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PETROLOGY OF THE MALÁ FATRA GRANITOID ROCKS (WESTERN CARPATHIANS, SLOVAKIA)

IGOR BROSKA, IGOR PETRÍK and PATRIK BENKO

Geological Institute, Slovak Academy of Sciences, Dúbravská 9, 842 26 Bratislava, Slovak Republic

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Abstract: The crystalline core of the Malá Fatra Mts. belongs to the basement of the Tatric Unit in the Western Carpathians. Two segments, the Lúka and Kriváň, are distinguished in the Malá Fatra Mts., both with large granite plutons. This paper deals with the granitoid rocks of the Kriváň segment. On the basis of their mineralogy and geochemistry the hybrid and Magura granite types of Ivanov & Kamenický (1957) were redefined as I- and S-type granitoids, respectively. The I-type granodiorites and tonalites have a characteristic mineral assemblage of plagioclase (An_{21-48}), Mg-biotite, epidote, interstitial K-feldspar, allanite, hornblende and zircons with $\overline{I.\ T.}$ parameter above 350. They are situated mainly on the southern slopes of the Kriváň part of the Malá Fatra Mts. The Al-in-hornblende barometer gives a pressure of 330 ± 60 MPa, the zircon and monazite saturation temperatures are between 745–810 °C and 750–810 °C, respectively. The water content of the granitoid magma, estimated on the basis of biotite composition, was about 5 wt. % at 700 °C. This granite suite also contains mafic magmatic enclaves. The S-types granites are localized to the north of the I -type granitoids. They contain plagioclase (An_{12-35}), Fe-biotite, K-feldspar and zircons with $\overline{I.\ T.}$ parameter below 300–350. In the absence of hornblende, we suppose the same pressure (330 MPa) for the emplacement of this granite suite. The zircon and monazite saturation temperatures are also within the same range as in the I-type granites (740–790 °C or 720–790 °C). However, the biotite of the S-type granites suggest a lower water content of about 2–4 wt. % at 750 °C. It is noteworthy that according to increasing body of data, the granitoid massifs in a 200 km long region in the present erosion cut between the Malé Karpaty and Malá Fatra Mts. were emplaced at similar temperature and pressure conditions. The pressures of 300–400 MPa indicate the similar 12–15 km emplacement depth of all the granitoid bodies in this area.

Key words: Malá Fatra granites, I- and S-type granites, petrology, biotite, zircon, monazite.

Introduction

Recent studies of the Western Carpathian Variscan granitoids have shown that they can be described well in terms of S- and I-types (Chappell & White 1974) in most of the granitic basement cores in Slovakia (Cambel & Vilinovič 1987; Petrík et al. 1994; Kohút & Janák 1994; Kohút et al. 1996). According to recent opinions the S-type granites originated during Early Carboniferous crustal thickening and prograde metamorphism and were probably localisated in an accretionary wedge. By contrast, the I-type tonalites were formed during the Late Carboniferous by dehydration melting of lower crustal lithologies possibly due to the presence of hot underplated mantle magmas (Petrík et al. 1994).

The two types of granitoids in the Western Carpathians were described in detail only in the Tribeč Mts. (Petrík & Broska 1994). On the basis of the chemistry of biotite, Al-in-hornblende barometry, and Fe-Ti oxides presence, the P-T-X conditions were established with model temperature of 700 °C. The resulting calculations yielded estimates of total pressure (350 MPa), oxygen fugacity (TMQA buffer) and water contents for I-type tonalites (5.17 wt. %), and for S-type granodiorites (2.3 wt. %, l.c.).

The Malá Fatra Mountains consist of the Lúka and Kriváň segments, both dominated by large granite plutons. According to the mapping work of Ivanov & Kamenický (1957), Haško & Polák (1978), the Kriváň as well as Lúka parts are formed by two intrusive granitic bodies: the older granite body in this crystalline core is represented by *hybrid biotite-oligoclase granite*, the younger one is the so-called *Magura type granite* (Ivanov & Kamenický, l.c.). The Kriváň part belongs to the external zone of granitic "cores" in the Tatric Unit of the Western Carpathians. It should be noted that the term "hybrid" granites traditionally used in Carpathian literature refers to inhomogeneous granites contaminated by xenoliths of metamorphic rocks rather than to products of mixing of felsic and basic melts (e.g. Pitcher 1993). The latter phenomenon is actually very rare in the studied region although some mafic enclaves have been observed. The "hybrid" granitoids presented on recent geological maps bear, as will be shown later, the signs of the I-type. Therefore, further on, we assign these granitoids to the I-type (Chappell & White 1974). On the other hand, the Magura granite shows more features of the S-type granites. Though the S-type (former Magura granite type) is usually strongly altered, some fresh parts can be found which are suitable for microprobe analyses and petrological interpretations. Similarly, in the I-type granitoids (former hybrid granitoid suite) the critical assemblage (hornblende–K-feldspar) of non-altered minerals can be found enabling us to calculate total pressure.

Basic petrographical description of the Malá Fatra granites is given in the papers of Ivanov & Kamenický (l.c.), Kamenický et al. (1987). Several biotite and chlorite analyses were reported by Macek (1992) and accessory minerals were described by Hovorka (1968), Broska (1986) and Broska et al. (1992). The principal aim of this work is to present a general description of the Kriváň part of the Malá Fatra granitic rocks and to contribute to the knowledge of their petrogenesis by establishing their P-T-X conditions.

Sampling and petrography

Thirteen samples were collected from both granite types as distinguished by geological mapping. The average weight of samples was about 2 kg, they were processed by standard procedures of crushing and sieving, Wilfy table separation, isodynamic magnetic separation, and finally heavy liquids were used to get heavy fractions. The granitoid rocks were named according to the IUGS classification (QAP diagram — Fig. 1).

The I-type granites are represented by medium to coarse-grained hornblende biotite tonalites (BMF-6, 14), two-mica granodiorites (BMF-4, 9, 10) and monzogranites (BMF-8). The rocks are usually cataclastic and strongly altered. While biotite is completely replaced by *chlorite + ore pigment*, plagioclase is sericitized and saussuritised. Muscovite commonly accompanies the secondary chlorite. The rocks which escaped the alteration (samples BMF-6, 14) contain deep red-brown/pale yellow *biotite*, *plagioclase* with An_{35-48} in cores and An_{21-35} in rims. *Titanite, magnetite, apatite, allanite* are characteristic accessories. *K-feldspar* is always microcline, perthitic or chess-board, often with developed myrmekite, interstitial, enclosing cumulus plagioclases. Bluish-green *hornblende* was found in samples BMF-6 and 14 in association with quartz, plagioclase, biotite, titanite, magnetite, microcline.

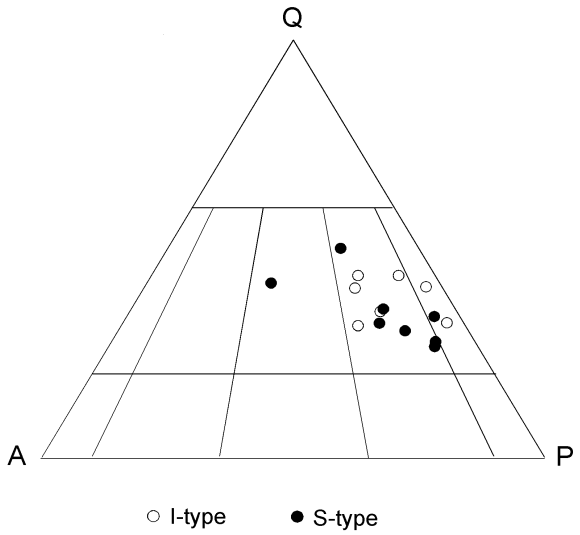

Fig. 1. QAP diagram (IUGS classification). Explanation of symbols: mG — monzogranite, sG — syenogranite, GD — granodiorite, T — tonalite. Open circle — I-type granitoids, full circle — S-type granitoids.

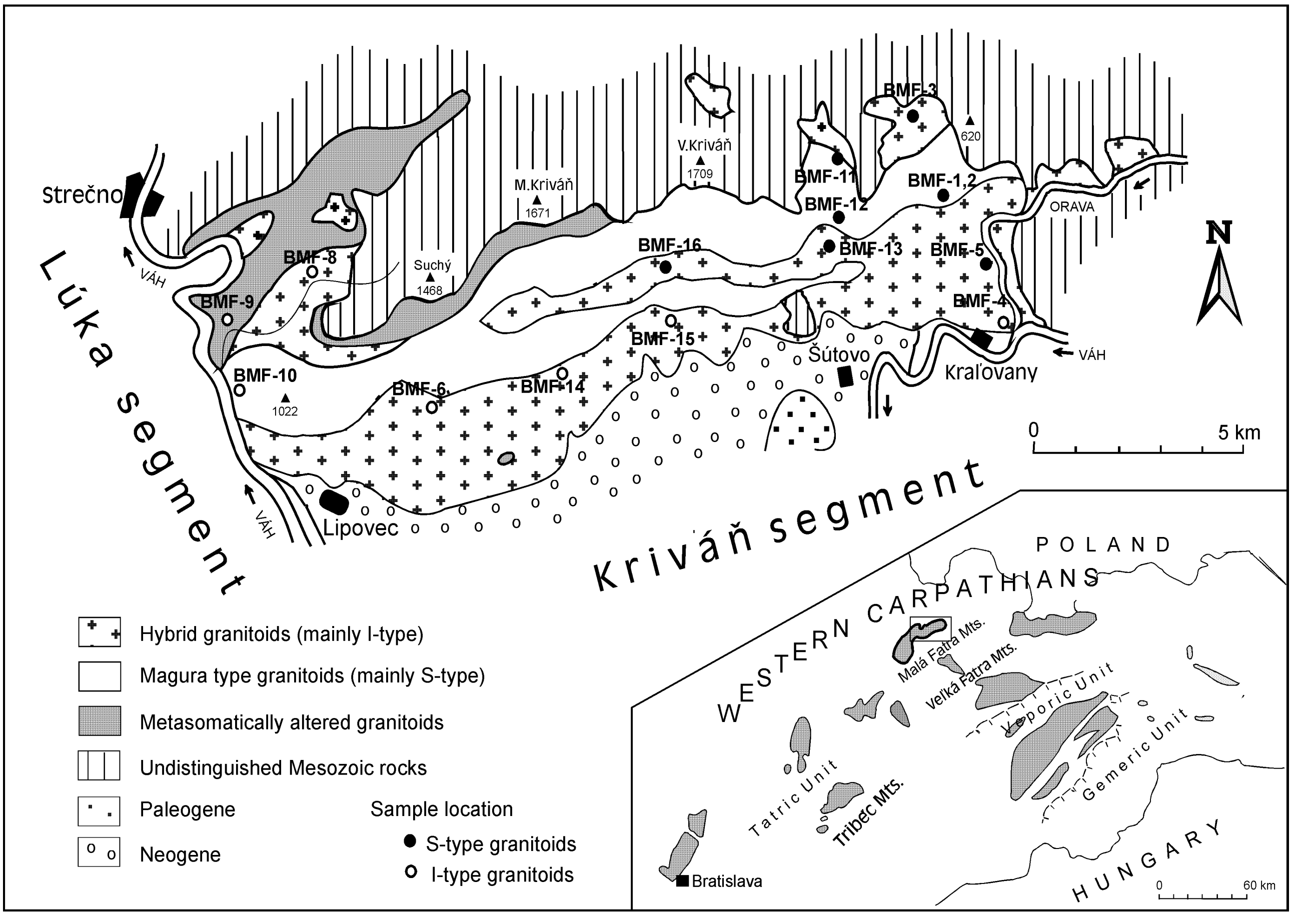

Fig. 2. Schematic geological map of the Kriváň part of the Malá Fatra Mts. (Ivanov & Kamenický 1957) and location of samples. See text for the I/S classification.

The S-type granites are represented by leucocratic, medium to coarse-grained granodiorites (BMF-1, 3, 5, 11, 13), less granites (BMF-12) and tonalites (BMF-2). They are also strongly altered. The most altered samples of the S-type are pinkish granites with K-feldspar porphyroblasts which are widespread mainly in the northernmost part of the body. The alteration is similar to that in the I-type granite: chlorite and ore pigment replace biotite. However, muscovite is more common and epidote is rare. In relatively fresh samples (BMF-2, 13) *plagioclase* is An_{35-21} in cores and An_{21-12} in rims. A protomylonitic sample (BMF-3) has albitic plagioclase (An_{11-4}). *Biotite* is red-brown/pale yellow. K-feldspar is microcline, interstitial in granodiorites and sub- to euhedral porphyritic in granites (Fig. 2).

Geochemistry

The samples were analysed for major and minor elements by X-ray fluorescence (University of Ottawa), trace elements by ICP-MS (Memorial University of Newfoundland). Analytical details for ICP-MS are given in Jenner et al. (1990).

Biotite and hornblende were analysed by electron microprobe at the Geological Survey of the Slovak Republic (JXA 633 Superprobe), monazite at Salzburg University (Jeol 845). Natural standards and 15 KV accelerating voltage were used for the measurements.

The main and trace elements are presented in Tables 1 and 2. The granitoids of both groups are peraluminious. The subdivision of samples into two groups based on the zircon typology (see below) was also used for further geochemical and petrological interpretations. Analogically to the other West-Carpathian granitoids those with a zircon $\overline{I.\ T.}$ parameter above 300 were regarded as I-type granitoids, and those containing zircons with $\overline{I.\ T.}$ parameter below 300 as S-type granitoids, Fig. 3 (Broska & Gregor 1992; Broska & Uher 1992). This procedure was used because chemical criteria usually do not work effectively with the altered rocks (sericitization, chloritization etc.) common among West-Carpathian granitoids. The effect of this criterion is highlighted by Harker type diagrams (Figs. 4, 5) where both types form more or less well separated trends. The I-type trace element trends usually show a higher degree of correlation with silica. The S-type granites seem to be more scattered. The SiO_2 contents range from 64 to 72 wt. % and from 68 % to 75 % for the I-type and S-type granitoids, respectively.

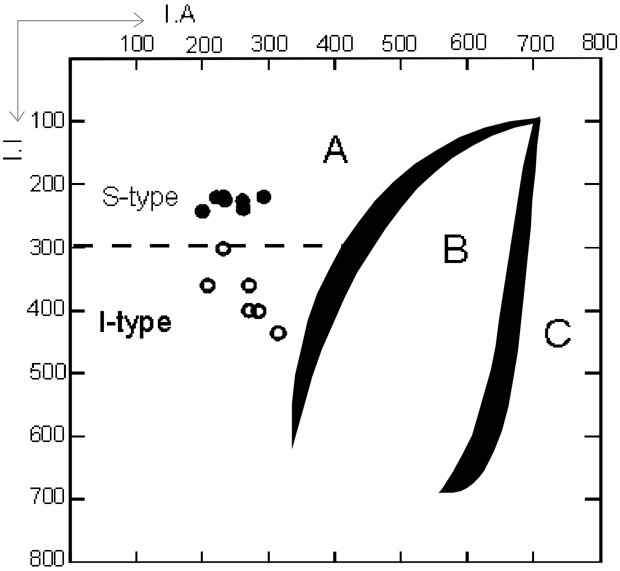

Fig. 3. Zircon typological mean points of the Kriváň part granitoids (Malá Fatra Mts.). Symbols as in Fig. 1.

Rare earth elements: Fig. 6 shows the REE standardized patterns of both granitoid groups represented by their averages and respective fields. They display negligible negative europium anomalies in both granite groups. The I-type granite suite has higher contents of the REE's and due to aplitic derivates somewhat steeper slope (La/Sm 3.9 for I-type and 3.6 for S-type). The concave pattern of heavy REE's of the I-type group suggests a possible role of hornblende, titanite and allanite in the fractionating assemblage.

Table 1: Major elements in granitoid rocks of the Kriváň part of the Malá Fatra Mts.

Type	S - type							I - type					
Sample	BMF-1	BMF-2	BMF-3	BMF-5	BMF-11	BMF-12	BMF-13	BMF-4	BMF-6	BMF-8	BMF-9	BMF-10	BMF-14
SiO_2	68.26	68.29	74.83	69.22	70.01	73.70	69.25	69.41	64.07	72.00	68.31	69.91	67.81
TiO_2	0.34	0.49	0.16	0.41	0.30	0.18	0.34	0.29	0.84	0.34	0.52	0.29	0.57
Al_2O_3	16.71	15.84	13.82	16.07	15.65	13.91	16.10	15.78	15.08	14.20	14.92	15.53	15.42
Fe_2O_3	2.49	2.96	1.16	2.64	2.31	1.50	2.43	2.07	5.20	2.14	3.53	2.19	3.73
MnO	0.04	0.05	0.02	0.04	0.05	0.03	0.04	0.02	0.10	0.03	0.07	0.04	0.07
MgO	0.71	0.98	0.48	0.95	0.94	0.68	0.92	1.09	2.98	0.78	1.56	1.05	1.74
CaO	2.81	2.64	1.02	1.55	1.07	0.70	1.91	1.18	3.07	0.62	2.85	0.99	3.43
Na_2O	5.09	4.71	3.89	4.89	4.49	3.49	4.84	3.70	3.23	3.56	3.74	4.23	3.96
K_2O	1.89	1.89	2.95	2.06	3.09	3.77	2.17	4.28	2.43	4.62	2.30	3.80	1.94
P_2O_5	0.06	0.16	0.08	0.15	0.13	0.09	0.13	0.19	0.35	0.13	0.21	0.17	0.22
L.O.I	1.3	1.4	0.9	1.6	1.6	1.3	1.3	1.2	2.3	1	1.4	1.1	0.8
Total	99.70	99.40	99.31	99.58	99.64	99.35	99.43	99.21	99.65	99.42	99.41	99.30	99.69

Table 2: Trace elements in granitoid rocks of the Kriváň part of the Malá Fatra Mts.

Type	S - type							I - type					
(ppm)	BMF-1	BMF-2	BMF-3	BMF-5	BMF-11	BMF-12	BMF-13	BMF-4	BMF-6	BMF-8	BMF-9	BMF-10	BMF-14
V	25.0	57.0	15.0	41.0	32.0	21.0	32.0	40.0	120.0	35.0	69.0	37.0	73.0
Cr	16.0	10.0	4.0	6.0	12.0	9.0	16.0	16.0	53.0	18.0	30.0	11.0	23.0
Co	2.0	5.0	0.0	2.0	4.0	4.0	2.0	2.0	13.0	4.0	8.0	3.0	10.0
Ni	0.0	0.0	0.0	0.0	1.0	0.0	0.0	2.0	27.0	3.0	9.0	3.0	10.0
Zn	60.0	68.0	139.0	54.0	62.0	33.0	75.0	43.0	99.0	45.0	77.0	55.0	79.0
Rb	54.0	59.0	72.0	61.0	91.0	93.0	55.0	88.0	70.0	108.0	87.0	92.0	79.0
Sr	498.0	505.0	355.0	506.0	381.0	254.0	687.0	581.0	902.0	318.0	824.0	566.0	791.0
Y	10.0	12.0	9.0	11.0	10.0	19.0	10.0	13.0	25.0	7.0	16.0	17.0	12.0
Zr	154.0	116.0	90.0	182.0	124.0	75.0	154.0	81.0	220.0	171.0	165.0	90.0	159.0
Nb	7.0	9.0	5.0	7.0	7.0	7.0	7.0	7.0	15.0	7.0	13.0	9.0	9.0
La	28.5	17.9	9.0	30.2	23.1	15.8	29.0	18.2	51.7	34.7	36.1	20.7	30.6
Ce	59.1	37.6	19.3	61.4	46.8	32.3	57.7	36.0	106.3	73.9	74.2	42.7	59.7
Pr	6.8	4.4	2.1	7.0	5.4	3.8	6.7	4.2	12.5	8.0	8.5	5.0	6.7
Nd	25.9	17.4	7.9	26.3	20.2	13.8	24.9	16.2	48.8	29.6	31.9	19.8	25.4
Sm	4.8	3.9	1.6	5.0	3.5	3.2	4.2	3.5	9.2	4.3	5.3	4.0	4.3
Eu	1.0	0.9	0.5	1.1	0.8	0.8	1.0	1.0	2.1	0.9	1.2	0.9	1.1
Gd	3.2	3.1	1.2	3.3	2.5	2.9	2.8	2.8	6.2	2.2	3.9	2.8	3.1
Tb	0.4	0.4	0.2	0.4	0.3	0.5	0.3	0.4	0.8	0.2	0.5	0.4	0.4
Dy	1.7	2.2	1.0	1.9	1.6	3.0	1.6	2.2	4.4	1.0	2.6	2.6	1.9
Ho	0.3	0.4	0.2	0.3	0.3	0.6	0.3	0.4	0.7	0.2	0.5	0.5	0.3
Er	0.6	0.9	0.6	0.8	0.7	1.8	0.7	0.9	2.0	0.5	1.4	1.4	0.9
Tm	0.1	0.1	0.1	0.1	0.1	0.3	0.1	0.1	0.3	0.1	0.2	0.2	0.1
Yb	0.6	0.8	0.5	0.7	0.7	1.8	0.6	0.6	1.8	0.5	1.2	1.3	0.7
Lu	0.1	0.1	0.1	0.1	0.1	0.3	0.1	0.1	0.3	0.1	0.2	0.2	0.1
Hf	3.7	2.8	2.1	3.9	2.9	1.9	3.8	1.9	6.0	4.7	4.7	2.3	4.6
Ta	0.3	0.9	0.4	0.4	0.5	0.6	0.3	0.3	0.7	0.2	0.7	0.5	0.4
Pb	24.0	33.0	45.0	68.0	14.0	17.0	25.0	31.0	60.0	61.0	83.0	43.0	17.0
Th	8.8	5.1	3.4	7.5	7.2	5.4	7.0	5.2	14.7	24.9	16.6	7.9	11.3
U	3.0	2.0	2.0	3.0	2.0	1.0	3.0	0.0	7.0	2.0	8.0	3.0	4.0

Rock-forming minerals

Biotite: Microprobe analyses of biotite from samples BMF-5, 9, 14 are given in Table 3. The sample KMF-17 which corresponds to our sample BMF-1 was taken from Macek (1992). The comparison of analyses KMF-17, BMF-5 with BMF-9, 14 shows that the biotite from the S-type granite is significantly more iron-rich (Fe/(Fe + Mg) is about 0.6), more Ti rich and more peraluminous. By contrast, the I-type granite biotite is more Mg-rich (Fe/(Fe + Mg) is 0.48) and poorer both in Ti and alumina. All the features are consistent with more oxidated nature of I-type granitoid series and reduced nature of the S-type granite group. This closely parallels the situation in the Tribeč Mts. where the oxidated granitoids were interpreted as belonging to the I-type and the reduced ones to the S-type (Petrík & Broska 1994).

Plagioclase from I-type tonalites is significantly more An-rich (An_{48} in cores) than in S-type granodiorites (An_{35}) which along with the presence of hornblende and absence of primary muscovite and generally more basic chemistry (Figs. 4–5) point to a different source rock.

Hornblende: Though present in accessory amounts hornblende is treated as a rock-forming mineral. It was observed only in I-type tonalites and granodiorites. It belongs to the group of Ca-amphiboles and according IMA classification it represents the Mg-hornblende (Leake 1967), Table 5. Hornblendes were observed in samples BMF-6 and 14 where they reach less than 2 vol. %. They typically occur as prismatic grains from 0.1 up 5 mm in size.

Accessory minerals

Accessory minerals were studied mainly from heavy fractions. The assemblages *magnetite, titanite, epidote* and *allanite* are characteristic of the I-type granite group, while typical S-type granites contain *monazite, ilmenite,* and sometimes, dusky *apatite.* They were observed in the eastern part of the mountain range. The black colour of apatite was interpreted by Broska et al. (1992) as being due to the presence of carbon-bearing phases (graphite, hydrocarbons, carbide) in centres of apatite crystals. This phenomenon is believed to be indicative of reducing conditions in the granitoid melt. Secondary *sillimanite* was observed in the S-type granite BMF-9. *Pyrite* is present in all samples, I-type granodiorite BMF-14 also contains arsenopyrite. The samples BMF-6 (I-type), 9, 10 (S-type) have *rutile* in their heavy fractions. Only *zircon* and *monazite* were studied in detail.

Zircon. Non-metamictic zircon is present in both granite groups of the Malá Fatra Mts. The plot of zircon typological mean points in the I.A vs. I.T diagram (Pupin 1980) indicates: (1) a crustal anatectic origin of these granitoids, and (2) the presence of two groups of granitoids in the crystalline core of the Malá Fatra Mts. The first one is dominated by L type zircons (the S-type granite), the second one is represented mainly by S (S_6, S_{23}) subtypes (I-type granitoids).

Table 3: Representative microprobe analyses of biotite. Note: 15% and 5% of total iron was assumed as ferric for I- and S-type biotites, respectively (based on unpublished Mössbauer data set of Western Carpathian granitoid biotites, Petrík & Lipka 1994).

Type	S - type		I - type			I - type			
Sample	KMF-17	BMF-5	BMF-9	BMF-9	BMF-9	BMF-14	BMF-14	BMF-14	BMF-14
Point	Bt 1	Bt 2	Bt 3-1	Bt 3-2	Mean	Bt 4-1	Bt 4-2	Bt 4-3	Mean
SiO_2	34.49	34.56	36.39	36.22	36.31	37.21	37.74	37.75	37.567
TiO_2	2.74	3.35	1.92	1.87	1.9	2.39	2.29	2.29	2.323
Al_2O_3	18.02	18.31	16.45	16.29	16.37	15.74	15.42	15.61	15.59
Fe_2O_3	1.05	1.16	3.15	2.91	3.03	3.04	3.02	2.99	3.015
FeO	17.95	19.89	16.08	14.84	15.46	15.49	15.38	15.26	15.378
MnO	0.35	0.38	0.47	0.43	0.45	0.47	0.52	0.37	0.453
MgO	7.63	7.84	10.31	10.57	10.44	10.8	10.71	10.96	10.823
CaO	0	0	0	0	0	0.02	0	0	0.007
Na_2O	0.08	0.06	0.13	0.16	0.15	0.17	0.16	0.13	0.153
K_2O	9.85	9.79	10.17	10.02	10.1	9.78	9.67	9.76	9.73
Total	92.16	95.35	95.075	93.305	94.19	95.089	94.91	95.119	95.039
22 oxygens per formula unit									
Si	5.452	5.325	5.554	5.595	5.575	5.64	5.719	5.701	5.687
Al	2.548	2.675	2.446	2.405	2.425	2.36	2.281	2.299	2.313
Sum X	8	8	8	8	8	8	8	8	8
Al	0.809	0.65	0.513	0.561	0.537	0.452	0.473	0.479	0.468
Ti	0.326	0.388	0.22	0.217	0.219	0.272	0.261	0.26	0.264
^{3+}Fe	0.125	0.135	0.362	0.338	0.35	0.346	0.344	0.34	0.343
^{2+}Fe	2.372	2.563	2.053	1.917	1.985	1.964	1.95	1.927	1.947
Mn	0.047	0.05	0.061	0.056	0.059	0.06	0.067	0.047	0.058
Mg	1.798	1.801	2.346	2.434	2.39	2.441	2.419	2.467	2.442
Sum Y	5.476	5.586	5.555	5.524	5.54	5.536	5.513	5.521	5.523
Ca	0	0	0	0	0	0.003	0	0	0.001
Na	0.025	0.018	0.038	0.048	0.043	0.05	0.047	0.038	0.045
K	1.986	1.924	1.98	1.975	1.978	1.887	1.869	1.88	1.879
Sum Z	2.011	1.942	2.019	2.023	2.021	1.941	1.916	1.918	1.925
Total cat.	15.487	15.528	15.574	15.547	15.56	15.477	15.43	15.439	15.448
XFe^{2+}	0.395	0.427	0.342	0.319	0.331	0.327	0.325	0.321	0.324
Fe/(Fe+Mg)	0.581	0.600	0.507	0.481	0.494	0.486	0.487	0.479	0.484

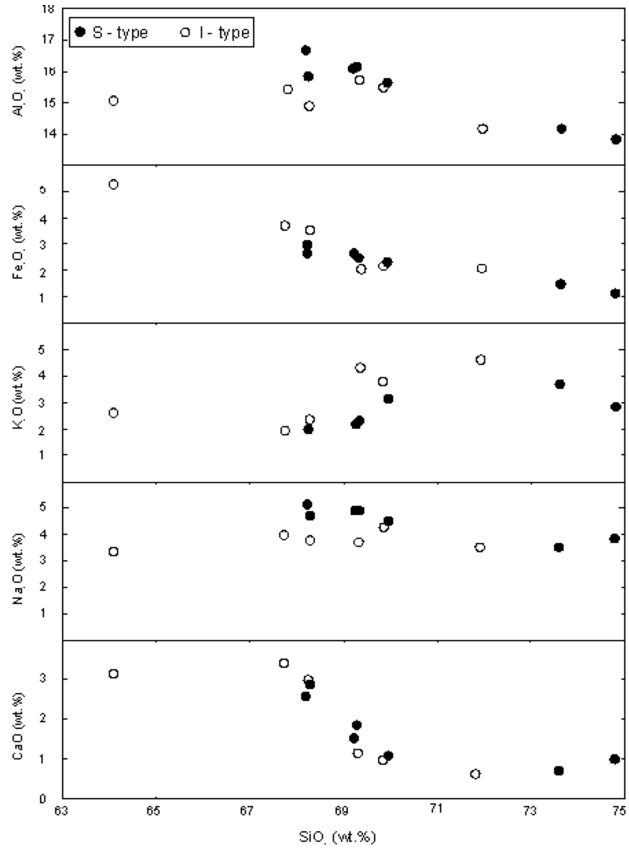

Fig. 4. Harker variation diagrams of selected major elements.

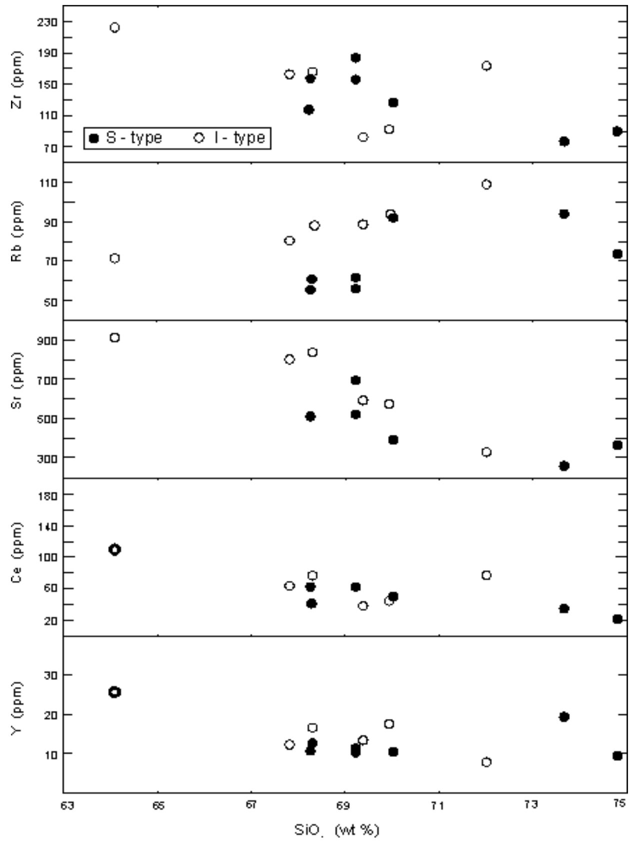

Fig. 5. Harker variation diagrams of selected trace elements.

Monazite. Orange coloured crystals of monazite are typical of the Malá Fatra granitoids. The chemical composition of monazite from the S-type granite (Bystrička quarry) was studied in detail. The mole fraction of monazite (X_{REEPO4}, Mo component in Table 4) in the structure, a parameter necessary for calculation of monazite saturation temperatures, was determined. The LREE show fractionation which is evident in most of the monazite grains: the centres have a higher amount of LREE (La, Ce, Pr) compared to the rims. The opposite is true for the middle REE and ytrium which are more concetrated in the rims (Table 4). The primary origin of monazite is documented by its magmatic zoning.

P-T-X conditions in the granitic melt

Pressure: Two samples (I-type granodiorite) have the mineral assemblage suitable for geobarometry (BMF-6 and BMF-14). Both samples which, after Ivanov & Kamenický (l.c.), come from the older (hybrid) granite group, consist of quartz, plagioclase, biotite, K-feldspar, hornblende and Fe-Ti oxides which is the critical mineral assemblage in the experimental calibration of Al-in-hornblende geobarometer (Hollister et al. 1988). In the following calculations only the rims of the hornblendes were used to meet the equilibrium conditions for the common crystallization of hornblende and K-feldspar.

Hornblende analyses are given in Table 5. They were used for the pressure calculations after Anderson & Smith (1995), who calibrated the barometer for various temperatures:

$$p(\pm 60\ \mathrm{MP}) = 4.76\mathrm{Al} - 3.01 - [T(^{\circ}\mathrm{C}) - 675]/85 \times 0.530\mathrm{A} + 0.005294[T(^{\circ}\mathrm{C}) - 675]$$

The temperatures neccessary for this equation were taken from the Zr saturation thermometry which for both studied samples gives approximately 770 °C (see below). The Al-in-hornblende barometer yielded pressures in the range of 2.4 to 4.0 kbar (240–400 MPa). The average pressure obtained was 3.3 kbar for both samples studied (BMF-14, n = 15, BMF-6, n = 8).

Temperature: In hydrous (2.0 % water) peraluminious and metaluminious granitic melts the zircon solubility can be described by the equation of Watson & Harrison (1983):

$$\ln D_{Zr} = [-3.80 - 0.85(M - 1) + 12900]/T$$

where $\ln D_{Zr}^{\mathrm{zircon/mellt}}$ is the concentration ratio of Zr in a sample to that in stochiometric zircon, M is the cation ratio (Na + K + 2Ca)/(Al*Si). Zircon saturation temperatures for the Malá Fatra granitic rocks range between 740 and 810 °C (Table 6).

The solubility of monazite can also be used as a thermometer. It is based on Montel's (1993) experimental study of the equilibrium between monazite and Ca-poor felsic melt, and the temperature is calculated from the total LREE content of the natural magmatic rocks:

$$\ln REE_t / X_{REEPO4} = [9.50 + 2.34D + 0.3879(H_2O - 13318)^{1/2}]/T$$

Table 4: Representative microprobe analyses of monazite from the Bystrička quarry (S-type granite). Note: Mo — monazite ($CePO_4$), Br — rabantite ($CaTh(PO_4)_2$), Hu — huttonite ($ThSiO_4$) mole fractions.

Sample	BMF-1							
Point	mon 1	mon1-1	mon 3-1	mon 3-2	mon 4-1	mon 4-2	mon 7-1	mon 7-2
	core	rim	core	rim	core	rim	core	rim
SiO_2	0.33	1.73	0.24	0.16	0.10	0.58	0.30	0.23
P_2O_5	28.12	27.00	28.08	28.01	28.36	28.64	26.99	27.15
CaO	1.14	1.09	0.97	1.01	0.86	1.46	0.98	0.95
Y_2O_3	1.15	2.42	0.86	2.14	2.44	2.75	1.28	1.51
La_2O_3	13.86	12.81	14.23	13.56	13.33	13.02	13.64	12.93
Ce_2O_3	29.11	26.75	28.14	27.40	27.40	27.00	28.75	28.41
Pr_2O_3	3.43	3.27	3.48	3.42	3.45	3.82	3.66	3.44
Nd_2O_3	11.73	11.49	11.80	11.43	11.22	11.31	12.00	12.53
Sm_2O_3	1.75	2.18	1.77	2.05	2.33	2.27	1.49	1.87
Eu_2O_3	0.76	0.66	0.94	0.66	0.68	0.80	1.31	0.68
Gd_2O_3	0.17	0.76	0.42	0.99	0.37	0.21	0.61	0.70
Er_2O_3	0.02	0.31	0.20	0.15	0.21	0.36	0.19	0.04
Yb_2O_3	0.24	0.10	0.00	0.20	0.04	0.17	0.04	0.09
ThO_2	4.50	5.79	4.70	4.52	4.48	4.69	5.07	4.30
UO_2	0.18	0.96	0.93	0.77	0.92	0.97	0.22	0.35
Al_2O_3	0.00	0.00	0.01	0.01	0.00	0.00	0.05	0.00
TiO_2	0.02	0.01	0.11	0.18	0.01	0.00	0.06	0.00
MnO	0.08	0.01	0.00	0.12	0.00	0.00	0.00	0.00
FeO	0.00	0.04	0.06	0.24	0.00	0.25	0.00	0.00
SrO	0.02	0.09	0.00	0.01	0.00	0.08	0.00	0.04
ZrO_2	0.05	0.11	0.11	0.06	0.00	0.00	0.12	0.00
PbO	0.00	0.07	0.11	0.08	0.10	0.11	0.00	0.02
F	0.12	0.23	0.34	0.41	0.27	0.32	0.60	0.24
O=FCl,C	0.05	0.10	0.14	0.17	0.11	0.13	0.25	0.10
Total	96.76	97.80	97.36	97.41	96.46	98.68	97.10	95.39
Si	0.013	0.070	0.010	0.006	0.004	0.023	0.012	0.010
P	0.971	0.922	0.967	0.961	0.978	0.960	0.942	0.960
Ca	0.050	0.047	0.042	0.044	0.038	0.062	0.043	0.042
Y	0.025	0.052	0.019	0.046	0.053	0.058	0.028	0.034
La	0.208	0.191	0.213	0.203	0.200	0.190	0.207	0.199
Ce	0.434	0.395	0.419	0.407	0.409	0.391	0.434	0.435
Pr	0.051	0.048	0.052	0.050	0.051	0.055	0.055	0.052
Nd	0.171	0.166	0.171	0.165	0.163	0.160	0.177	0.187
Sm	0.025	0.030	0.025	0.029	0.033	0.031	0.021	0.027
Eu	0.011	0.009	0.013	0.009	0.009	0.011	0.018	0.010
Gd	0.002	0.010	0.006	0.013	0.005	0.003	0.008	0.010
Er	0.000	0.004	0.003	0.002	0.003	0.005	0.002	0.001
Yb	0.003	0.001	0.000	0.002	0.000	0.002	0.000	0.001
Th	0.042	0.053	0.043	0.042	0.042	0.042	0.048	0.041
U	0.002	0.009	0.008	0.007	0.008	0.009	0.002	0.003
Al	0.000	0.000	0.001	0.001	0.000	0.000	0.003	0.000
Ti	0.001	0.000	0.003	0.005	0.000	0.000	0.001	0.000
Mn	0.002	0.000	0.000	0.003	0.000	0.000	0.000	0.000
Fe	0.000	0.001	0.002	0.008	0.000	0.006	0.000	0.000
Sr	0.001	0.002	0.000	0.000	0.000	0.001	0.000	0.001
Zr	0.001	0.002	0.002	0.001	0.000	0.000	0.002	0.000
Pb	0.000	0.001	0.001	0.001	0.001	0.001	0.000	0.000
F	0.015	0.030	0.043	0.053	0.035	0.040	0.078	0.032
Mo	0.9103	0.9012	0.9155	0.9159	0.9219	0.8977	0.9130	0.9200
Br	0.0765	0.0299	0.0748	0.0779	0.0740	0.0798	0.0752	0.0707
Hu	0.0131	0.0689	0.0097	0.0062	0.0040	0.0225	0.0118	0.0094

Table 5: Representative microprobe analyses of hornblende. The pressures were calculated according to Anderson & Smith (1995). BMF-14 biotite granodiorite, BMF-6 hornblende biotite granodiorite (I-type).

Sample	BMF-14										BMF-6	
Point	Hbl 4-1	Hbl 4-2	Hbl 4-3	Hbl 4-5	Hbl 4-6	Hbl 4-8	Hbl 5-1	Hbl 5-3	Hbl 5-4	Hbl 5-5	Hbl 1-2	Hbl 1-3
	core	rim	rim	rim	rim	rim	core	rim	rim	rim	rim	rim
SiO_2	45.93	45.79	45.93	45.71	45.99	45.96	45.72	44.92	44.72	46.57	46.02	45.85
TiO_2	0.91	0.87	0.74	0.82	0.87	0.98	0.85	0.93	0.96	0.18	0.42	0.4
Al_2O_3	9.12	8.23	8.84	9.4	9.24	8.73	9.36	9.8	10.34	9.53	8.82	8.78
FeO	17.64	17.84	17.35	17.61	17.31	17.73	17.37	18.16	17.7	18.09	15.3	16.17
MnO	0.68	0.9	0.67	0.61	0.78	0.87	0.73	0.66	0.72	0.67	0.45	0.53
MgO	10.49	10.84	10.89	10.65	10.36	10.6	10.42	9.85	9.77	10.29	12.74	12.44
CaO	11.35	11.22	11.3	11.46	11.42	11.18	11.53	11.28	11.47	11.8	12	11.63
Na_2O	1.22	1.37	1.09	1.11	1.14	1.13	0.97	1.24	1.21	1.01	1.29	1.34
K_2O	1.1	0.97	1.06	1.11	1.11	1.03	1.13	1.22	1.11	0.77	0.61	0.65
Total	98.44	98.03	97.87	98.48	98.22	98.21	98.08	98.06	98	98.91	97.65	97.79
Si	6.760	6.766	6.768	6.712	6.785	6.762	6.749	6.666	6.636	6.804	6.730	6.696
Ti	0.101	0.097	0.082	0.091	0.097	0.108	0.094	0.104	0.107	0.020	0.046	0.044
Al^{IV}	1.240	1.234	1.232	1.288	1.215	1.238	1.251	1.334	1.364	1.196	1.270	1.304
Al^{VI}	0.342	0.199	0.304	0.339	0.392	0.276	0.377	0.380	0.444	0.445	0.250	0.207
Fe^{3+}	0.563	0.715	0.685	0.637	0.485	0.704	0.548	0.571	0.500	0.586	0.689	0.869
Fe^{2+}	1.615	1.501	1.464	1.535	1.656	1.489	1.603	1.690	1.702	1.632	1.193	1.122
Mn	0.085	0.113	0.084	0.076	0.097	0.108	0.091	0.083	0.090	0.083	0.056	0.066
Mg	2.302	2.388	2.392	2.331	2.279	2.325	2.293	2.179	2.161	2.241	2.777	2.708
Ca	1.790	1.776	1.784	1.803	1.805	1.762	1.824	1.794	1.824	1.847	1.880	1.820
Na	0.348	0.392	0.311	0.316	0.326	0.322	0.278	0.357	0.348	0.286	0.366	0.379
K	0.207	0.183	0.199	0.208	0.209	0.193	0.213	0.231	0.210	0.144	0.114	0.121
Pressure (MPa)	300	240	280	320	310	270	320	360	400	330	280	270

Table 6: The summary of P-T data (Malá Fatra granitoid samples).

	H_2O (wt.%)	zirkon T(°C)	monazit T(°C)	P (60 MPa)
S-type				
BMF-1	2.5	779	779	330
BMF-2	2.5	757	746	330
BMF-3	2.5	754	721	330
BMF-5	3	741	765	330
BMF-11	3	773	785	330
BMF-12	2.5	738	769	330
BMF-13	3	789	791	330
Average		762	765	
I-type				
BMF-4	4.5	809	810	330
BMF-6	4.5	810	810	330
BMF-8	4.5	804	777	330
BMF-9	4.5	790	801	330
BMF-10	4.5	745	780	330
BMF-14	4.5	792	762	330
Average		792	786	

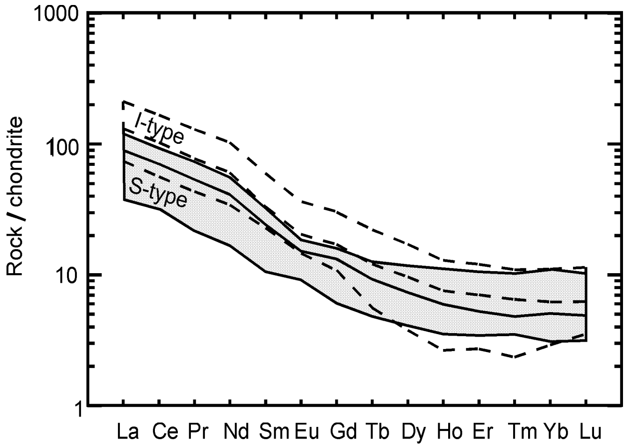

Fig. 6. The REE patterns of the Kriváň part granitoids (Malá Fatra Mts). Shaded (S-type) and open (I-type) fields are shown together with averaged compositions (solid and dashed lines respectively).

where $LREE_t$ = $\Sigma LREE_i$ (ppm) (LREE = La+Ce+Pr+Nd+Sm+Gd) and D = (Na+K+Li+2Ca)/Al × × 1/(Al+Si). T is in Kelvins.

The calculation of water content is described in next paragraph, X_{REEPO4} is the sum of the mole fractions of REE phosphate components in monazite which, in the case of the S-type granites of the Malá Fatra Mts. (locality Bystrička), average 0.9 (Table 4). This value was used for all monazite saturation temperature calculations. They range between 720 and 810 °C correlating quite well with the zircon saturation temperatures. I-type granite samples show generally higher temperatures than S-type granites belonging to the

Table 7: The summary of oxygen and water fugacity data (S- and I-type granitoids of the Malá Fatra Mts.).

Sample	Buffer	Temp. (^{o}C)	Biotite X_{Fe}	log fO_2 (bar)	fH_2O (bar)	a_{H2O}	X_{H2O}	water wt%
S-type								
BMF-1	FMQ	750	0.395	-15.45	453	0.208	0.253	2.27
	NN	750	0.395	-15.01	749	0.343	0.325	2.32
BMF-5	FMQ	750	0.427	-15.45	572	0.263	0.284	2.66
	NN	750	0.427	-15.01	946	0.434	0.365	3.80
I-type								
BMF-9	TMQA	700	0.331	-14.90	1178	0.595	0.428	4.89
		750	0.331	-13.55	2368	1.081[1]	0.553[1]	7.82[1]
BMF-14	TMQA	700	0.324	-14.90	1104	0.558	0.414	4.63
		750	0.324	-13.55	2220	1.014[1]	0.553[1]	7.82[1]

Notes:
Calculations were performed at P_{total} = 300 MPa, X_{OH} in biotite = 1, $a_{K\text{-feldspar}}$ = 0.8.
[1]Molar fractions and water contents calculated at the a_{H_2O} set to 1.

Magura type group. Due to the possible inheritance of old zircon cores which increase the actual Zr contents in the melts the zircon temperatures may be overestimated.

Water content in the melt: The water content was for the first time in the West-Carpathian granites estimated for the Tribeč I-type and S-type tonalites (Petrík & Broska 1994). The presence of the critical assemblage for pressure calculations as well as the fresh biotite in the I-type tonalite enable us to make similar calculations also for the Malá Fatra granitoids. Because our samples of the S-type granites contained only strongly altered biotites (chlorites) we used the biotite analysis published by Macek (1992).

The calculation is based on Burnham's (1979) model of water dissolution in silicate melts (albite-H_2O). It requires knowledge of total pressure, temperature and oxygen fugacity of the melt. The water fugacity was calculated using the annite mole fraction in biotite according to the equation of biotite stability of Wones (1972). The oxygen fugacity was approximated by the NN buffer in the case of S-type granitic rocks (samples BMF-1, 5) and by the TMQA (Noyes et al. 1983) buffer for I-type tonalites (samples BMF-9, 14). Water activity was then calculated according to the equation $a_{H_2O} = f_{H_2O}/f_{H_2O}^{o}$ (Table 7). The values of $f_{H_2O}^{o}$ (Burnham et al. 1969) were taken from Tables 6–10 of Carmichael et al. (1974). Water activity was converted to mole fraction of water X_{H_2O} according to equations 16–3 or 16–4 of Burnham (1979), and to wt. % using the molecular weights of albite and water.

The water content calculation is extremely sensitive to both the oxygen fugacity and the mole fraction of annite. The use of zircon or monazite saturation temperatures in the calculation would yield unrealistically high water contents. To explain this we suggest that annite content of biotite actually reflects the last re-equilibration in the system

$$KFe_3AlSi_3O_{10}(OH)_2 + 1/2O_2 = KAlSi_3O_8 + Fe_3O_4 + H_2O$$

The re-equilibration (= increasing of biotite Fe/Mg ratio) must have continued to lower temperatures than those of zircon and monazite precipitation. We therefore choose the temperatures 700 °C for I-type and 750 °C for S-type granitoids (Table 7). Water contents are about 4.9 wt. % for BMF-9, 14 (I-type) and 2.3–3.8 wt. % for BMF-1, 5 (S-type). Table 7 also shows that if the temperature 750 °C is used for I-type biotites, a_{H_2O} exceeds 1. The value 7.82 % then refers to the water saturation (a_{H_2O}= 1).

Discussion and conclusions

The results of mineralogical, geochemical and petrological research on the Malá Fatra granitoids confirmed the presence of two groups of granitoids in this mountain range distinguished originally on the basis of field observations (Kamenický & Ivanov 1957), although, some of our samples are not consistent with the older field discrimination (samples BMF-3, 5, 10, 13). Typical hybrid granites were not observed in the Kriváň part of the Malá Fatra Mts. and we, therefore, suggest that this term should not longer be used in the Malá Fatra mountain range. The granitoids show no significant hybridization or mixing of mafic and felsic magmas and are only slightly inhomogenous and locally show features of tectonic deformation. We have not observed any schlieren or transitions to the metamorphic mantle in the Kriváň segment of the Malá Fatra Mts. (this phenomenon is much more common in the Lúka part not dealt with in this paper). The robust I/S type classification fits well the "hybrid" and Magura types in the Malá Fatra Mts. Areally, the I-type granitoids crop out on the southern slopes of the Kriváň part, the S-types lie to the north of the I-type occurrences. The map (Fig. 2) also shows some occurrences of the "hybrid" granite on the northern crystalline slope in the end of the Bystrička valley, but our study did not confirm them (BMF-3). On the other hand, the western occurrences of Magura granites along the Váh River do not show S-type characterization and the sample BMF-10 belongs to the I-type.

The zircon $\overline{I.\,T.}$ typological parameter was used as a critical discrimination factor which helped us to subdivide the samples into the above groups (Fig. 3). The granitoids of I-type, characterized by the $\overline{I.\,T.}$ zircon parameter above 350, typically contain the assemblage of allanite, hornblende, interstitial K-feldspar and are represented mainly by tonalites and granodiorites. Harker diagrams of major and trace elements show better correlations than for the S-type group, this being one of the criteria for determining I-type granites according to Chappell & White (1974). The contents of REEs are higher compared to the S-type group which is also true for the I-type granitoids in other Carpathian mountain ranges. The Al-in-hornblende barometer gives the pressure of 330 ± 60 MPa, the zircon saturation temperatures are between 745 and 810 °C and monazite saturation temperatures between 750 and 810 °C. The water content is about 5 wt.% at 700 °C. This granite suite also contains mafic magmatic enclaves the occurrences of which are accompanied by increased magnetic susceptibility (above 300 × 10^{-6} SI units). All these data correlate with other I-type granitoids in the Western Carpathians.

The *S-type* granites have zircon parameters below 300–350. Although the hornblende barometry could not be done in this case we assume the same pressure (330 MPa) for the emplacement of this granite suite. The zircon and monazite saturation temperatures are also within the range of I-type granitoids (740–790 °C and 720–790 °C). However, their magmas were drier, water content reaching only about 2–4 wt. % at 750 °C.

It is noteworthy that in the Tribeč Mts. (Fig. 2) S- and I-type tonalites were observed in a similar position (Petrík & Broska 1994): the former are situated on the northern or north-western slope of this mountain range, the latter in the southwest. The P-T-X conditions of the Tribeč granitoids are also almost identical with those in the Malá Fatra Mts.: total pressure of 350 MPa for the I-type, 5.17 wt. % of H_2O, and 250 MPa pressure for the S-type and 2.32 wt. % H_2O (both at 700 °C model temperature). Indirect pressure estimates from the surrounding metapelites of the S-type granites of the Malé Karpaty and Považský Inovec Mts. also yielded pressures of about 300–350 MPa (Korikovsky et al. 1984). Recently, Janák & Kohút (1996) gave a similar pressure estimate (400 MPa) for an adjacent granite core, the Veľká Fatra Mts. (Fig. 2) on the basis the presence of cordierite in its metamorphic mantle.

Thus pressures of 300–400 MPa are reported from the 200 km long belt between the Malé Karpaty and Malá Fatra Mts. Although, this span refers to the present erosion cut, we believe that the presented PTX values have a wider application in the West-Carpathian granite history. The pressure 300–400 MPa corresponds to approximately 11–14 km emplacement depth for both granite types in the studied area.

However, the oxygen fugacity or water contents were different in I- and S-type granite melts. The first one indicates oxidation conditions which are recorded by the accessory mineral asemblage dominated by hornblende, allanite, titanite, magnetite, and the low fraction of annite component in biotite. On the other hand, monazite, ilmenite, and sometimes black apatite, accessory mineral phases characteristic of S-type granitoids, are indicative of reducing conditions and lower water contents. The biotite in these granites has a significantly higher annite content. Mafic magmatic enclaves only occur in the I-type granitoids. They were found for example in the western part of the I-type body (BMF-6, Kľačianska Magura).

The I/S subdivision of the Malá Fatra granitoids makes it possible to relate them to other suites of the Western Carpathians and the wider geotectonic framework of the Variscan orogen during Carboniferous. In this sense the S-type granites in the Malá Fatra Mts. may have formed as a response to the crustal thickening and prograde metamorphism during Early Carboniferous times. The S-type granite melts may have arisen due to fluid-absent melting of flyschoid source rocks in an accretionary prism. By contrast, the I-type tonalites may have originated from lower crustal lithologies by dehydration melting during a Late Carboniferous thermal event. The necessary heat may have been provided by hot underplated mafic magmas (Petrík et al. 1994). The characteristic presence of the mafic enclaves in the Tribeč I-types (Sihla type s.l. Broska & Petrík 1992) supports this idea.

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Localization of the samples

BMF-1 Biotite granodiorite. Kraľovany, Bystrička valley, a quarry. 1500 m S from the elev. p. Kykuľa (919 m a. s. l.), the second terrace of the quarry.

BMF-2 Biotite tonalite. Locality as BMF-1.

BMF-3 Coarse-grained two-mica leucocratic granite. Kraľovany, valley Bystrička, 3 km from the end of valley, a cliff on the right side of the valley (660 m a. s. l.).

BMF-4 Coarse-grained leucocratic granodiorite. Kraľovany, old quarry above affluent of the Orava River into the Váh River. 2250 m N from the elev. p. Kopa (1187 m a. s. l.) and 3500 m southward from the elev. p. Kykuľka.

BMF-5 Coarse-grained muscovite-biotite granite, Kraľovany. Railway-cut, 1 km of the creek mouth Bystrička.

BMF-6 Hornblende-biotite granodiorite. Turčianske Kľačany. 1200 m S from the Kľačianska Magura chalet, 2000 m S from the elev. p. Kľačianska Magura.

BMF-7 Biotite paragneiss. Lipovec, Hoskora valley.

BMF-8 Coarse-grained two-mica granite. Lipovec, Hoskora valley, 2000 m W from the elev. p. Lipovská Magura (1101 m a. s. l.), a cliff.

BMF-9 Coarse-grained granodiorite. Lipovec. Hoskora valley (Na pltisku). 450 m E-S elev. p. Krivé, a cliff.

BMF-10 Coarse-grained two-mica granite. 250 m S-E from the end of the Hoskora valley on the right bank of the Váh River.

BMF-11 Coarse-grained two-mica granite. Šútovo, 500 m above the Šútovo waterfall, canyon.

BMF-12 Two-mica granodiorite. Šútovo, 1200 m S form the elev. p. Vlčkovské. 765 m a. s. l., a cliff.

BMF-13 Biotite granodiorite. Šútovo, 750 m S from the elev. p. Vlčkovské, a cliff on the right side of the Šútovo valley, 100 m above the chalet Vodopád.

BMF-14 Coarse-grained biotite granodiorite. Sučany, 1250 m N-E form the elev. p. Jarolím, 788 m a. s. l., asphalt road-cut in the forrest.

BMF-15 Two-mica granodiorite. Turany, Studenec valley, a cliff.

BMF-16 Coarse-grained biotite granite/granodiorite. Sučany, Studenec valley, the end of the Studenec valley.

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