Petrology and geochemistry of the Běstvina granulite body metamorphosed at eclogite facies conditions, Bohemian Massif

Petrologie a geochemie běstvinských granulitů metamorfovaných v eklogitové facii, Český masiv

(9 figs, 7 tabs)

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The high-pressure granulites from the Běstvina body contain a mineral association garnet-kyanite-biotite-plagioclase-K-feldspar-quartz ± antiperthite. Based on petrology, as well as major- and trace-element whole-rock geochemistry, the studied eight samples can be subdivided into four types: (1) metamorphosed greywacke, (2) felsic granulite with a low CaO/Na_2O and K_2O/Na_2O ratio (type I), (3) felsic granulite of leucogranitic composition (type II), and (4) kyanite-garnet-biotite migmatitic gneiss. These rocks are associated with minor garnet peridotite and a crustal eclogite with a prograde metamorphic record, as described in the literature. Garnet in the quartz-feldspathic rocks typically contains 24–35 mol. % Prp and 5–14 mol. % Grs components with Ca zoning across grains. Using compositions of garnet cores and the associated plagioclase and biotite, the geothermobarometric calculations prove the equilibration under eclogite facies conditions (P = 1.8–2.2 GPa and T = 800–920 °C). Two of the samples important for thermobarometry (felsic granulites type I and II) are free of antiperthite. The associated Ky-Grt-Bt migmatitic gneiss recording conditions near 1.4 GPa and 670 °C may represent a foreign component in the Běstvina granulite body. Although one meta-greywacke sample shows incipient replacement of garnet by biotite + plagioclase, the other samples are free of a decompression recrystallization record. Thus the granulites of the Běstvina body stand in sharp contrast to the better known granulites in the Moldanubian Zone, by their lack of evidence for an extensive decompression recrystallization.

Key words: high-pressure granulites; eclogite facies; Běstvina granulite; Kutná Hora – Svratka Unit; Bohemian Massif

Introduction

The Bohemian Massif features several types of Variscan granulites (granulites of the Moldanubian type following Pin – Vielzeuf 1983), showing a variety of P-T-t histories (Table 8 in Janoušek et al. 2006a): a) high-PT stage followed by high-T, mid- to low-P retrogression in sillimanite stability field, typical of majority of granulite massifs in the Moldanubian Zone, b) low-P metamorphism at T=670–900 °C, Lišov granulite massif (Janoušek et al. 2006a), and c) high-PT stage followed by a weak or partial retrogression in amphibolite facies, Ohře Crystalline Complex (Kotková 1993), Rychlebské Mts. (Pouba et al. 1985, Kryza et al. 1996).

Clearly, granulites free (or nearly free) of the high-T decompression recrystallization event bear the best potential for preserving record of the high-PT stage. The Běstvina granulite body, positioned outside, but directly at the border of the Moldanubian Zone, is now recognized as a domain with abundant, high-pressure granulites, deserving additional studies.

The aim of this study was to obtain basic petrologic and geochemical characteristics of quartz-feldspathic rocks, which represent the dominant rocks types in the Běstvina body: granulites and granulitic gneisses.

Pouba et al. (1987) presented an introductory and concise geological and petrological description of the Běstvina body. Fiala et al. (1987) published a set of chemical analyses of granulitic rocks, including some minor- and trace-element data, but no information on mineral compositions and PT conditions of equilibration was included. Medaris et al. (2006) undertook a detailed study of metamorphic evolution of Spačice eclogite, recording prograde evolution history.

The current study presents detailed geochemical information on eight samples of granulitic rocks. This database is supplemented by four analyses of felsic granulites from Fiala et al (1987). One of the present authors (M.F.) was involved in a geological mapping of the 1:25 000 map sheet Vilémov, including the whole Běstvina granulite body and the adjacent geological units (awaiting publication). There is a set of ca. 300 thin sections that were used for lithological and petrographic characterization of the mapped area.

The information obtained from the Běstvina granulite body is of prime interest in deciphering the structural and lithological relations between the Kutná Hora – Svratka Unit (including the Běstvina body) and the Moldanubian complex further to the southwest (Fig. 1). Preliminary information indicated contrasting P-T-time paths of these two major units. While the Běstvina body preserves the original eclogite facies mineral assemblages equilibrated in the kyanite stability field, the Moldanubian rocks show an evidence for a typically late, nearly isothermal decompression in the sillimanite stability field.

Whole-rock geochemical data are implemented to define compositionally distinct major rock types and constrain their possible petrogenetic relations. They also provide important background information for comparison of rock types showing contrasting petrological history of their protolith but a common eclogite facies metamorphic imprint.

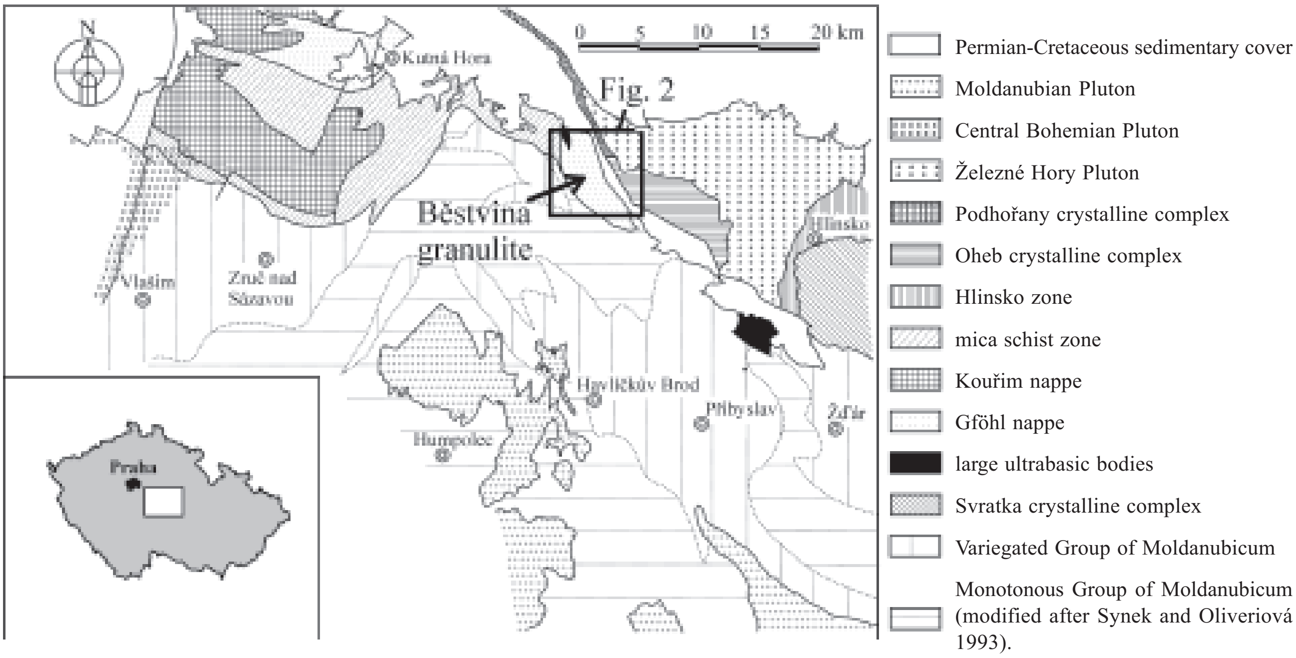

Fig. 1 Geologic setting of the Běstvina granulite (figure courtesy of Drahota et al. 2005).

Geological setting

The granulitic rocks around Běstvina form a body 8 km long and 4 km wide, elongated in the NW-SE direction (Pouba et al. 1987). Based on tectonic subdivision of the central – eastern parts of the Bohemian Massif (Synek and Oliveriová 1993), the Běstvina granulite belongs to the Kutná Hora – Svratka crystalline Unit. At the southwest the body is directly bordering the Moldanubian Zone of eastern Bohemia (Fig. 1). In the Moldanubian Zone adjacent to the Běstvina body, there is a zone of muscovite-biotite gneiss or mica schist 0.5–1 km wide. The zone contains numerous bodies of amphibolite, metagabbro and peridotite/serpentinite, which are too small to be shown in Fig. 2. The reader is referred to the published geological map 1:50 000 Golčův Jeníkov 13–43 for a more detailed information. At the northeast, Upper Cretaceous sediments onlap onto the Běstvina body, but in the northwest the Běstvina rocks border fine-grained biotite gneisses of the Malín Unit, belonging to the Kutná Hora – Svratka Unit. Position and metamorphic characteristics of granulites from the Běstvina body provide information significant for recognition of contrasting lithological units at the northeastern margin of the Moldanubian Zone.

Samples and methods

The list of analyzed samples, sample locations, rock types and analytical methods are presented in Table 1. Sample location is indicated in Fig. 2. Figure 3 shows photographs of the major rock types studied. Whole-rock analyses were acquired using wet analysis for major-elements, XRF analysis for minor- and trace-elements, and ICP-OES for REE determination (laboratories of the Czech Geological Survey, Prague). Mineral analyses were carried out using a CAMECA SX 100 WDS electron microprobe at the Joint Laboratory of Electron Microscopy and Microanalysis, Institute of Geological Sciences, Masaryk University and Czech Geological Survey, Brno. Analytical conditions were 15 kV accelerating voltage, probe current 10–20 nA, acquisition time 10–30 s. Standards used were augite (Si, Mg), almandine (Al), andradite (Fe, Ca), rhodonite (Mn), TiO (Ti), orthoclase (K), jadeite (Na), and chromite (Cr). Analyst R. Čopjaková.

Petrography

The studied rocks are fine-grained (Fig. 3), show granoblastic structure with grains mainly 0.2–1 mm across. Some K-feldspar and quartz grains reach 1–2 mm. Fig. 4 documents the equilibrium mosaic structure of Bt-Ky-Grt rock with paragneiss composition. Approximate modal compositions are given in Table 2. Notable is the presence of significant quantities of antiperthite in the rocks of paragneiss composition; only felsic granulites type I (sample MF153) and type II (sample KMV98), with rather sodic plagioclase, lack antiperthite. Light-coloured quartz-feldspathic mobilisate in samples MF159 and MF7 (Fig. 3) also contains kyanite and small-size garnet.

Geochemistry

Major- and trace-element data are presented in Tables 3a, b and plotted in diagrams (Figs 5 and 6) with the use of *GCDkit* (Janoušek et al. 2006b). Classification of the rocks is based on petrography, mineralogical composition

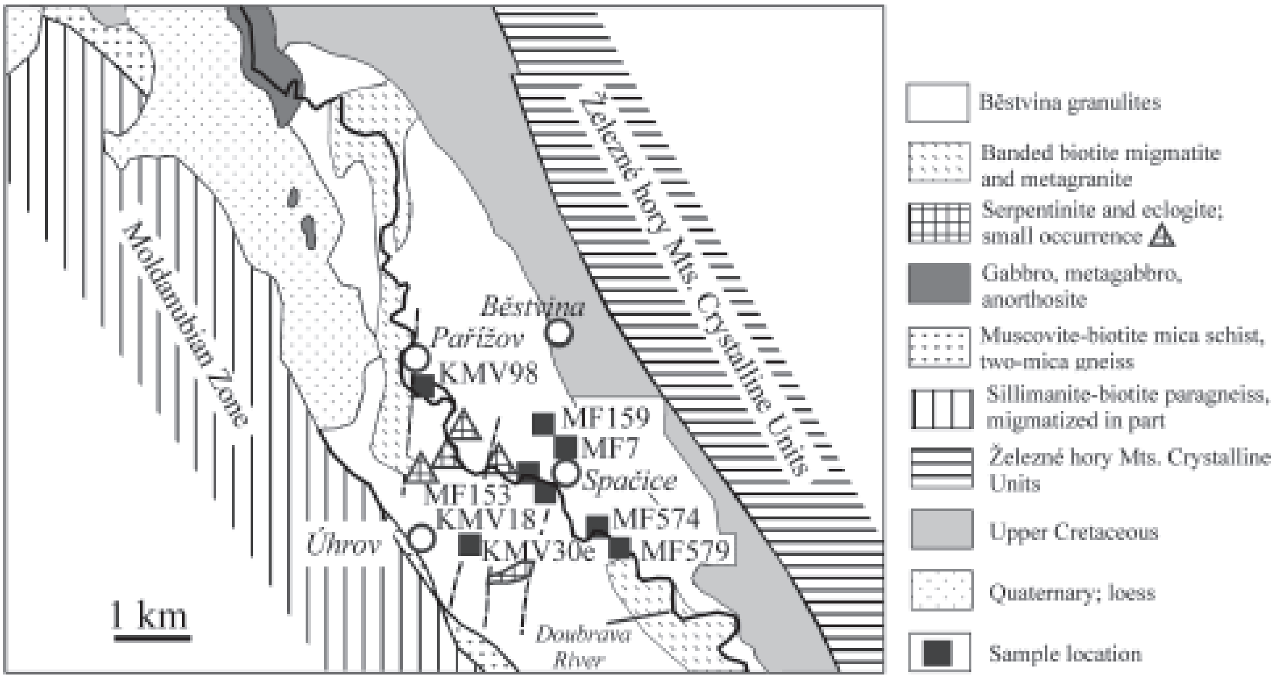

Fig. 2 Sample location in the Běstvina granulite body.

and chemical data. The following rock types have been distinguished:

1. Ky-Grt-Bt gneiss, similar to paragneiss (Fig. 3). It has SiO_2/Al_2O_3 and K_2O/Na_2O ratios corresponding to greywacke (Wimmenauer 1991) (samples MF159, KMV18 and KMV30e) or clayey greywacke (MF7). The high values of A/CNK = 1.4–2.15 are expressed by the content of kyanite and garnet. The Ky-Grt-Bt gneisses show low K_2O, Rb and P_2O_5, at relatively high Zr, Sr and REE, and increased abundances of Fe and Mg contained in garnet and biotite. The zirconium correlates positively with increasing SiO_2, corresponding to detrital zircon abundance increasing with rising proportion of quartz in the detrital material. The gneisses are weakly migmatitic with incipient stromatitic texture or small patches of leucosome (Fig. 3).
2. Ky-Bt-Grt felsic granulite, type I (sample MF153) is exposed in 20 m high cliff in the Doubrava River valley. The rock has a banded structure with minute biotite replaced by fine-grained garnet in the light-coloured domains. The rock has low CaO, Y, extremely low Zr contents and a low K_2O/Na_2O ratio; the REE contents are about half of those typical of other samples (Fig. 7). As the geochemical features rule out the presence of an ordinary detrital material, the likely protolith was a felsic igneous rock.
3. Ky-Grt-Bt felsic granulite, type II (sample KMV98 from outcrop at the Pařížov dam). It is fairly homogeneous and fine-grained rock similar in appearance to a weakly foliated leucogranite. Accessoric kyanite forms blue crystals up to 8 mm long. There is sporadic late biotite in a several mm wide veinlets of recrys-

Table 1 Sample location and types of analyses.

Sample No.	location	rock type	analyses
MF7	quarry at the northern edge of the Spačice village	Ky-Bt-Grt granulitic gneiss similar to paragneiss	WR, XRF, ICP, MP
MF159	outcrop in forest NNW of the Spačice village	Ky-Bt-Grt granulitic gneiss similar to paragneiss	WR, XRF, ICP, MP
KMV18	Spačice village, outcrop at the bridge across Doubravka River	Ky-Bt-Grt granulitic gneiss similar to paragneiss	WR, XRF, ICP
KMV30e	granulite blocks next to serpentinite quarry between Úhrov and Spačice	Ky-Bt-Grt granulitic gneiss similar to paragneiss	WR, XRF, ICP
MF153	Doubrava River valley west of the Spačice village	Bt-Ky-Grt felsic granulite, type I	WR, XRF, ICP, MP
KMV98	Pařížov dam, outcrop 60 m NE of the wall	Ky-Bt-Grt felsic granulite, type II	WR, XRF, ICP, MP
MF579	Doubrava River valley opposite the mill, north of Ostružno	Ky-Grt-Bt migmatitic gneiss	WR, XRF, ICP, MP
MF574	Doubrava River Valley north of the Ostružno village	Ky-Grt-Bt migmatitic gneiss, strong cataclastic/mylonitic deformation	WR, XRF, ICP

WR – whole-rock silicate analysis; XRF – minor- and trace-element analysis; ICP – REE analysis; MP – microprobe mineral analyses

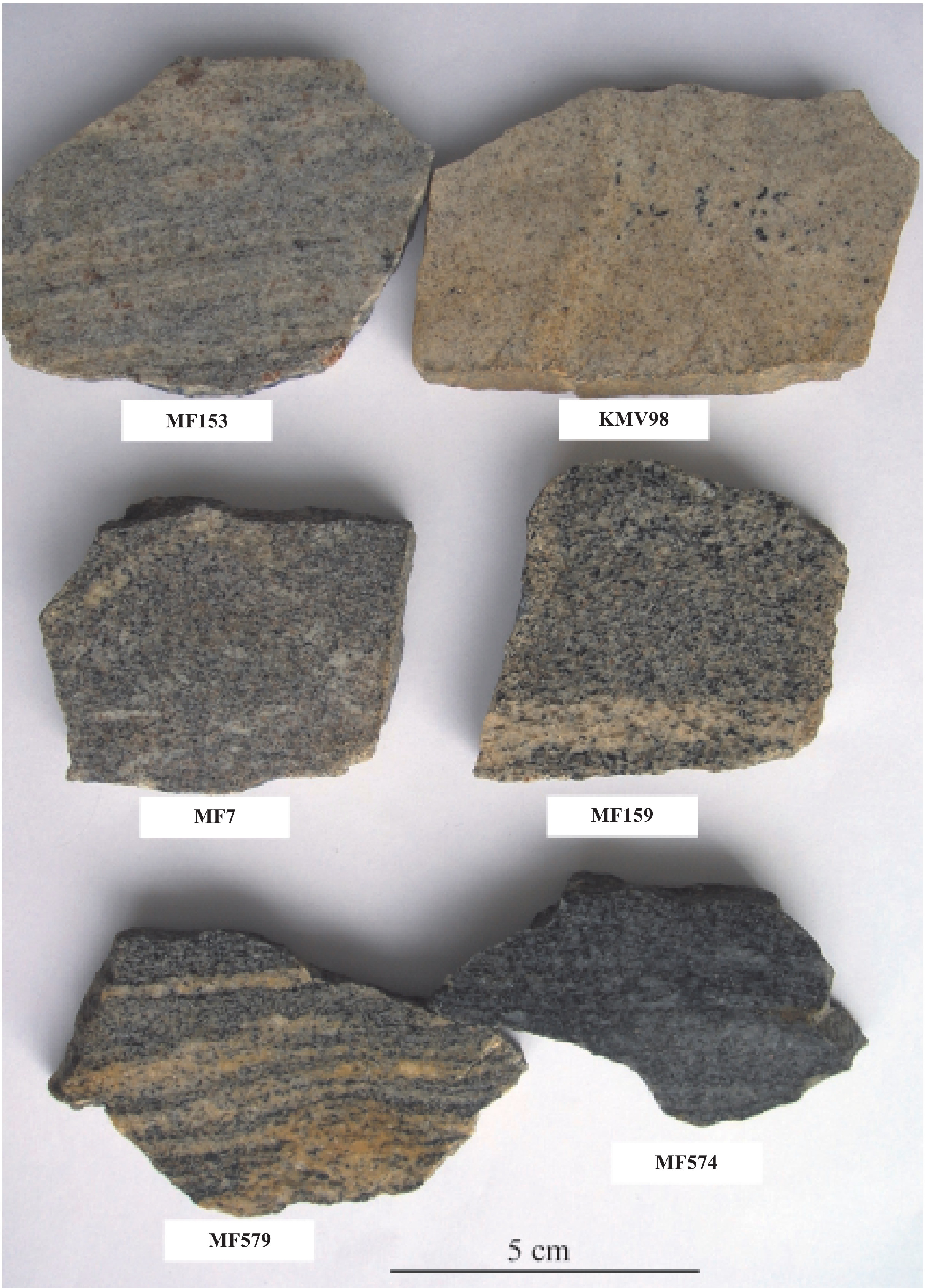

Fig. 3 Photographs of the main types of studied samples. MF153 – Ky-Bt-Grt felsic granulite type I; KMV98 – Ky-Bt-Grt felsic granulite type II; MF7 and MF159 – Ky-Grt-Bt granulitic gneiss with meta-greywacke composition; the rocks contain small domains of quartz-feldspathic leucosome; MF579 – Ky-Grt-Bt migmatitic gneiss (MF574 is a cataclastic derivate of a similar migmatitic gneiss). Sample location is given in Table 1 and Fig. 2.

Table 2 Modal composition of studied samples (vol.%).

Sample	MF7	MF159	KMV18	MF153	KMV98	MF579
Garnet	16	10	10	8	5	2
Biotite	8	10	6	4	2	8
Kyanite	10	4	5	5	1	1
Quartz	28	34	30	40	34	32
K-feldspar	7	6	12	12	30	27
Plagioclase	15	5	14	30	28	8
Antiperthite	14	30	22	–	–	21
Rutile	1	1	<1	1	0.5	<0.2
Apatite	1	+	<1	+	+	1
Graphite	+	+	+	–	–	+

Note: volume percentages are based on microscopic estimates.

tallized material (Fig. 3). Except of P and Y contents, the SiO_2/Al_2O_3 and K_2O/Na_2O ratios and abundances of some minor- and trace-elements indicate that the four chemical analyses of granulites from Pařížov reported by Fiala et al. (1987) (samples F82, F83, F84 and F109A, plotted in Figs 5 and 6) also belonged to this type II granulite.

4. Ky-Grt-Bt migmatitic gneiss MF579 has a banded stromatitic texture and a low garnet and kyanite contents. The rock has elevated K_2O and Rb at a moderate Sr concentration. The sample contains garnet with exceptionally high grossular component in cores (up to 27 mol. %), suggesting a metamorphic history dif-

Table 3a Whole-rock chemical analyses of granulites and granulitic gneisses, Běstvina, and calculated catanorm values.

Number	1	2	3	4	5	6	7	8	9	10	11	12
Sample No.	**MF7**	**MF159**	**KMV18**	**KMV30e**	**MF153**	**KMV98**	**MF579**	**MF574**	**F82**	**F83**	**F84**	**F109A**
SiO_2	59.18	70.04	66.98	66.00	76.4	73.26	72.86	72.46	73.22	73.86	74.60	74.25
TiO_2	0.50	0.44	0.66	0.44	0.14	0.10	0.30	0.28	0.41	0.40	0.31	0.28
Al_2O_3	19.58	13.61	14.75	15.52	12.91	13.96	13.70	13.97	13.37	13.91	13.11	13.53
FeO	6.82	3.69	5.12	5.26	1.43	2.16	2.02	1.98	3.17	2.50	2.37	2.24
Fe_2O_3	1.11	0.81	0.71	0.86	0.35	0.26	0.49	0.54				
MnO	0.096	0.060	0.078	0.088	0.058	0.053	0.052	0.052	0.05	0.04	0.05	0.05
MgO	2.90	1.51	2.42	2.51	1.43	0.55	1.32	0.62	0.72	0.71	0.49	0.47
CaO	1.62	1.34	1.57	1.71	0.86	1.13	1.32	1.41	1.61	1.30	1.16	1.17
Li_2O	0.011	0.010	0.010	0.012	0.023	0.007	0.007	0.007				
Na_2O	2.12	2.75	2.41	2.12	3.21	2.76	2.99	2.96	3.27	2.72	3.35	3.23
K_2O	2.57	2.50	2.34	2.56	2.38	4.42	4.72	4.49	3.92	4.23	4.32	4.53
P_2O_5	0.140	0.152	0.174	0.141	0.246	0.148	0.159	0.157	0.25	0.24	0.23	0.24
F	0.068	0.044	0.040	0.040	0.051	0.054	0.094	0.068				
CO_2	0.01	0.01	*	*	0.01	<0.01	0.01	0.01				
C	0.060	0.031			<0.005	0.026	0.015	<0.005				
S	0.209	<0.005	*	*	<0.005	<0.005	0.056	0.044				
H2O$^+$	0.61	0.71	*(1.04)	*(0.92)	0.40	0.37	0.59	0.55				
H2O$^-$	0.07	0.11	0.17	0.13	0.10	0.07	0.10	0.10				
F(eqv)	-0.029	-0.019	-0.017	-0.017	-0.021	-0.023	-0.040	-0.029				
S(eqv)	-0.052	0.000			0.000	0.000	-0.014	-0.011				
Total	97.75	97.91	98.46	98.32	99.21	99.39	100.20	99.80	100.08	99.30	100.23	98.51
Catanorm												
Q	24.071	36.421	33.042	32.188	41.945	34.159	29.903	31.701	31.031	34.773	32.140	31.816
C	12.411	5.041	6.731	7.515	4.626	3.413	2.058	2.456	1.573	3.411	1.510	1.948
Or	15.911	15.538	14.497	15.864	14.334	26.813	28.147	27.150	23.516	25.454	25.879	27.127
Plag	26.985	31.690	29.479	27.687	31.875	29.902	32.070	32.906	36.266	29.848	34.811	33.690
Ab	19.947	25.976	22.691	19.966	29.382	25.446	27.099	27.202	29.814	24.875	30.499	29.396
An	7.037	5.714	6.787	7.721	2.493	4.456	4.971	5.705	6.452	4.972	4.312	4.294
Hy	18.075	9.257	13.966	14.686	5.928	4.75	6.152	4.189	6.503	5.436	4.734	4.515
Mt	1.216	0.891	0.778	0.943	0.373	0.279	0.517	0.578	0	0	0	0
Il	0.730	0.645	0.964	0.643	0.199	0.143	0.422	0.399	0.580	0.568	0.438	0.395
Ap	0.345	0.376	0.429	0.348	0.590	0.357	0.378	0.378	0.531	0.511	0.488	0.509
Fr	0.256	0.141	0.113	0.127	0.131	0.185	0.355	0.243	0	0	0	0
Total	100	100	100	100	100	100	100	100	100	100	100	100

* loss on ignition given as H_2O^+
the last four analyses are from Fiala et al. (1987)

Table 3b Analyses of minor- and trace-elements in granulites and granulitic gneisses, Běstvina (in ppm).

Number	1	3	7	8	2	6	5	4	9	10	11	12
Sample No.	MF7	MF159	KMV18	KMV30e	MF153	KMV98	MF579	MF574	F82	F83	F84	F109A
Cr	104	59	98	88	19	15	20	17	27	23	19	<5
Ni	61	8	30	23	13	<2	9	8	<5	<5	7	<5
Cu	42	11	24	27	6	6	14	19				
Zn	117	62	57	67	51	27	41	37				
As	<1	<1	5	5	<1	<1	<1	<1				
Rb	86	73	76	83	123	141	166	155	117	108	121	133
Sr	104	156	103	113	79	56	126	135	66	61	56	60
Y	33	28	31	30.8	11	29	41	41	51	51	52	52
Zr	169	213	223	199	<1	74	117	140	101	79	76	52
Nb	14	13	12	11	5	4	6	8				
Mo	<1	<1	<1	<1	<1	<1	<1	<1				
Sn	<2	<2	<2	<2	4	<2	10	9				
Pb	<2	<2	4	<2	<2	<2	10	9				
U	4	<2	4	<2	<2	2	3	<2	0.36	0.86	0.40	0.47
La	39.90	34.10	38.50	32.00	8.90	15.60	25.50	23.30				
Ce	78.90	71.60	83.70	67.40	19.80	36.50	55.30	50.60				
Pr	10.00	8.40	9.60	8.10	2.70	4.60	5.70	5.90				
Nd	35.30	32.40	37.40	29.90	8.50	17.60	23.40	22.50				
Sm	9.14	9.65	7.28	7.47	2.98	4.90	6.00	5.38				
Eu	1.38	1.26	1.30	1.26	0.42	0.52	0.71	0.75				
Gd	7.30	6.00	7.50	6.81	2.40	4.90	5.62	5.58				
Tb	<0.70	0.90	<0.70	<0.70	<0.70	<0.70	<0.70	<0.70				
Dy	6.03	5.11	5.80	5.81	2.17	5.18	6.99	7.15				
Ho	1.62	1.19	1.18	1.33	<0.5	1.12	1.45	1.50				
Er	2.56	1.91	2.70	2.31	0.82	2.56	4.13	3.91				
Tm	0.50	0.39	0.58	0.63	<0.30	0.59	0.76	0.76				
Yb	3.61	3.19	3.43	3.46	0.98	2.97	4.15	4.06				
Lu	0.45	0.54	0.38	0.43	0.13	0.44	0.62	0.60				

ferent from the other samples. Based on chemical composition, the cataclastic/mylonitic sample MF574 can be correlated with the Ky-Grt-Bt migmatitic gneiss MF579.

Mineral chemistry

Representative mineral analyses are given in Tables 4–6.

Garnet

Garnet forms anhedral grains, 0.2–1 mm in diameter, which are free of reaction products. Quartz, kyanite, alkali-feldspar and rutile occur as its inclusions. The general zoning pattern was observed in high-contrast BSE images. Two garnet crystals have been analyzed in each of the four samples, with two spot analyses positioned at opposite rims and two analyses in the centre of the same crystal. In sample MF579 only a single garnet grain has been analyzed. The analyses demonstrate the presence of compositional zoning in garnet, of variable range in individual samples. In Ky-Grt-Bt paragneiss (sample MF 7) garnet contains 9.3 mol. % grossular (Grs) in core and 6.4 or 7.9 % Grs in rims; MF159 contains 14.6 % Grs in core and 2.4 or 4.3 Grs in rims. Felsic granulite type I (sample MF153, with a low CaO/Na_2O whole-rock ratio) contains garnet with 6.6 mol.% Grs in core and 3.6 or 5.0 Grs in rims. Felsic granulite type II of leucogranitic composition, (sample KMV98), contains 14.6 Grs in cores and 7.1 or 10.1 Grs in rims. The Ky-Grt-Bt migmatitic gneiss, (sample MF579), is poor in garnet, which shows a very strong zoning with Grs content of 24.9 mol.% in core and 2.2 or 2.9 Grs in rims. The main substitution is between Ca and Fe, as pyrope (Prp) varies only between 22 and 35 mol. %, with a slight pyrope decline in outermost rim. The sample MF579 shows a prograde zoning in Prp and overall significantly lower Prp- content of 10.0 mol.% in core and 14.9 Prp in rim. Spessartine (Sps) content is generally low (0.7–2.1 mol.%), reflecting manganese dilution in the relatively abundant garnet. The sample MF579 with a low amount of garnet (c. 2 vol. %) contains 2.6 to 3.9 Sps.

Biotite

Biotite in samples MF7 and MF153 is relatively rich in TiO_2 (4.2 to 4.4 wt. %), unlike in the rest of the samples examined (TiO_2 = 3.0 to 3.9 wt.%). The Fe/Mg ratio is rather variable, with maximum Fe/(Fe+Mg) = 0.57 in sample MF 579 and minimum of 0.29 in MF7. Biotite shows typically equilibrium relations with garnet (Fig. 4); only sample MF159 contains some secondary biotite produced at the retrogression stage.

Feldspars

Plagioclase is a sodic oligoclase ($An_{13.1–18.3}$) showing a weak zoning, with two exceptions. Homogeneous plagioclase (albite $An_{8.2–9.0}$) is present in felsic granulite type I (MF153) that has a low CaO/Na_2O whole-rock ratio. The Ky-Grt-Bt migmatitic gneiss MF579 contains a more calcic oligoclase ($An_{21.0–21.4}$). In meta-greywacke gneisses plagioclase is accompanied by significant quantities of antiperthite (Table 2), in which the host plagioclase contains c. 10 to 30 vol. % of unmixed K-feldspar. Textural relations indicate that the primary feldspar assemblage in these rocks was antiperthite, plagioclase and a weakly to moderately perthitic K-feldspar.

Potassic feldspar contains 10.2 to 19.3 mol. % Ab and 0.2 to 0.6 mol.% An components, as indicated by spot

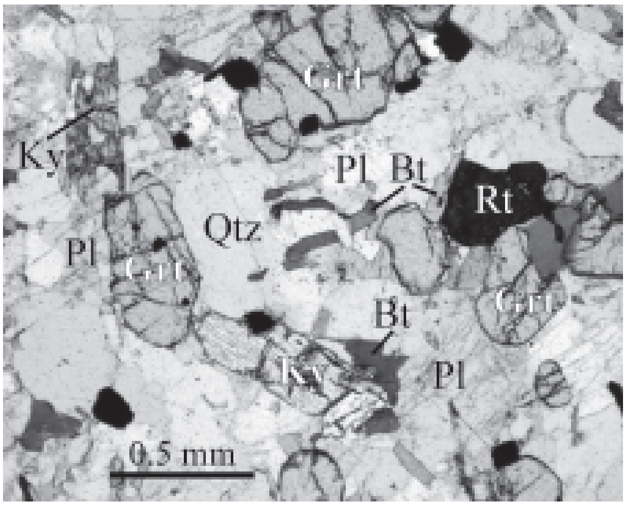

Fig. 4 Equilibrium mosaic of garnet (Grt), kyanite (Ky), biotite (Bt), plagioclase (Pl), quartz (Qtz) and rutile (Rt) in sample MF7, Spačice. Antiperthite is present elsewhere in the thin section, small opaque grains are mainly pyrrhotite. Transmitted light photomicrograph.

Table 4 Chemical composition of garnet.

Sample No.	**MF153**			**MF7**		**MF159**			**MF579**			**KMV98**		
Analysis No.	**3c***	**12c**	**4r**	**19c**	**29r**	**33c**	**34c**	**41r**	**58c**	**59c**	**57r**	**70c**	**72c**	**71r**
SiO_2	38.94	39.06	38.89	39.23	38.85	38.80	38.80	38.30	38.04	37.87	37.47	38.97	38.47	38.42
TiO_2	0.02	0.05	0.02	0.05	0.02	0.06	0.05	0.00	0.05	0.03	< 0.01	0.04	0.04	0.01
Al_2O_3	22.09	21.85	21.92	22.12	21.79	21.82	21.77	21.61	21.33	21.12	21.01	21.76	21.75	21.68
Cr_2O_3	< 0.01	< 0.01	<0.01	< 0.01	0.02	< 0.01	0.00	0.02	0.00	< 0.01	0.02	< 0.01	0.01	0.03
FeO^t	27.35	27.85	29.16	25.63	27.24	26.42	26.36	32.62	28.45	30.23	35.21	26.89	26.61	31.11
MnO	0.93	0.92	0.94	0.33	0.37	0.39	0.39	0.69	1.18	1.30	1.74	0.57	0.56	0.69
MgO	8.54	8.70	8.23	9.28	8.83	7.17	7.15	6.38	2.44	2.69	3.76	6.79	6.78	6.07
CaO	2.78	2.34	1.63	4.12	3.02	6.00	6.06	1.46	9.23	7.26	1.37	5.86	5.92	2.81
Na_2O	0.05	0.04	0.03	< 0.01	< 0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
Total	100.70	100.82	100.83	100.76	100.17	100.67	100.61	101.10	100.75	100.54	100.60	100.90	100.17	100.84
Number of ions (16 cats)														
Si	5.970	5.986	5.986	5.961	5.974	5.963	5.968	5.966	5.994	6.000	5.980	5.994	5.957	5.988
Ti	0.002	0.006	0.002	0.006	0.002	0.007	0.006	–	0.006	0.004	–	0.005	0.005	0.001
Al	3.991	3.946	3.976	3.961	3.959	3.952	3.947	3.976	3.961	3.944	3.952	3.945	3.969	3.982
Cr	–	–	–	–	0.002	–	–	0.002	–	–	0.003	–	0.001	0.004
Fe^{3+}	0.035	0.061	0.033	0.072	0.072	0. 077	0.079	0.065	0.038	0.048	0.063	0.056	0.067	0.025
Fe^{2+}	3.471	3.509	3.720	3.185	3.430	3.318	3.311	4.184	3.711	3.957	4.636	3.403	3.379	4.029
Mn	0.121	0.119	0.123	0.042	0.048	0.050	0.050	0.091	0.158	0.174	0.235	0.074	0.073	0.091
Mg	1.952	1.988	1.889	2.102	2.024	1.643	1.640	1.481	0.573	0.635	0.895	1.557	1.565	1.410
Ca	0.457	0.384	0.269	0.671	0.498	0.988	0.999	0.244	1.558	1.232	0.234	0.966	0.982	0.469
Na	–	–	–	–	–	–	–	–	–	–	–	–	–	–
End-member mol. %														
Alm	57.84	58.45	61.99	53.05	57.16	55.28	55.16	69.73	61.82	65.94	77.26	56.69	56.30	67.15
Sps	2.01	1.99	2.04	0.71	0.80	0.85	0.85	1.52	2.62	2.91	3.92	1.24	1.22	1.52
Prp	32.52	33.11	31.47	35.02	33.73	27.36	27.31	24.69	9.55	10.59	14.91	25.94	26.08	23.50
Grs	6.65	4.78	3.57	9.28	6.38	14.41	14.55	2.37	24.91	19.16	2.23	14.61	14.58	7.08
TiGrs	0.06	0.14	0.06	0.14	0.06	0.17	0.14	–	0.15	0.09	0.03	0.12	0.12	0.03
Adr	0.89	1.53	0.84	1.80	1.82	1.93	1.99	1.63	0.96	1.22	1.60	1.40	1.68	0.63
Uvr	–	–	–	–	0.06	–	–	0.06	–	–	0.06	–	0.03	0.09

* – c and r denote core and rim position, respectively.
FeO^t – all iron given as FeO.

Table 5 Chemical composition of plagioclase

Sample No.	MF153		MF7		MF159		MF579	KMV98
Analysis No.	5/Pl	6/Pl	25/Pl	26/Pl	38/Pl	39/Pl	61/Pl	73/Pl
SiO_2	66.69	66.78	65.11	65.66	64.93	65.65	63.28	65.06
Al_2O_3	21.01	21.06	22.08	21.84	22.09	21.48	23.36	22.14
FeO^t	0.01	0.00	0.00	0.00	0.00	0.00	0.13	0.00
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	1.75	1.86	3.22	2.82	3.57	2.77	4.51	3.20
SrO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na_2O	10.62	10.44	9.91	9.93	9.66	9.79	9.17	9.73
K_2O	0.24	0.30	0.34	0.26	0.44	0.51	0.36	0.37
BaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P_2O_5	0.06	0.10	0.07	0.03	0.06	0.05	0.02	0.00
Total	100.37	100.58	100.75	100.60	100.78	100.29	100.85	100.56
Number of ions (20 cats)								
Si	11.676	11.693	11.400	11.519	11.383	11.562	11.100	11.422
Al	4.335	4.346	4.556	4.516	4.564	4.458	4.829	4.581
Fe^{3+}	–	–	0.084	–	0.051	–	0.170	–
Fe^{2+}	0.010	–	–	–	–	–	–	–
Mn	–	–	–	–	–	–	0.004	–
Mg	–	–	–	–	–	–	–	–
Ca	0.328	0.349	0.604	0.530	0.671	0.523	0.848	0.602
Na	3.605	3.544	3.364	3.378	3.284	3.343	3.119	3.312
K	0.053	0.067	0.075	0.058	0.098	0.115	0.081	0.082
Sr	–	–	–	–	–	–	–	–
Ba	–	–	–	–	–	–	–	–
End-member mol. %								
Ab	90.42	89.50	83.19	85.17	81.03	83.99	77.07	82.87
An	8.23	8.81	14.94	13.37	16.55	13.13	20.95	15.06
Or	1.34	1.69	1.88	1.47	2.43	2.88	1.99	2.07
Cs	–	–	–	–	–	–	–	–

FeO^t – all iron given as FeO.

analyses. Sample MF579 contains both mesoperthite and antiperthite. It is beyond the scope of the current contribution to attempt to re-integrate the original compositions of the ternary feldspars.

Kyanite

Colourless and non-pleochroic kyanite forms crystals 0.1–1 mm in size, but the felsic granulite KMV98 contains widely scattered blue crystals up to 8 mm long. Kyanite is typically free of reaction products, except for scarce late sericite aggregates.

Accessory minerals include mainly apatite, zircon, monazite, ilmenite, rutile (0.1–1 mm) and graphite.

Thermobarometry

Garnet analyses in cores of crystals were used for pressure and temperature estimates. Plagioclase and biotite analyses employed in calculations came from cores of grains adjacent to the analyzed garnet. Fig. 8 shows an example of analyzed sites distribution in the mosaic of mineral grains**.** The granular fabric is free of indication of disequilibrium relations among the minerals. Biotite does not form reaction rims around garnet. Exception is the sample MF159, which contains garnet partly replaced by biotite flakes rimmed by narrow plagioclase zones against the garnet.

Numbers of atoms per formula unit for individual minerals were entered into Excel spreadsheet

Table 6 Chemical composition of biotite.

Sample No.	MF153			MF7		MF159		MF579		KMV98
Analysis No.	15	16	17	22	23	36	37	64	65	75
SiO_2	37.97	37.56	37.70	37.96	37.73	36.32	36.50	36.44	35.84	36.74
TiO_2	4.41	4.42	4.16	4.42	4.34	2.97	3.07	3.41	3.48	3.94
Al_2O_3	16.94	16.89	17.73	17.78	17.58	19.04	19.53	19.60	18.34	18.30
Cr_2O_3	0.06	0.06	0.06	0.07	0.09	0.07	0.05	0.05	0.04	0.05
FeO^t	13.18	13.77	12.34	10.81	11.17	16.27	16.08	19.18	20.11	14.82
MnO	0.02	0.08	0.03	0.04	0.00	0.00	0.00	0.04	0.06	0.00
MgO	13.59	12.96	13.61	15.39	15.09	11.38	11.32	8.29	8.59	12.12
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na_2O	0.04	0.06	0.09	0.14	0.13	0.09	0.05	0.09	0.11	0.11
K_2O	9.76	9.73	9.64	9.43	9.46	9.40	9.41	9.69	9.63	9.43
H_2O^+	4.09	4.07	4.11	4.14	4.13	4.04	4.05	3.99	3.95	4.06
Total	100.06	99.61	99.47	100.18	99.72	99.58	100.06	100.78	100.15	99.57
Number of ions based on 24 (O+OH)										
Si	5.563	5.551	5.531	5.485	5.491	5.417	5.405	5.438	5.426	5.447
Al^{IV}	2.437	2.449	2.469	2.515	2.509	2.583	2.595	2.562	2.574	2.553
Al^{VI}	0.488	0.493	0.597	0.513	0.506	0.764	0.813	0.885	0.699	0.644
Ti	0.486	0.491	0.459	0.480	0.475	0.333	0.342	0.383	0.396	0.439
Cr	0.007	0.007	0.007	0.008	0.010	0.008	0.006	0.006	0.005	0.006
Fe^{2+}	1.615	1.702	1.514	1.306	1.360	2.029	1.991	2.394	2.546	1.837
Mn	0.002	0.010	0.004	0.005	–	–	–	0.005	0.008	–
Mg	2.968	2.855	2.977	3.315	3.274	2.530	2.499	1.844	1.939	2.679
Ca	–	–	–	–	–	–	–	–	–	–
Na	0.011	0.017	0.025	0.039	0.036	0.026	0.014	0.026	0.032	0.031
K	1.824	1.834	1.804	1.738	1.756	1.789	1.778	1.845	1.86	1.783
Fe/(Fe+Mg)	0.352	0.373	0.337	0.283	0.293	0.445	0.443	0.565	0.568	0.407

FeO^t – all iron given as FeO; crystallochemical calculations indicate Fe^{3+} < 0.001or 0.
H_2O^+ – calculated.

GPT designed for PT calculations (Reche – Martinez 1996). The results of Bt-Grt thermometry and GASP barometry are presented in Table 7. In the calculation mode A calibrations by Ferry – Spear (1978) and Koziol – Newton (1988), in the mode B calibrations by Hodges – Spear (1982) and Koziol (1989), have been used, respectively. Plots of K_D values for the pair Grt-Bt and K_{eq} values of GASP barometry in superimposed diagrams Figs 15-6 and 15-8 in Spear (1993) were used as an independent check of the results obtained by the GPT. The preferred PT estimates (mode A) are indicated by bold numbers in Table 7. Given the accuracy of thermodynamic data, the calculated values have precision limits of ± 50 °C and ± 0.15 GPa.

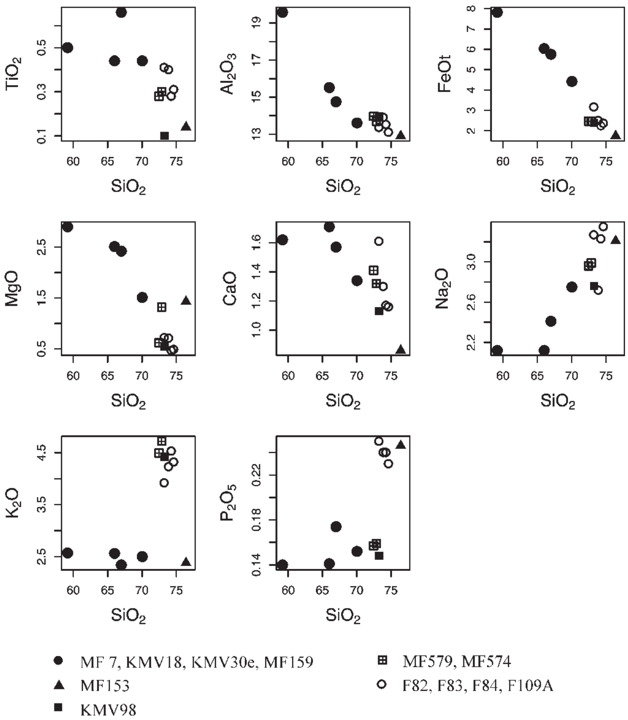

Fig. 5 Variation diagram of SiO_2 (wt.%) vs. major-element oxides (wt.%).

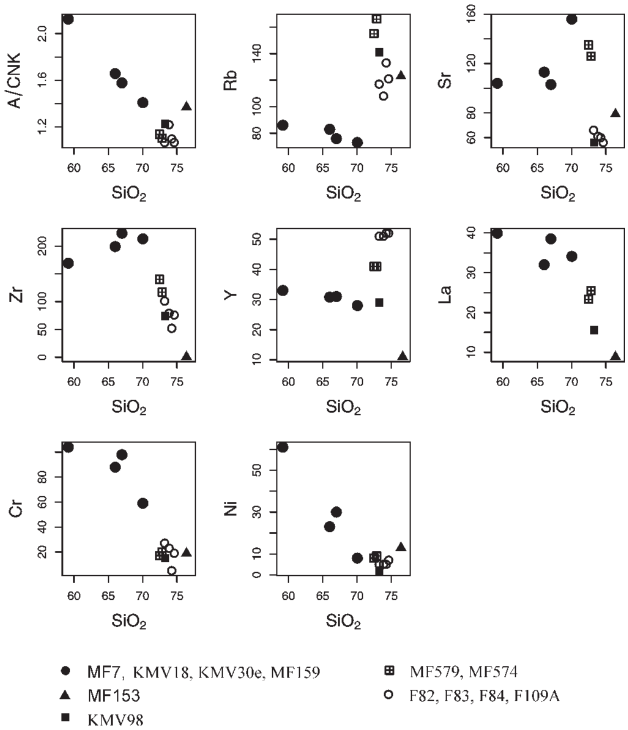

Fig. 6 Variation diagram of SiO_2 (wt.%) vs. A/CNK and selected trace elements (ppm).

Discussion and conclusions

Thermobarometry

As indicated by textural relations (Fig. 4 and description in text), the key assemblage garnet-kyanite-biotite-plagioclase-quartz can be considered as an equilibrium association. In particular, garnet and kyanite are free of coronas. Biotite does not show textural indication of crystallization due to the garnet consumption.

The presence of biotite in the assemblage that crystallized under rather high temperature and pressure conditions is due to instability of orthopyroxene in adamellitic compositions under pressures > 1.6 GPa and T > 900 °C (Fig. 9). Another factor was probably relatively high activity of H_2O (Nahodilová et al. 2005).

Three samples (MF7, MF153 and KMV98) from the original set of five samples are considered as indicative of the eclogite facies equilibration (800–920 °C and 1.8–2.2 GPa, Fig. 9). The size of P-T fields for individual samples varies depending on the number of mineral pairs (one to three) used in individual calculations.

Worth noting is that closely similar values of T = 835–935 °C and P = 1.8–2.0 GPa have been obtained in a detailed study of a subalkaline, hypersthene-normative Spačice eclogite with a prograde metamorphic record (Medaris et al. 2005).

The migmatitic gneiss MF579 shows an equilibration temperature by ca. 200 °C lower at pressures of 1.4 GPa. Theoretically, it could have been derived from granulite, assuming a complete erasing of a former high PT mineralogy. Pouba et al. (1987) concluded that migmatized gran-

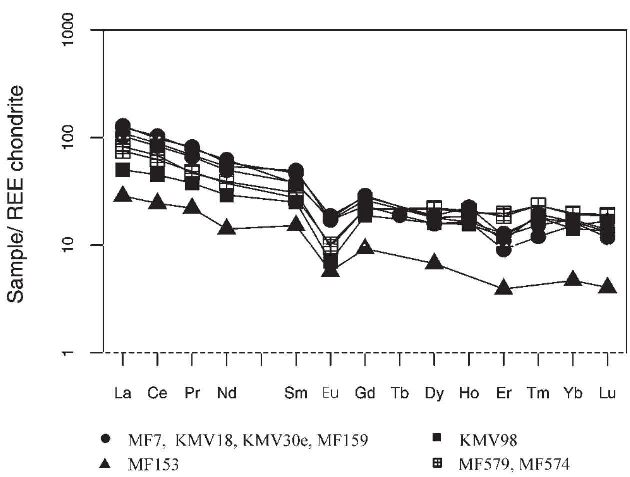

Fig. 7 Chondrite-normalized REE patterns (Boynton 1984) for the analyzed granulitic rocks.

ulitic gneisses cropping out along the road from Spačice to Běstvina (Fig. 2) are former granulitic rocks that were later variably migmatized. However, the authors did not present conclusive evidence to support their interpretation.

It is difficult to interpret the migmatitic gneiss MF579 as having formed by retrogression of the other rocks studied, since its accessory garnet contains significantly higher grossular component than garnet in the granulites. In addition, the associated plagioclase is rather rich in Ca. Thus the sample MF579, although probably similar to rocks mentioned by Pouba et al. (1987), does not conform to the suggested retrogressive migmatization scenario. Rather, the available information suggests that the migmatitic gneiss is probably an exotic component in the composite Běstvina body. Clearly, additional work on migmatitic gneisses is needed and the estimate of PT conditions given here should be considered as preliminary.

The sample MF159, which yielded exceptionally high temperature estimate of c. 1100 °C and pressure of 2.7–2.9 GPa, is interpreted as representing a disequilibrium assemblage involving a partially consumed garnet. The resorption of this mineral resulted in production of newly formed biotite with minor rim of newly formed plagioclase. The low TiO_2 content in biotite in sample MF159 (Table 6) indicates crystallization in local domains deficient in Ti.

Rather sophisticated approaches had to have been applied to thermobarometry of Moldanubian granulites with a complicated record of evolution, peak conditions and decompression (Cooke et al. 2000, O'Brien – Rötzler 2003 and references in these works). On the other hand, thermobarometry in granulites of the Běstvina body, which exhibit simple stable mineral associations, can be done using straightforward methods as adopted in this study. Three granulitic rocks with contrasting whole-rock compositions yield closely comparable pressure and temperature estimates, which compare well with the data obtained independently on the crustal Spačice eclogite (Medaris et al. 2006).

Relationships between high-pressure granulites and associated eclogites

There are two types of eclogites in the Běstvina body. The first type (Spačice, Medaris et al. 2006) preserves the evidence for prograde evolution, followed by equilibration under metamorphic conditions comparable to quartz-feldspathic high-pressure granulites characterized in the current study. The second type of eclogite, associated with garnet peridotite and garnet pyroxenite (Úhrov locality), has probably equilibrated under lithospheric mantle conditions. The accompanying garnet peridotite corresponds to type III in the typology of Variscan peridotites in the Bohemian Massif (Medaris et al. 2005). For this eclogite type, a 20 cm wide layer in partly serpentinized garnet peridotite at Úhrov, Medaris et al. (2005) obtained T = 1170 °C and P = 4.38 GPa. A recent study by Faryad (2005) of additional samples of Úhrov eclogites, which show a polyphase evolution history, gave equilibration conditions of ~ 4.0 GPa and 750 °C. The recognition of the ultrahigh-pressure eclogite, associated with garnet peridotite, is important in that it shows that, at some point in their history, the Běstvina granulites have been juxtaposed to the upper mantle rocks.

Fiala (1992) described interbanding of granulites and eclogites at the elevation near the village of Spačice. The granulites were represented by felsic Ky-Cpx-Grt-Pl granulite (Cpx corresponds to sodic augite) of tonalitic

Table 7 Estimates of temperature and pressure of granulitic rocks equilibration.

Calculation mode		**A**	**B**	**A**	**B**
		RM*: Ferry-Spear (1978)	RM*: Hodges-Spear (1982)	**RM*: Koziol-Newton (1988)**	RM*: Koziol (1989)
Sample	Rock type	**T °C**	T °C	**P GPa**	P GPa
MF153	Bt-Ky-Grt felsic granulite type I	**891**	926	**2.09**	2.21
MF153	Bt-Ky-Grt felsic granulite type I	**845**	880	**1.94**	2.05
MF153	Bt-Ky-Grt felsic granulite type I	**890**	922	**1.99**	2.13
MF153	Bt-Ky-Grt felsic granulite type I	**844**	876	**1.84**	1.97
MF7	Ky-Bt-Grt eclogitic paragneiss	**789**	834	**1.80**	1.83
MF7	Ky-Bt-Grt eclogitic paragneiss	**816**	861	**1.81**	1.84
KMV98	Ky-Bt-Grt felsic granulite type II	**913**	974	**2.23**	2.26
KMV98	Ky-Bt-Grt felsic granulite type II	**922**	984	**2.27**	2.30
MF579	Ky-Grt-Bt migmatitic gneiss	**659**	763	**1.42**	1.65
MF579	Ky-Grt-Bt migmatitic gneiss	**674**	756	**1.42**	1.55
MF159**	Ky-Bt-Grt eclogitic paragneiss	**1115**	1171	**2.91**	2.91
MF159**	Ky-Bt-Grt eclogitic paragneiss	**1098**	1154	**2.69**	2.70

RM* – calculation following Reche-Martinez (1996)
** – probably a disequilibrium assemblage
See text for explanation.

or quartz dioritic composition, grading to Grt-Cpx plagiogranulite and then to garnet pyriclasite. Garnet of average composition $Alm_{40}\,Prp_{25}\,Grs_{35}$ is zoned with increasing Prp and decreasing Grs from core to rim. The associated eclogite contains omphacite close to sodic augite and garnet $Alm_{40}\,Prp_{30}\,Grs_{30}$. These relations also indicate, independently of the GASP barometry and Grt-Bt thermometry presented here, that metamorphism of local felsic granulites took place under eclogite facies conditions.

Tectonic interpretation

Similarly to the model of O'Brien – Rötzler (2003), also the HP granulites of the Běstvina body seem to have been transported tectonically to the heat source, i.e. into the Upper Mantle. At such a deep level, the rocks could have equilibrated under eclogite facies HP-HT conditions and subsequently were uplifted rather quickly to the mid-crustal levels. The connection with mantle rocks is indicated by pyrope peridotite occurrences in the Běstvina body (Pouba et al. 1987, Medaris et al. 2005).

Quartz-feldspathic granulites of the Běstvina body, including rocks with very dissimilar protolith histories, show a comparable eclogite facies metamorphic imprint. For the first time in this part of the Bohemian Massif, Ky-Grt-Bt gneisses with megascopic aspect of biotite paragneiss and whole-rock composition of meta-greywacke are demonstrated to have equilibrated under conditions of eclogite facies.

The exhumation of the Běstvina granulites was extremely rapid. This stands in sharp contrast with the granulites in the adjacent Moldanubian Zone, which experienced nearly isothermal decompression partial recrystallization in the sillimanite stability field.

The information presented by Fišera (1992) for an excursion locality at the margin of the Spačice village indicates that the Běstvina granulites at least exceptionally experienced a retrograde stage associated with a flat-lying refoliation fabric, biotitization, crystallization of sillimanite and a different type of garnet zoning. Compared to the extensive collection of thin sections, this evolution appears as rather exceptional.

Terminology of high-pressure granulites

The terminology of various high-pressure granulite rock-types equilibrated in the eclogite-facies PT field (O'Brien – Rötzler 2003; O'Brien 2006) becomes quite complicated. What may be misleading to a wider gesocientific community is the fact that there are two types of granulitic rocks: (1) several rock-types of diverse mineralogical and whole-rock composition that indeed equilibrated under granulite facies conditions, and (2) high-pressure granulites, which evolved at eclogite facies conditions. High-pressure meta-greywacke paragneisses associated with high-pressure felsic granulites in the Běstvina body are neither granulites, nor eclogites and could be somewhat provisionally termed as eclogitic paragneiss (or high-pressure granulitic gneiss?).

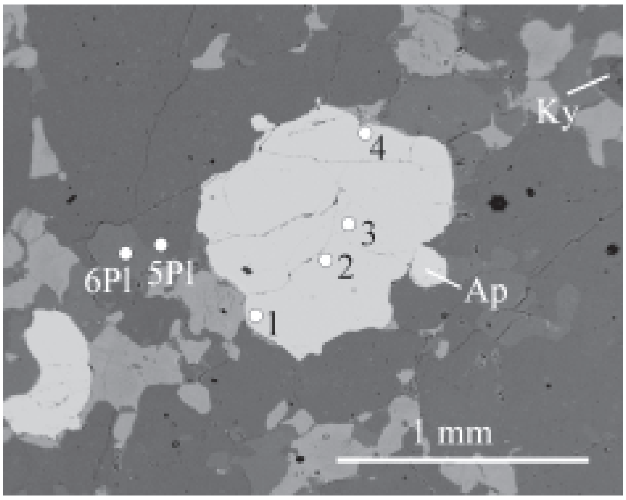

Fig. 8 Location of electron microprobe analyses in garnet (Nos 1–4) and plagioclase (5Pl, 6Pl); Ky – kyanite, Ap – apatite; biotite is present outside the field of view. Sample MF153, felsic granulite type I. BSE image.

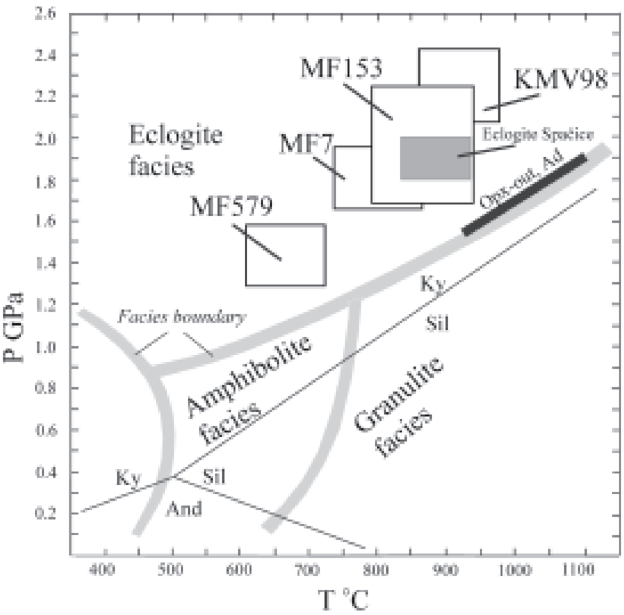

Fig. 9 Calculated P-T equilibration conditions for several samples of Běstvina granulitic rocks and the Ky-Grt-Bt migmatitic gneiss MF579. Granulite, amphibolite and eclogite facies fields are from Spear (1993). Opx-out curve in adamellite composition (bold contour) is from Green – Lambert (1965). The samples MF7, MF153 and KMV98 plot in the field of high-pressure granulites as defined by O'Brien – Rötzler (2003). Data for Spačice crustal eclogite are plotted for comparison (Medaris, G., Jr. et al. 2006)

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Petrologie a geochemie běstvinských granulitů metamorfovaných v eklogitové facii, Český masiv

Vysokotlaké granulity tělesa Běstvina obsahují minerální asociaci granát-kyanit-biotit-plagioklas-K-živec-křemen±antipertit. Osm studovaných vzorků lze rozdělit na základě petrologických a geochemických vlastností na čtyři hlavní typy hornin: (1) metamorfované droby, (2) felsický granulit s nízkými poměry CaO/Na_2O a K_2O/Na_2O (typ I), (3) felsický granulit leukogranitového složení (typ II), (4) kyanit-granát-biotitická migmatitická rula. Tyto horniny jsou sdružené s malými tělesy granátického peridotitu a krustálního eklogitu, popsanymi v literatuře. Granát v křemen-živcových horninách obsahuje typicky 24–35 mol. % Prp a 5–14 mol. % Grs komponent se zonálností Ca v profilu zrn. Na základě údajů o složení granátu ve středech zrn a složení sdruženého plagioklasu a biotitu poskytují geotermobarometrické výpočty hodnoty teplot a tlaků odpovídající podmínkám eklogitové facie (P = 1.8–2.2 GPa a T = 800–920 °C). Dva ze vzorků důležitých pro termobarometrii (felsické granulity typu I a II) neobsahují antipertit a představují poměrně jednoduchý systém. Sdružená Ky-Grt-Bt migmatitická rula s indikací podmínek 1.4 GPa a 670 °C pravděpodobně představuje cizorodou horninu v tělese Běstvina. Ačkoliv jeden vzorek metadrobových hornin obsahuje granáty částečně zatlačované biotitem a plagioklasem, ostatní vzorky nejsou postižené dekompresní rekrystalizací. Uvedené vlastnosti vysokotlakých granulitových hornin v tělese Běstvina představují podstatnou odlišnost od granulitů v moldanubiku, které prodělaly výraznou vysokoteplotní dekompresní rekrystalizaci v poli stability sillimanitu.