg over Fe (Mg/Mg + Fe = 0.58–0.61), reminiscent of the composition in the granite host (Table 3, Fig. 2). The amphibole (Mg/Mg + Fe = 0.68–0.8) not only forms individual grains, but also aggregates of small grains (Pl. I: Fig. 4), which are probably pseudomorphoses after higher temperature amphiboles. The amphibole composition is displayed in Table 5 (calculated to 13 cations). The majority of amphiboles are zonal and their composition ranges from magnesium-rich hornblende in the crystal centres, to actinolite at the margins. Using Al (Anderson & Smith 1995) as hornblende barometer, pressure during growth of aggregates, can be assessed to 1.5–2.5 kbar.

The accessory minerals comprise the elongated, prismatic, to needle-shaped apatite, locally with dusky centres, sphene, allanite, zircon and metallic ore minerals.

The amoeboidal shape of larger dioritic enclaves (Pl. I: Fig. 2) indicates that they formed fluid vesicles within the granite magma. Pale grey and pink enclaves are smaller and oval (Pl. I: Fig. 3). Their composition is more alkaline, approaching that of monzonite or alkaline-felspathic syenite. K-feldspar forms here small anhedral grains.

The microfabrics indicate that the beginning of rapid diorite magma crystallization, and formation of the dark enclaves, started after the crystallization of first generation plagioclase and quartz in the granitic magma. These, early-crystallized minerals, were later included in a form of much larger xenocryst within the fine-grained matrix. The ocellar quartz xenocrysts, surrounded by tangentially oriented amphiboles (Pl. II: Fig. 2) or biotites and plagioclases (Pl. II: Fig. 3). The thermal effects of a hotter dioritic magma observed in the immediate contacts of enclaves with the host granitic magma are demonstrated by the formation of plagioclase envelopes, surrounding K-feldspar crystals (Pl. II: Fig. 4), thus resembling a rapakivi structure.

Geochemical and Sm/Nd isotope characteristics of a MME and a granite

Owing to the small amount and size of enclaves the chance to collect a sample for chemical analysis (Table 6) was quite limited. Only one granite sample taken at the depth of 1222 m and one MME sample from 1036.6 m (borehole KV-3) were submitted to the Sm/Nd isotope analyses (Table 7).

Geochemical characteristics of a MME

The MME sample (Table 6) represents a monzonitic variety. The petrographic observations have shown that its composition, enriched in K, reflects a process of mingling and mixing of the mafic and felsic components and biotitization processes, rather than the primary magma composition of the MME.

Comparing the composition of the MME with granite, an enrichment in Fe, K, Li, Rb, Cr, Zr, LREE, Y and Th can be noted. This difference is partially of primary origin. The chemical transfer between the granite and the enclave can result in the increased contents of SiO_2, K_2O, Li, Zr, Nb, Y and REE in enclaves (Orsini et al. 1991). Mechanical mixing of the granite magma crystals with the MME magma enhances the effects of this process.

Several authors (in Orsini et al. l.c.) noted that the least acidic composition enclaves has in each association the highest contents of K_2O, Rb and Li. They relate this to a chemical transfer of alkalies from the acidic magma. Increased contents of Y, Nb, Zr and REE can be explained in the same way. Thus this process is probably controlled by the modal abundances of biotite and amphibole — the principal concentrators of the above mentioned elements in an enclave. K, Rb, Zr

Table 5: Compositions of the amphiboles from the MME (depth 1145.3 m)

Point in	Core	Inner part	Rim
SiO_2	46.61	47.89	52.31
Al_2O_3	6.32	5.21	2.22
TiO_2	0.63	0.51	0.18
FeO	14.49	13.46	10.49
MgO	12.96	13.16	16.14
CaO	11.32	11.60	11.68
MnO	0.94	0.74	0.97
K_2O	0.59	0.46	0.19
Na_2O	1.27	1.06	0.60
Total	95.13	94.09	94.78
recalculated to 13 cations			
Si	6.982	7.240	7.665
AI-IV	1.018	0.760	0.335
Post. T	8.000	8.000	8.000
AI-VI	0.099	0.168	0.049
Fe 3+	0.663	0.309	0.374
Ti	0.071	0.058	0.020
Mg	2.895	2.967	3.525
Fe 2+	1.153	1.393	0.912
Mn	0.119	0.095	0.120
Pos. M1-3	5.000	4.990	5.000
Ca	1:816	1.878	1.833
Na	0.184	0.122	0.167
Pos. M4	2.000	2.000	2.000
Na	0.184	0.190	0.003
K	0.113	0.089	0.036
Pos.A	0.297	0.279	0.039
Mg/(Mg+Fe2+)	0.715	0.681	0.795
Type	Mg hornblend	actinol. hornblend	actinolite

Table 6: Chemical composition of the MME and granite. Explanations: ( ) — average value for granites from the borehole KV-3.

Type	MME	Granite	Granite
Depth (m)	1036.60	1131.30	1222.00
SiO_2	58.51	71.25	70.31
Al_2O_3	16.34	13.84	14.06
TiO_2	0.40	0.27	0.30
Fe_2O_3	2.54	1.20	1.08
FeO	2.75	1.22	1.37
CaO	3.40	2.29	2.58
MgO	2.07	1.14	1.16
MnO	0.176	0.051	0.057
Na_2O	3.59	3.49	3.45
K_2O	7.45	3.87	4.01
P_2O_5	0.63	0.19	0.28
H_2O+	0.03	0.25	0.48
H_2O-	0.18	0.38	0.25
Total	98.07	99.44	99.39
		ppm	
Li	32.0	32.0	32,0
Rb	190.0	106.0	98.0
Sr	509.0	440.0	520.0
Ba	1,349.9	828.6	848.4
Co	8.0	6.0	6.0
Cr	35.0	18.0	17.0
Ni	6.0	4.0	6.0
Zr	260.7	150.0	159.0
Hf	8.6	4.6	4.6
La	221.8	80.3	81.5
Ce	373.6	142.4	144.2
Nd	176.4	47.0	51.0
Sm	17.9	8.98	9.72
Eu	2.9	(1.53)	(1.53)
Tb	<1.0	0.6	0.9
Yb	3.5	2.9	2.7
Lu	0.4	0.37	0.42
Y	38.0	23.0	26.0
Nb	16.8	<20.0	20.0
Ta	<1.0	<0.2	<0.2
U	7.0	10.1	9.2
Th	34.9	24.9	28.6

and LREE enrichment in the enclaves as compared to the host granitoids and average diorites, was proved by Petrík & Broska (1989) and Broska & Petrík (1993) in the Variscan I-type granitoids of the Western Carpathians. The authors assign this enrichment to the migration of ions towards the enclave from the granitoid magma environment, in a process accompanied by biotitization. A similar, but more pronounced enrichment trend has been observed in the granite-MME pair from Rochovce.

Sm/Nd characteristics of the Rochovce Granite and MME

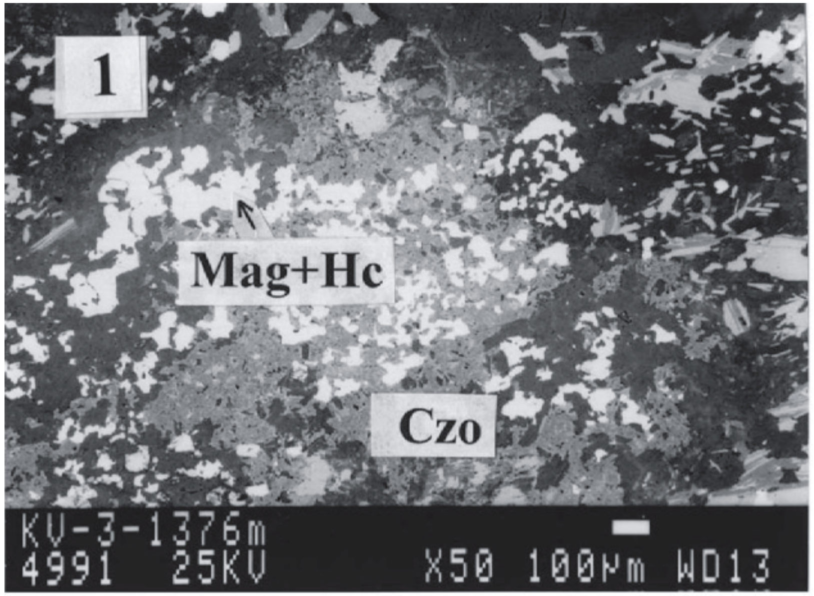
The results are shown in Table 7.

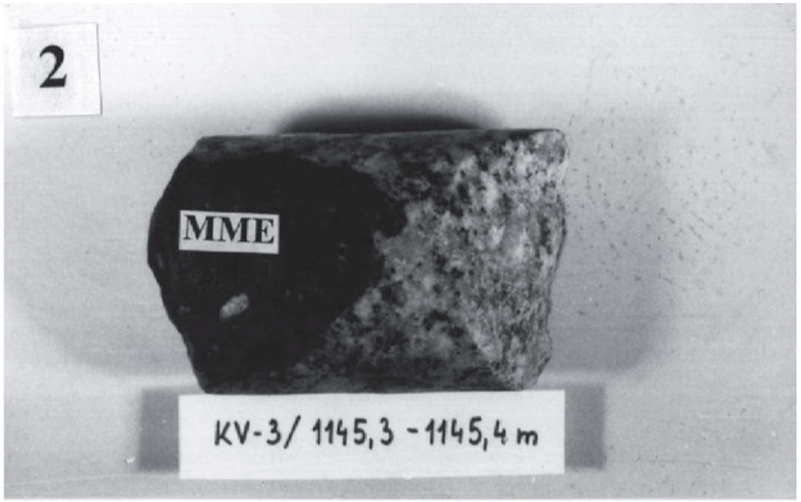
Analytical technique: Rock powders for Sm-Nd studies were analysed following the method of Richard et al. (1976). They were totally spiked with ^{149}Sm-^{146}Nd mixed solution and dissolved in a mixture of $HF+HNO_3+HClO_4$. Sm and Nd were separated using conventional cation-exchange chromatography and then extraction chromatography on HDEHP covered with teflon powder. The total blanks during the study were 0.1–0.2 ng for Sm and 0.1–0.5 ng for Nd. Isotopic measurements were performed at the Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences, St. Petersburg on a Finnigan MAT 261 8-collector mass-spectrometer in static mode. The accuracy of the measurements is: Sm and Nd isotopes ±0.5 %, $^{147}Sm/^{144}Nd$ — ±0.5 %, $^{143}Nd/^{144}Nd$ — ±0.005 % (2s). During this work the weighted average of 31 La Jolla Nd-standard runs yielded 0.511845 ± 4(2s) for $^{143}Nd/^{144}Nd$, using 0.7219 for $^{146}Nd/^{144}Nd$ to standardize. A linear model with parameters $^{147}Sm/^{144}Nd = 0.2136$, $^{143}Nd/^{144}Nd(0) = 0.513151$ was used for depleted mantle (DM) (Goldstein & Jacobsen 1988) and modern values for chondrite uniform reservoir (CHUR) (Jacobsen & Wasserburg 1980). Details of analytical technique were described in Neymark et al. (1993).

Interpretation of results: The closeness of the ∈ Nd (T) values was probably caused by an isotopic equilibration between

Table 7: Sm-Nd isotope characteristics of the granite and MME from the borehole KV-3. ($T^*_{(DM)}$— according to model Liew & Hofmann 1988).

Rock	Depth	Sm	Nd	Measured ratios			T (DM)	T*(DM)	T=81 Ma	
				$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	ENd(0)			$^{143}Nd/^{144}Nd$	ENd(T)
MME	1036.6	19.04	139.33	0.08286	0.512454+/-4	-3.6	813	1042	0.512410	-2.42
Granite	1222.0	6.73	39.28	0.10385	0.512435+/-4	-4.0	994	1115	0.512380	-3.00
	m	ppm	ppm				Ma	Ma	initial values	





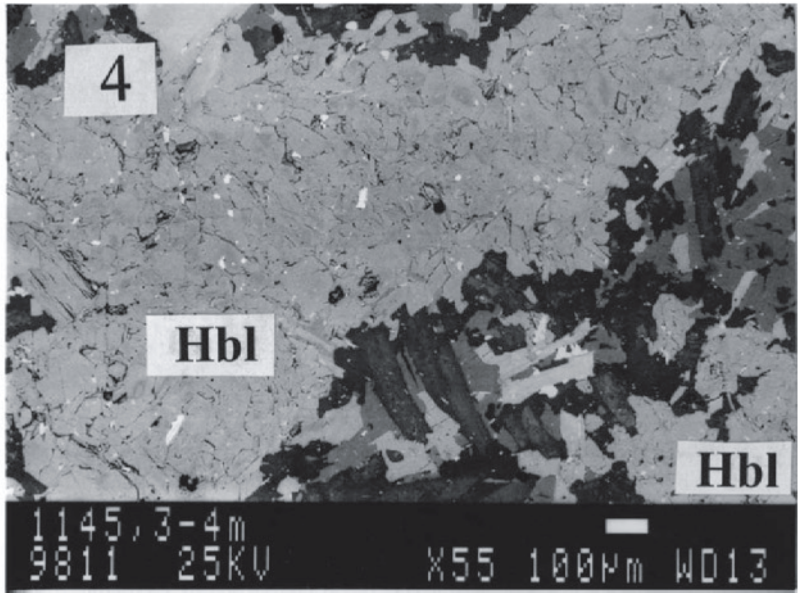
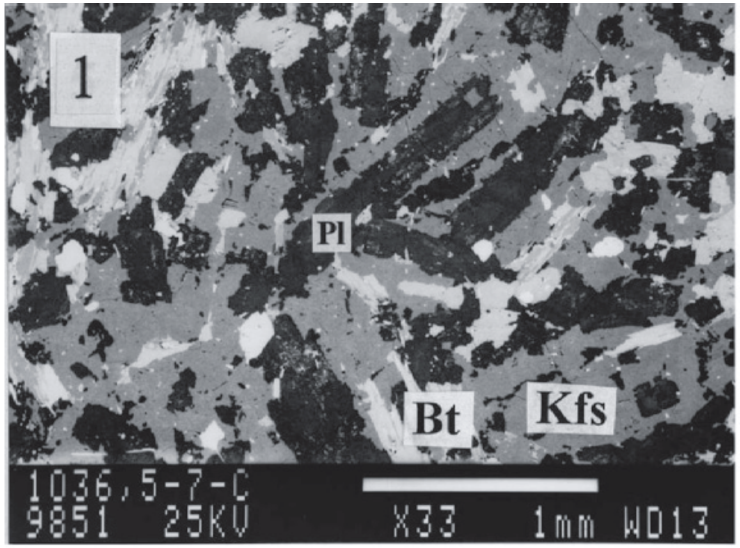
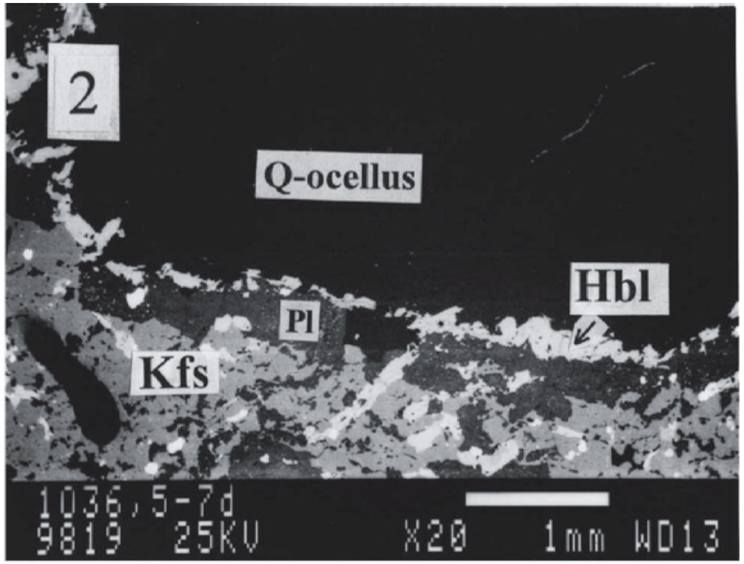
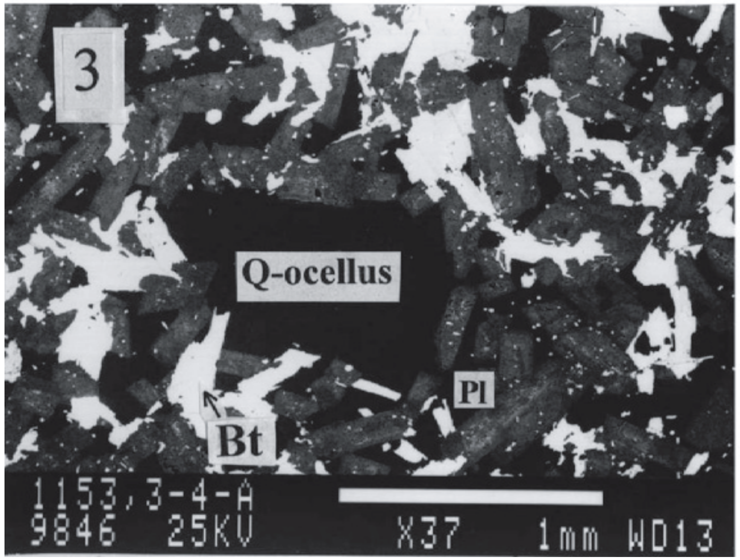


Plate I: Fig. 1 — Structure of a micaceous enclave; Mag — magnetite, Hc — hercynite, Czo — clinozoizite/zoizite, Pl — plagioclase. **Fig. 2** — Amoeboidal microdioritic enclave in granite, core diameter 7 cm. **Fig. 3** — Disc-shaped enclave rich in K-feldspar; core diameter 7 cm. **Fig. 4** — Amphibole glomeroblast in MME; BEI image.







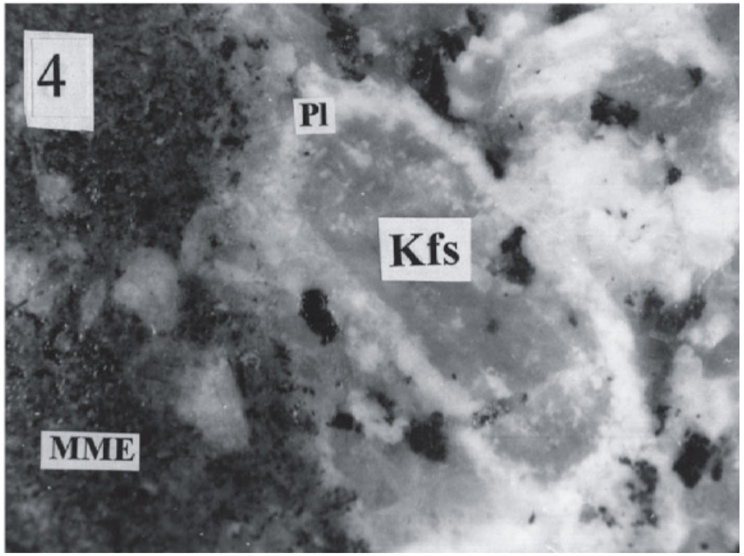


Plate II: Fig. 1 — Lath-shaped plagioclases in poikilitic K-feldspar. BEI image. **Fig. 2** — Ocellar quartz grain rimmed by tangentially oriented amphiboles (Hbl); BEI image. **Fig. 3** — Ocellar quartz grain rimmed by tangentially oriented plagioclases (Pl); microtonalitic part of the enclave (quartz — black — is poikilitic); BEI image. **Fig. 4** — Orthoclase crystal (Kfs) in granitic matrix at the contact with the MME (left side of the photo) with a plagioclase margin; photo width — 4 cm.

the granite host and the MME. This is also one of the reasons why this enclave does not have a Sm/Nd characteristic corresponding to a mantle derivation, even though it is closer to the field of the depleted mantle than granite. An example of a missing isotopic contrast between granite and associated enclaves was given by Pin (1991) to demonstrate the presence of re-equilibration processes during the high temperature magmatic regimes. Apparent crustal residence ages T(DM) characterize the time span needed for the separation of the material precursor for the Rochovce Granite from the mantle materials (including possible multiple recycling in a crustal environment). The T(DM) value indicates the existence of an old crustal, probably Proterozoic source.

Discussion

Enclaves in granitoid rocks — a source of information on the origin of magmas

Study of enclaves in granitoid rocks can provide information on the source of granitoid magmas.

Micaceous enclaves

Can be regarded as a metamorphosed crustal material. Its metamorphic nature is shown by the occurrence of planar fabric. Locally observed microfabrics indicate a considerable plastic deformation. The existence of Al-rich minerals, such as corundum and hercynite (the other Al-minerals could not be identified due to superimposed alterations), found in the intrusive granitoids, have been described especially in the enclaves enriched in micas. These minerals normally result from high temperature melting reactions of micas, aluminosilicates and Fe-Mg containing minerals, such as garnet, cordierite, staurolite, etc.

Montel et al. (1991) described the enclaves in the granites of the French Massif Central whose compositions is similar to that found in the Rochovce Granite. The micaceous enclaves from the Sidobre Massif have the following composition: 45 % biotite, 35–46 % plagioclase, less than 1 % hercynite and 3–4 % corundum. These enclaves are considered to be rocks from the source area, which did not melt owing to their special chemical composition, or they represent fragments of the host rocks, incorporated in the deeper parts — the so called deep xenoliths.

The micaceous enclaves are referred to by some authors as being the restites after the granite magma melting (e.g. Didier 1973). However, such quartz-less rocks can also develop due to the repetition of melting episodes (Montel et al. 1986), or due to a continual removal of the granite melts, generated at the beginning of partial melting (Harris 1981).

Corundum in association with spinel has been described in high degree metamorphic rocks, which formed under nearly anatectic conditions (Godard 1990), from granulites (Perchuk et al. 1989; Bertrand et al. 1992), from enclaves of predominantly metapelitic xenolithic nature, found in magmatites of either more basic (Owen & Greenough 1991), or more acid composition (Montel et al. 1991; Suarez et al. 1992). The corundum is stable in the rock free of quartz.

The stability field of hercynite expands as the gahnite component increases (Schulters & Bohlen 1989), or when the oxygen fugacity increases in the system (Hensen 1986). Increasing content of Zn shifts the hercynite stability toward higher pressures. The hercynite usually exists in both quartz-rich and quartz-free associations under either higher amphibolite facies (Harley & Fitzsimmons 1991), or contact metamorphism conditions (Pattison & Tracy 1991). Formation of the Zn-hercynite due to thermal desintegration of staurolite has also been described (Cesare 1994).

Pattison & Tracy (1991) refer to dehydration-melting reactions of biotite associated with the Al_2SiO_5, with cordierite and/or garnet, and the resulting formation of corundum and/or spinel. In all cases the K-feldspar forms simultaneously. This also happens when the muscovite melts. The corundum occurs more frequently at the contacts between the metasediments and intermediary or basic intrusives, indicating that higher reaction temperatures are needed for corundum to form.

The association of corundum with hercynite + magnetite (Fig. 3) suggests that these minerals were formed as a result of high temperature melting of a Fe-Mg-Al mineral, probably biotite. Experiments of high temperature dehydration-melting of biotite at T = 800 °C and p = 1 kbar with the f_{O2} at the level of QFM buffer (Brearley 1987a), led to the formation of hercynite and a melt along the cleavage plains of biotite, according to the reaction:

Al-rich biotite = 0.2 hercynite +0.13 melt + 0.83 Al-poor biotite.

Under natural conditions at the contact with a dolerite sill, Brearley (1987b) found that the biotite in a pelitic gneiss melts, following the reaction:

Fe-Al biotite = Mg-Al biotite + magnetite + hercynite + K-feldspar + melt/vapour.

He inferred, that the temperature of this dehydration-melting exceeded 770 °C. Such reaction could also explain the hercynite + magnetite formation in the enclaves of the Rochovce Granite and should also be responsible for the shift of the biotite composition in the enclaves (Table 3, the first two analyses) towards more magnesian types (Table 3, the third analysis), which occur in the most recrystallized parts of the enclaves.

At the same time decreasing Al content in the biotite could contribute to the formation of corundum. The presence of an An-rich plagioclase may be explained by the reaction (Suarez et al. 1992):

biotite + plagioclase$_{Ca\text{-}Na}$ = hercynite + An-rich plagioclase + melt.

Experimental melting of metagreywacke (biotite–plagioclase–quartz) composition (Vielzeuf & Montel 1994) leads

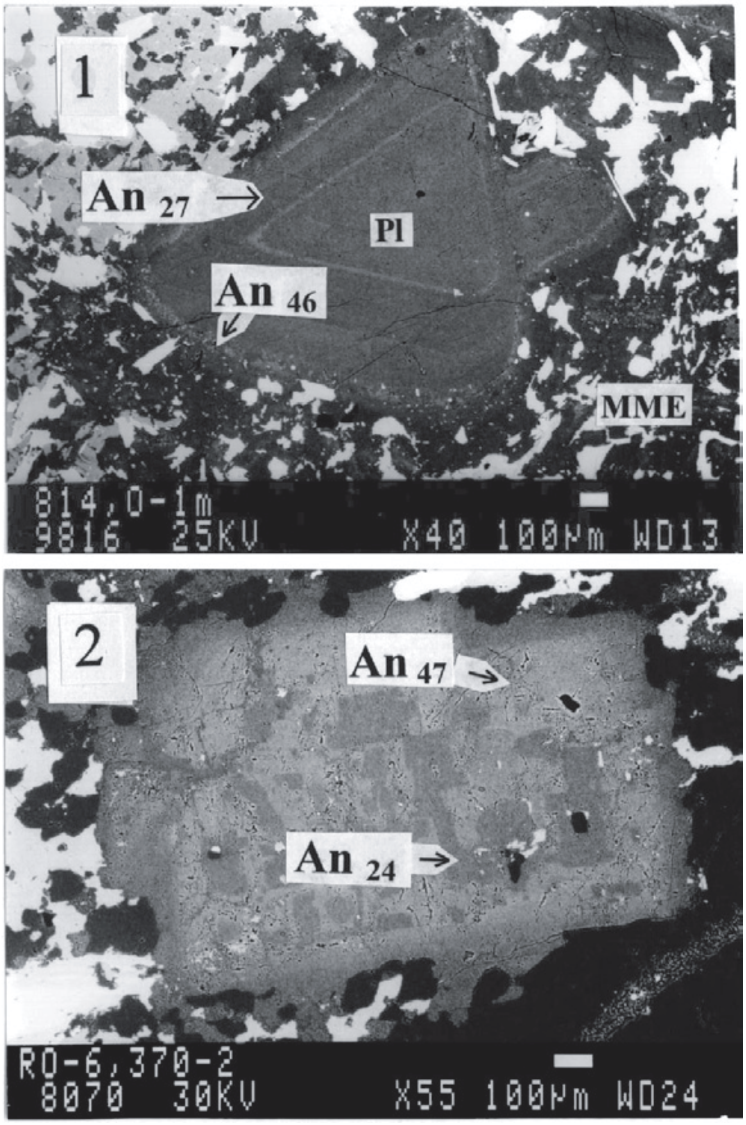


Plate III: Fig. 1 — A “granite” plagioclase xenocryst (Pl) with a calcic rim (arrow); BEI image. **Fig. 2** — Boxy cellular plagioclase in a microgranitic matrix; the lighter phase is more calcic; BEI image.

to formation of a new mineral association: garnet/cordierite/spinel + orthopyroxene + K-feldspar + melt. The temperature required for this type of melting exceeded 800 °C. Spinel was stable over the temperature range of 800–850 °C and the pressures of less than 500 MPa.

It is probable that the biotite-plagioclase gneiss enclaves in the Rochovce Granite, either represent the restites after separation of the granite melt within the Rochovce Granite magma source area (but this should produce Na-rich melt), or the so-called abyssal biotite-plagioclase gneissic xenoliths, which are the restitic mineral association after the melting of older granites. This type of xenolith was brought into the higher crustal horizons by the Rochovce granitoid. Their location at depth cannot be far away from the source area of the Rochovce granitic magma.

The high temperature melting of the biotite, obviously exceeding the boundary 800 °C, at the time of micaceous enclave melting, accompanied by corundum, hercynite and magnetite, could have taken place within a quite large pressure interval ranging from the magma source up to the area of its emplacement. The increased content of Zn in hercynite allows us to assume its formation under relatively high pressure conditions.

Occurrence of retrograde alteration of corundum or spinel with resulting formation of white micas (phengite and margarite) were already described in micaceous enclaves by several authors (Rosing et al. 1987; Montel et al. 1991; Suarez et al. 1992).

Mafic microgranular enclaves (MME)

Several hypotheses to explain the origin of MME were summarized in Didier & Barbarin (1991). The most popular is that MME are globullae of mantle-derived magmas.

The petrographic description of MME given above has shown that the magma of hotter (dioritic or more alkaline) MME had the consistency of a fluid. Due to the difference in the temperatures of the solidus of the MME magma versus the granite magma, the globullae of a more mafic magma crystallized suddenly in a form of microgranular textures. Mutual enclosures of different minerals indicate that this had taken place after the crystallization of quartz, plagioclase and also biotite and amphibole of the first stage crystallization of the granite magma, but before the crystallisation of quartz and K-feldspar of the last generations.

However, a portion of MME has a remarkably alkaline character, they are K-feldspar-rich. Didier (1987) explains the existence of K-feldspar-rich enclaves and the presence of dioritic enclaves as a result of the coexistence of various types of magma. Alkalinity increases partially due to the marginal MME poikilitic minerals being trapped in the granitic K-feldspars or in sodic plagioclase and due to high temperature diffusion (biotitization). System MME–plagioclase–poikilitic K-feldspar did not reach an equilibrium, which resulted in a substitution of plagioclase and frequent resorption (Pl. II: Fig. 1).

The following mineralogical indicators for the mixing of the felsic and mafic magma can be observed in the MME textures:

1. plagioclase margins in the orthoclase crystals developed at the contacts of dioritic MME (Pl. II: Fig. 4). It is a result of cooling-provoked epitaxial nucleation of plagioclase at the surface of orthoclase, which already existed in the granitic magma (Hibbard 1991).
2. formation of poikilitic quartz or K-feldspar or plagioclase (Pl. II: Figs. 1, 3) developed due to crystallization of large quartz or K-feldspar or plagioclase crystals from the granitic magma environment, together with crystallization of small MME minerals. This led to a dispersion of fine MME minerals throughout the quartz-K-feldspar-plagioclase poikilocrysts (Hibbard 1991).

3. ocellar texture composed of large quartz grains fringed by tangentially oriented small amphibole, biotite (or/and plagioclase) crystals (Pl. II: Figs. 2–3). It is often described in hybrid systems as being a result of mafic and felsic magma mechanical mixing (Palivcová 1978; Lindberg & Eklund 1988; Vernon 1991; Hibbard 1991).

4. acicular apatites — referred to often as being a result of mixing (Didier 1987), suggest in any case that a rapid cooling of the mafic system versus the felsic has taken place.

5. small lathy plagioclases in the MME with a length/width ratio up to 10:1 (Pl. II: Fig. 1) also indicate that cooling takes place in the MME system with respect to the granite magma. The development of more sodic margins here indicates an equilibration within a hybrid system.

6. trapping of early crystallized plagioclase xenocrysts (Barbarin 1990) from granite magma in the MME environment with typical calcic margins (Pl. III: Fig. 1).

7. boxy cellular plagioclases (composed of more calcic and more sodic feldspars) (Pl. III: Fig. 2). Hibbard (1991) noted that cooling of a more mafic system can be, at a certain stage, ideal for the development of such plagioclases. This type of plagioclase has been found in the microgranitic matrix (borehole RO-6).

The last two types of interaction can be explained using a simple binary albite–anorthite system (Fig. 5). An acidic melt with a composition L_1 begins to crystallize at the temperature T_1 , coexisting with a plagioclase P_1. Gradual crystallization and lowering of the temperature results in a compositional modification to the L_2 and coexistence with a more sodic plagioclase P_2. This system is intruded by a more calcic and hotter dioritic melt with a composition D and the temperature T_D. The resulting hybridic melt L_H has a more calcic composition and a higher temperature T_H, compared to the L_2 and a more calcic plagioclase with a composition P_3 crystallizes out of it at the T_3 liquidus temperature. The P_3 plagioclase with a composition close to An_{50} crystallized in the form of tiny laths and represents a dioritic matrix, or has formed more calcic thin margins fringing the older plagioclase xenocrysts, or has resorbed the older, more acidic plagioclases, accompanied by formation of the boxy cellular plagioclases.

The plagioclases with the An_{50} (more calcic ones could not be identified due to alterations), as well as the occurrence of boxy-cellular plagioclases in granite we consider to be mineralogical indicators of mixing in the granites. Interrupted zoning and resorption in plagioclases of the first generation of granite (observed by Klinec et al. 1980 and Határ et al. 1989), may not only be a result of decreasing pressure, but also of an increase of temperature, caused by more mafic and hotter magmas.

The mafic magma could have been primarily derived from a more basic — mantle source. The MME magma could also have been modified by mixing of mafic magma with a small amount of acidic magma of crustal composition, or could have been contaminated with crustal material. In any case, its temperature exceeded that of the granitic magma, which conforms with a higher temperature source, located at greater depths.

A similar problem refers to the granite. The above mentioned mineralogical indicators for the mafic and felsic magma interactions support the concept of a hybrid origin of the granitic magma. At a shallower level the extent of interaction was time-limited due to both, considerable differences between the two contrasting magmas and by the small volume of the mafic member. However, in deep areas of felsic magma ascent the conditions should have been favourable for a complete mixing (Barbarin & Didier 1992), which would result in formation of a chemically homogeneous product. The generation of a hybrid magma due to mixing of contrasting magmatic members could only have taken place if their rheologic properties were compatible (Huppert et al. 1984; Barbarin & Didier 1992). Decreasing temperature induces the crystallization of basaltic magma and an increase in its viscosity to match that of the granitic magma (inversion temperature T_I of Fernandez & Barbarin 1991). The overstepping of the T_I due to rapid crystallization of small MME in the Rochovce Granite probably resulted in their behaviour as relatively rigid objects within a more plastic environment; this is why the elliptic features, resembling boudins, were formed. The larger MME, whose viscosity was lower, whilst the crystallization process slower, behaved as liquid bodies in the granite magma.

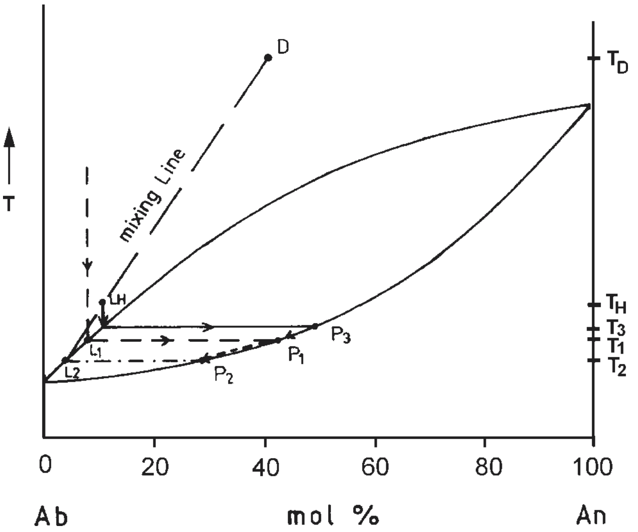


Fig. 5. Schematic representation of changing in plagioclase compositions in the albite–anorthite binary system, as a function of granitic and dioritic magma mixing (for a more detailed explanation see text).

The Sm/Nd isotope characteristics for the Rochovce Granite differ in several aspects from the isotopic data obtained for Hercynian granitoids and sedimentary-metamorphic lithologies of Central Europe (Liew & Hofmann 1988) and also for Hercynian granitoids of the Western Carpathians (Kohút et al. 1995). These are as follows:

1. The apparent crustal residence ages for the Hercynian granitoids, metamorphics and sediments range between 1400 and 1700 Ma (rarely more than that), which is a result of melting of mainly Proterozoic lithologies with some contribution from a Paleozoic component. The value for the Rochovce Granite is ~1100 Ma, some 300 Ma younger compared to the above mentioned values of Liew & Hofmann (1988), but still in the lower part of the T_{DM} span of the West-Carpathian Hercynian granitoids (Kohút et al.1995). This

difference should either be attributed to a contribution of juvenile material introduced into the magma chamber (Upper Cretaceous mantle input), or to an extensive entry of Paleozoic crustal material, while the recycled crustal source material of Proterozoic age played an important role.

2. The initial ∊ value is higher compared to that in granitoids of Central Europe. This value approaches the values for small amphibole-bearing plutons with granodiorite-dioritic composition, which occur in association with the gabbros. Such plutons are known from the area of Odenwald-Spessart, where they represent a mixture of mantle and crustal material (Liew & Hofmann 1988). Compared to ∊Nd(T) for the West-Carpathian granitoids, the value for Rochovce Granite falls again within the lower limb of this span. If we recalculate our value to the same age as the recalculated Sm/Nd isotopic values of the West-Carpathian Hercynian granitoids, our sample will have a positive ∊Nd value (~+0.4), which indicates larger input of mantle material into source region of the Rochovce granite magma.

Didier (1987) argued that the granites containing two types of enclaves, the first, rich in micas, of metamorphogenic origin and the second, mafic microgranular, of magmatogenic origin, belong to the mixed type (crustal-mantle) granites. The provenance of such granites should be sought in the lower crustal levels at the contacts with the upper mantle.

In Rochovce the granite magma ascended to a considerable level. The ultimate depth of the granite emplacement estimated on the basis of contact mineral parageneses should be of the order 100–200 MPa (Korikovsky et al. 1986; Vozárová 1990). Its prolonged crystallization history allows us to assume that this magma remained hot for a relatively long period of time. It lacked water and originated in the deeper crustal horizons. This assumption agrees with the findings, observed in these enclaves, that an abyssal source was responsible for the generation of the Rochovce Granite. The magma differentiates derived from the mantle could, to a certain degree, also participate as the co-sources of this magma. The results of Nd-Sm isotope study have shown that the source also contained some crustal material with an old history. The upper mantle played an important role in the generation of the Rochovce granite magma as a source of heat, and to some extent perhaps as a source of material.

Conclusion

Upper Cretaceous coarse grained to porphyritic, granites with phenocrysts of pink potassium feldspars and accessory mineral association: allanite–titanite–magnetite(+maghemite)–zircon–apatite–thorite, from Rochovce contain micaceous enclaves with metamorphogenic origin and mafic microgranular enclaves (MME) with predominantly dioritic compositions. The micaceous enclaves are quartz-free, biotite-plagioclase gneisses (more than 40 % biotite and more than 45 % plagioclase with An-content up to 60 %, rarely more), which are probably restites. They contain corundum–hercynite–magnetite mineral association. These minerals were formed as a result of a high temperature dehydration-melting of biotite, indicating, that the temperature of the granite magma exceeded 800 °C at the time the micaceous enclave melted.

Interactions between dioritic MME and granitic magmas show, that MME magma was hotter and chilled in a colder granite magma environment. This happens after crystallization of quartz, plagioclase (+biotite, amphibole) of the first stage crystallization of the granite magma, but before the crystallization of quartz and K-feldspar of the last generations. The MME with monzonitic to syenitic compositions are also present. Various textures in MME and granite indicate the mixing and mingling of the felsic and mafic magmas. The closeness of the ∊Nd(T) values of the granite and the MME results from isotopic equilibration. It demonstrates the presence of re-equilibration processes during the high temperature magmatic regimes. The initial ∊Nd (–3.0) value in granite allows us to assume that some mantle material has been added into the magma chamber. The apparent crustal residence age T^*_{DM} = 1100 Ma indicates an old, Precambrian history of the crustal source material. The upper mantle participated in the generation of the Rochovce granite magma as a source of heat, and to some extent as a source of material.

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