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MAFIC ENCLAVES IN GRANITOID ROCKS OF THE TRIBEČ MTS., WESTERN CARPATHIANS: GEOCHEMISTRY AND PETROLOGY

(10 Figs., 9 Tabs.)

Abstract: Small, microgranular, mafic enclaves have been found in biotite tonalite, a basic rock type in the Tribeč Mts. They are biotite-rich, of two petrographic types: quartz-bearing (tonalitic), and quartz-free (dioritic). In accord with their occurrence in basic rock type, rounded shape, small size, fine-grained texture, presence of acicular apatite, Fe-group trace element content, they are interpreted as blobs of mafic magma (intermediate in composition) entrapped and chilled by host granitoide magma. The presence of the enclaves suggests contemporaneous existence of both granitoid and mafic magmas during the granitoid plutonism in the Tribeč Mts. A characteristic feature of all enclaves is the strong interaction with fluid phase. This appears as the formation of felsic domains in tonalitic enclaves, the reequilibration of enclave and host rock plagioclase and biotite, the formation of two zircon generations, and replacing of primary minerals by secondary associations. High K, Rb, Ba contents of enclaves are explained as being due to alkali diffusion from granitic to mafic magma, which results in the biotite stabilization.

Резюме: В биотитическом тоналите — основном типе гранитоидной породы в горной цепы Трибеч — обнаружились небольшие, микрогранулярные мафические энклавы. Они насыщены биотитом и представляют два петрографические типа: с кварцом (тоналиты) и без кварца (диориты). В соответствии с присутствием энклав имеющих овальный облик, небольшие размеры, мелкозернистую структуру, иголчатые апатиты, повышенное содержание группы Fe элементов, их можно интерпретировать как капли мафической магмы (интермедиарного состаяния) захватенной гранитоидной магмой. Присутствие энклав нам дает возможность предполагать во времени гранитоидного плутонизма в горной цепы Трибеч современное присутствие двух типа расплава — гранитоидного и мафического. Характерной чертой исследованных энклав является их связ с воздействием флюидной фазы. Проявление этого показывается появлением фельзических домен в тоналитическом типе энклав, достижением равновесия плагиоклазов и биотитов в энклавах и окружающей породе, образованием двух генераций циркона и замещением первичных минералов вторичными. Высокое содержание K, Rb, Ba в энклавах обясняется процессом щелочной дифузии из гранитоидной в мафическую магму, что проявилось стабилизацией биотита в энклавах.

Introduction

Considerable attention has recently been devoted to mafic enclaves, a typical feature of calc-alkaline plutonic and volcanic rocks. It results from the significance they have for petrogenesis of host granitoids, for the contem-

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poraneous existence of both silicic and basic magmas, and for processes of mixing and mingling in magmatic chambers. In the present paper we are concerned with the mafic enclaves of microgranular character which we consider as globules of mafic magma solidified in the environment of felsic, granitic s.l. magma. The interpretation is in accord with opinions of many authors dealing with enclaves both in plutonic rocks (Vernon, 1983; Reid et al., 1983; Wall et al., 1987; Ayrton, 1988) and volcanic rocks (Eichelberger, 1980; Bacon, 1986). Nevertheless, we emphasize that the accepted model is one of possible interpretations. It is believed, however, to explain the observed facts best.

The presence of mafic enclaves is in favour - if we accept the presented interpretation - of the coexistence of two contrasting magma types in the crust and has consequences also for petrogenetic interpretation of the host granite. In fact, the presence of mafic (basaltic, dioritic) magma is increasingly more often considered as the main source of heat and the cause of melting of overlying crustal rocks (Eichelberger — Gooley, 1977; Eichelberger, 1978; Huppert — Sparks, 1988a, b; Ayrton, 1988).

A variety of possible interactions exists between two contrasting magma types in magma chamber: from total immiscibility to thorough mixing. The resultant effect depends on physical properties (temperature, density, viscosity) and chemical properties (compositional contrast, water content) of both magmas. A considerable experimental and theoretical effort exerted on the understanding of interrelations made it possible to reveal the significance of water content in the mafic magma (Eichelberger, 1980; Huppert et al., 1982), viscosity (Huppert et al., 1984, 1986), and compositional contrast of coexisting magmas (Sparks — Marshall, 1986).

Intrusion of the hot mafic magma into the continental crust may rise the temperature in the crust sufficiently to iniciate the extensive melting and formation of granitic magma. Two contrasting magma types come to contact in this way. At the interface of both magmas the heat transfer occurs from mafic to felsic magma resulting in the crystallization of mafic magma. Whether the hybridization (thorough mixing) occurs, or the magmas maintain their identity depends on the interplay of number of factors: possible water saturation (bubbles formation) may lower the mafic magma density to that of the overlying felsic one and cause the effective hybridization (Huppert et al., 1982). To the contrary, compositional and temperature contrasts of both magmas, and the small proportion of the mafic magma in the mixture (small blobs of mafic magma trapped and carried by felsic magma) prefer a rapid viscosity growth inhibiting the effective mixing, are favourable for the origin and/or retaining of mafic enclaves (Marshall — Sparks, 1986).

Occurrence and description of enclaves

Except the remarks in geologically oriented papers (Koutek, 1930; Siegl, 1976; Határ et al., 1989) small attention has been given to enclaves from granitic rocks (with regard to their scarcity) in Slovak (West Carpathian) literature. The enclaves in Neoalpine subvolcanic granitoids of the Hodruša-

-Štiavnica intrusive complex (Š a l á t, 1954) and enclaves from volcanic rocks (e.g. F i a l a, 1954; H o v o r k a — L u k á č i k, 1972; Š u c h a, 1985) are exceptions.

The studied enclaves have been found in biotite tonalite of Variscan age (a fundamental rock in the Tribeč Mts., K r i s t, 1960), on southwestern slopes and the ridge of the mountain range, Fig. 1. They range typically

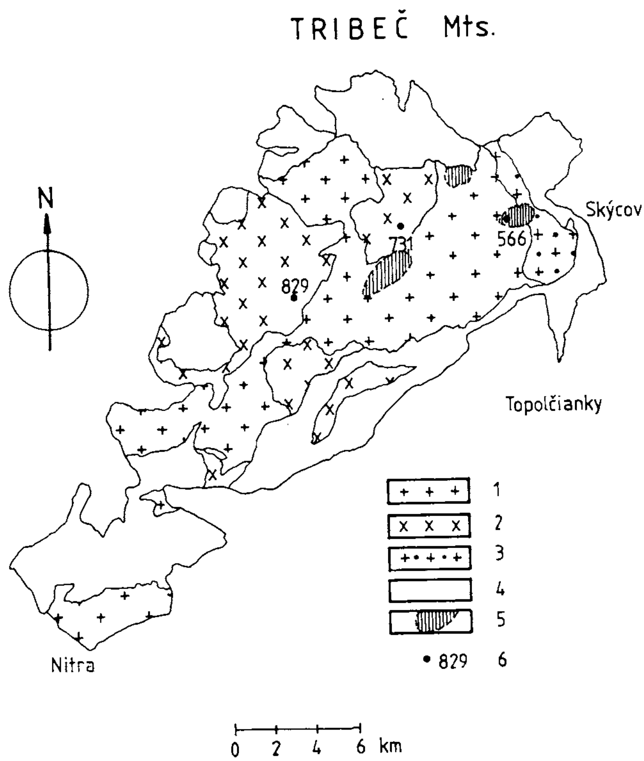


Fig. 1. Geological sketch map of the Tribeč—Zobor crystalline complex.
Legend: 1 — coarse-grained biotite tonalite to granodiorite (basic rock type); 2 — medium-grained tonalite to granodiorite (basic rock type); 3 — leucocratic muscovite and two-mica granite; 4 — Mesozoic cover rocks (mainly quartzites); 5 — occurrences of enclaves; 6 — elevation points.

from 3 to 15 cm in size, though larger enclaves (up to 1 m) have also been found. Most of them are spherical or discoid, Fig. 3a, the larger ones being less rounded. Against the host tonalite they often form the positive relief, or, to the contrary, cavities can be found after the fallen out pieces. Although they are not rare at the found localities (see Tab. 1) their number does not exceed a few tens per outcrop of 200—250 square meters in area.

Petrography

The studied enclaves have the fine-grained texture with grain size ranging between 0.2—0.8 mm. Plagioclases and hornblendes sometimes reach 1—2 mm. The small enclaves (generally less than 15 cm) have monotonous dark appearance, Fig. 3a, owing to the abundance of mafic minerals, Tab. 1. We have, however, found several large, less rounded enclaves bearing characteristical light patches, or felsic domains, composed mainly of plagioclases, quartz, and very often with the large crystals of sphene in centres, Fig. 2 (enclaves T62 T65, T66).

Table 1

Modal compositions of Tribeč enclaves (in vol. %)

Sample	Qz	Plg	Bi	Hb	Sph	Chlo	Epi	Apa	Ores	All	Zir
T-62	16.01	55.40	25.45	0.40	0.32	—	0.61	0.61	1.10	0.09	0.03
T-63 E	0.32	51.66	45.61	—	—	—	0.75	1.34	0.27	0.05	0.05
T-63[1]	25.76	56.66	10.91	—	0.78	—	1.95	0.42	0.17	0.15	—
T-64	1.87	57.94	23.26	6.76	0.67	4.54	2.85	1.29	—	0.67	0.13
T-65	18.25	53.46	23.68	1.11	1.31	0.24	0.43	0.48	0.92	0.05	0.05
T-66	15.31	56.70	21.22	4.13	0.77	—	0.95	0.55	0.23	0.09	0.04
GTB-10 E	20.16	45.28	31.08	0.16	—	—	1.49	1.26	0.36	0.12	0.10
GTB-12	0.33	59.13	38.11	—	0.56	—	1.03	0.33	—	0.37	0.14
GTB-16	0.09	53.41	39.07	—	0.94	0.23	4.89	0.47	0.66	0.19	0.05
GTB-17	0.98	51.43	20.37	19.11	2.01	—	4.39	0.76	0.63	0.22	0.09
GTB-22	1.08	47.83	39.88	—	1.98	7.06	1.65	0.52	—	—	—

[1]Host rock (tonalite)
Sample localities: T62, T63E, GTB10E, T63, GTB22 — 1500 m S from elev. p. 731 m, Javorový vrch Mt.; T65, T66 — 1000 m SW from Javorový vrch Mt.; T64, GTB 12 — 500 m SW from elev. p. 568 m Čierny hrad Mt. (3 km SW from Javorový vrch Mt.); GTB16, GTB17 — 700 m ENE from elev. p. 566 m Krásny vrch Mt.

Plagioclase and biotite are the major minerals of the enclaves. Quartz, hornblende, accessory, and secondary minerals occur in variable amounts. The modal compositions of studied enclaves are given in Tab. 1 and in Fig. 5. According to them two petrographic types may be distinguished: tonalitic (quartz-bearing) and dioritic (essentially quartz-free). The signs of the strong interaction with fluid phase are a common feature of all enclaves: the primary minerals are replaced by secondary association, or are re-equilibrated under lower P-T conditions.

Plagioclase is subhedral to euhedral, heavily sericitised and saussuritised. In the most intensely altered enclaves plagioclase is replaced by the association albite + + zoisite + secondary biotite + chlorite. Microprobe analyses (Tab. 5) of the more preserved plagioclase parts show a characteristical basicity range An = 26—31. In all enclaves albite (An = 5—10) is also present.

Biotite is very abundant, subhedral invariably with secondary sphene exsolutions, Fig. 4d, often epidotised, but rarely chloritised. It often encloses prismatic apatite, Fig. 3b, magnetite, zircon and sometimes allanite. In some enclaves the primary biotite is replaced by secondary cross-oriented, or vermicular biotite, Fig. 3d.

Hornblende varies in amount, is anhedral (T65) to euhedral (GTB17), sometimes replaced by secondary biotite.

Sphene is characteristic, almost ubiquitous accessory mineral. It occurs in several forms as subhedral probably primary mineral with ilmenite inclusions (GTB17,

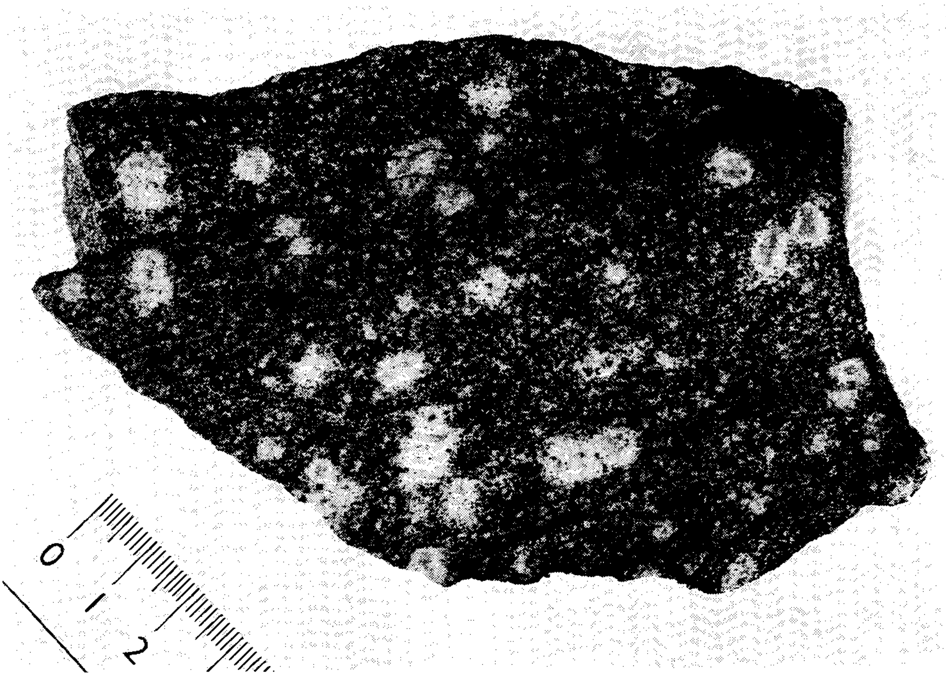


Fig. 2. Portion of large tonalitic enclave (T62) showing felsic domains composed mainly of plagioclase, quartz and sphene. Scale in cm.

host tonalite T63), Fig. 4a, b, as the common secondary product of biotite Ti exsolution where it forms tiny exsolutions, Fig. 4d. In central parts of the felsic domains (Fig. 2) as well as in the matrix sphene forms dendritic anhedral crystals usually at plagioclase and quartz grain contacts, Fig. 4c.

Quartz is intersticial in the tonalitic type where it fills the space between plagioclase and mafics. In the dioritic type quartz is present only as a secondary product of chloritization and in veinlets.

Chlorite is rare, in T64, GTB22 occurs as chloritised biotite and in saussuritised plagioclase.

Apatite is ubiquitous as short prismatic crystals enclosed mainly in biotite, Fig. 3b. The prismatic apatite contributes the conclusive portion to the bulk apatite content. In plagioclases and quartz, also acicular, discernibly younger apatite is present, characteristic of the rapidly cooling magmas (W y l l i e et al., 1962), Fig. 3b, c.

Ores are represented mainly by magnetite and pyrite, the latter being often goethitised. Magnetite occurs typically in agglomerates with biotite and hornblende, sometimes is rimmed by minute secondary sphene crystals. The secondary magnetite can often be observed in association with the secondary biotite (GTB18), Fig. 3d. Ilmenite was identified in sub- to euhedral sphenes in several enclaves (GTB17, GTB18) and the host rock (Fig. 4a). Galena, sphalerite, and As-pyrite were identified in heavy fractions of T62 enclave, and anatas in T63E enclave.

Epidote is abundant product of biotite alteration where it forms typical spindle--shaped forms or agglomerates. Plagioclases are invariably crowded by minute zoisite crystals.

Zircon is abundant, enclosed in biotite, forming two different populations: non--metamict and metamict one (see discussion).

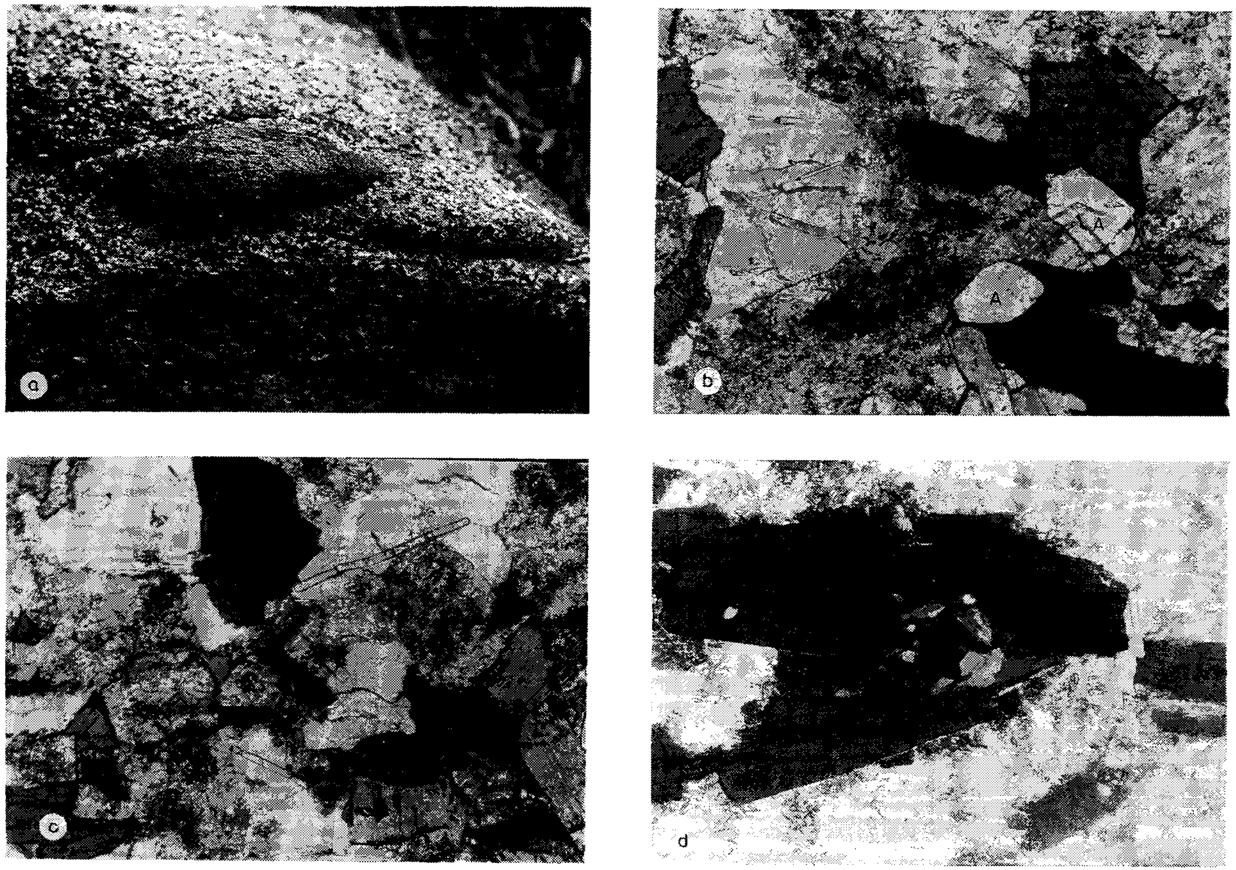


Fig. 3a — Rounded ellipsoidal dioritic enclave (length about 15 cm) showing positive relief against the host tonalite. Fig. 3b — Two generations of apatite crystals: short prismatic — A, and acicular coexisting in tonalite enclave (T62). Base 1.25 mm. Fig. 3c — Acicular apatite in quartz, in tonalitic enclave (T62). Base 1.25 mm. Fig. 3d — Secondary biotite + magnetite replacing primary biotite in dioritic enclave (GTB18). Base 1.25 mm. All photomicrographs in plane polarized light.

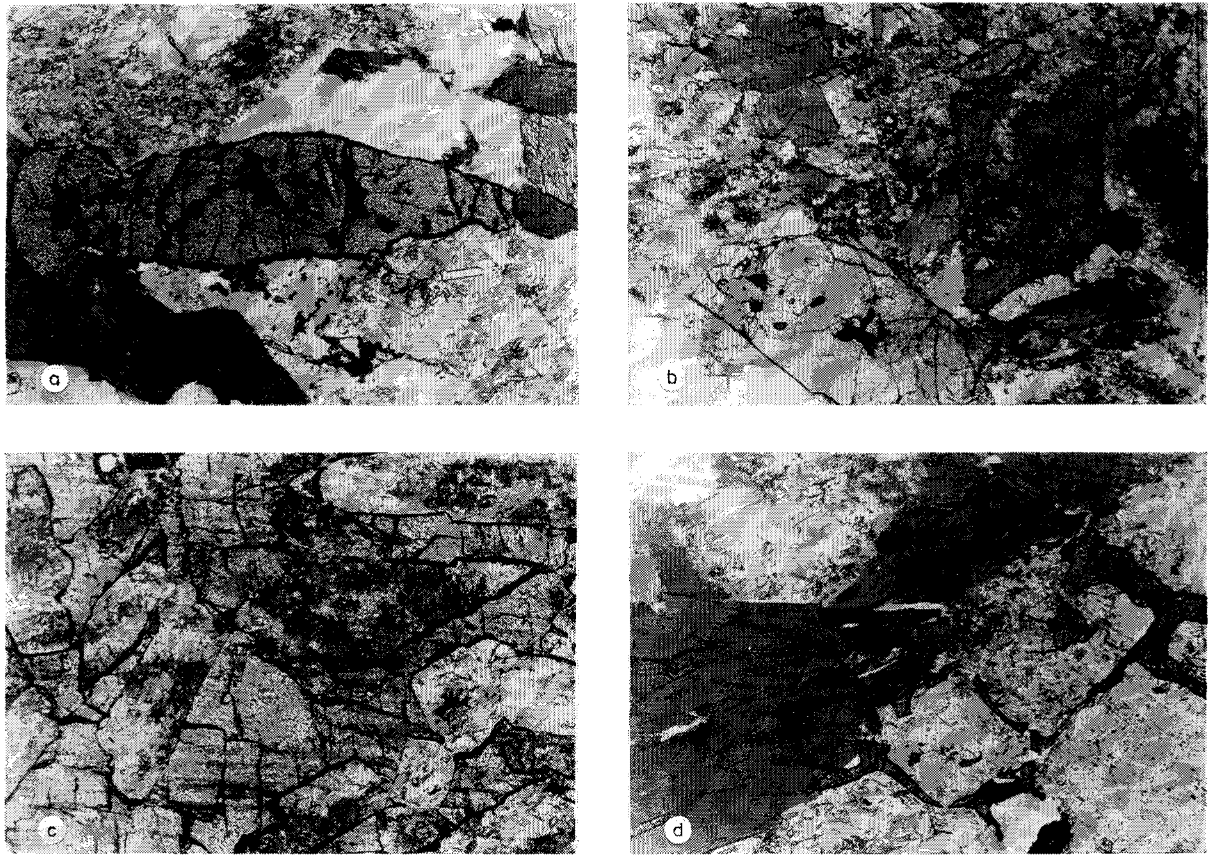


Fig. 4. Photomicrographs of various kinds of sphenes. a) Subhedral primary-looking sphene with ilmenite inclusions, in enclave (GTB17). Base 1.25 mm. b) Two kinds of sphene coexisting at the contact of T62 enclave with its host tonalite: enclave sphene is anhedral enclosing small sericitised plagioclases, host rock sphene is subhedral with ilmenite inclusions. Base 2.95 mm. c) Anhedral sphene (T62 enclave) enclosing a number of small sericitised plagioclases. The sphene has grown in the centre of a felsic domain typical for T62 enclave (Fig. 2). Base 1.25 mm. d) Secondary dendritic sphene growing along biotite cleavage and in plagioclase interstices (GTB18). Base 1.25 mm. All photomicrographs in plane polarized light.

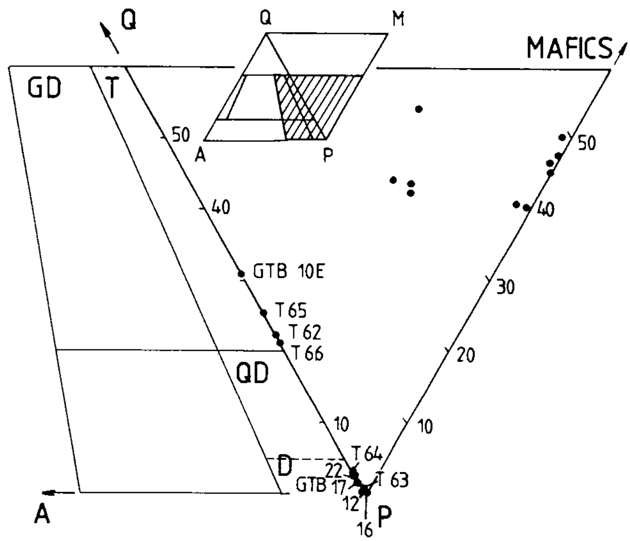


Fig. 5. Modal abundances of minerals of enclaves studied in the QAP diagram after IUGS classification.

Analytical techniques

Eight enclaves were analysed by wet chemical analysis (Cambel — Walzel, 1982), analyst E. Walzel, and by spectral analysis (Medveď — Plško, 1979), analysts H. Beličková, J. Medveď. The spectral analyses were checked against the standard DR-N (De la Roche — Govindaraju, 1969). Results are listed in Tabs. 2, 3. Two enclaves (T62, T63E) and host tonalite (T63) were analysed by X-ray fluorescence, analyst B. Toman, and by INAA method for trace elements (Geoindustria laboratories), analyst Moučka. Results are listed in Tab. 4.

Geochemistry

Chemical composition of enclaves is ilustrated in variation diagrams (Fig. 6) where petrogenic oxides are correlated against MgO content. At the MgO-poor end of the diagrams are plotted granitic rocks of the Tribeč Mts. as solid circles (I. Broska, unpublished data). The open square in variation diagrams refers to average diorite according to Taylor et al. (1969). The quartz-bearing tonalitic enclaves are similar to the average diorite while dioritic ones are MgO, Al_2O_3, FeO_{tot} richer, and SiO_2 poorer. All the enclaves, however, are characterized by higher K_2O, TiO_2, P_2O_5 contents, and, with some exceptions, lower in CaO and MnO contents than the average diorite.

Granitoids together with enclaves form more or less well defined trends of major elements and poorly defined trends of minor elements. The trends appear generally linear (SiO_2, FeO_{tot}, TiO_2, V, Zr, Sc) often with a consi-

Table 2
Major element chemistry for Tribeč enclaves (in wt. %)

	T-62	T-63[1]	T-63E	T-64	T-65	T-66	GTB-10E	GTB-12	GTB-16	GTB-17	GTB-22
SiO_2	54.99	68.87	46.49	48.66	57.32	59.66	56.49	48.82	43.99	48.64	48.75
TiO_2	1.51	0.76	1.79	1.11	1.03	1.14	1.07	1.46	1.46	1.53	1.46
Al_2O_3	17.90	13.87	20.07	19.98	19.13	16.54	17.43	19.54	19.35	18.67	20.46
Fe_2O_3	—	—	—	2.68	1.96	1.96	2.03	3.03	3.35	3.49	1.68
FeO	6.83[2]	4.37[2]	9.61[2]	5.27	3.84	3.45	4.07	5.50	4.67	5.34	5.92
MnO	0.09	0.05	0.17	0.09	0.06	0.07	0.02	0.04	0.05	0.10	0.05
CaO	5.30	3.54	5.60	6.68	4.53	4.67	4.58	5.56	6.37	7.36	4.08
MgO	3.86	1.19	6.02	5.24	3.10	3.64	4.09	4.72	5.26	5.62	6.13
K_2O	2.54	2.46	3.65	3.66	2.98	3.19	3.77	5.16	4.35	3.51	3.87
Na_2O	4.71	3.30	3.09	3.61	4.19	3.74	3.98	3.56	3.61	3.40	3.82
H_2O^-	0.14	0.08	0.29	0.52	0.48	0.40	0.78	0.54	0.72	0.60	0.64
H_2O^+	1.17	1.01	2.10	1.62	0.98	1.04	0.96	1.36	1.34	1.16	2.46
P_2O_5	n. a.	n. a.	n. a.	0.95	0.42	0.41	0.60	0.64	0.53	0.68	0.56
Total	99.04	99.50	99.88	100.07	100.02	99.91	99.87	99.93	100.05	100.10	99.88

[1]Host rock, [2]all Fe as FeO, n.a. not analysed.

Analysts: Ing. E. Walzel
RNDr. B. Toman

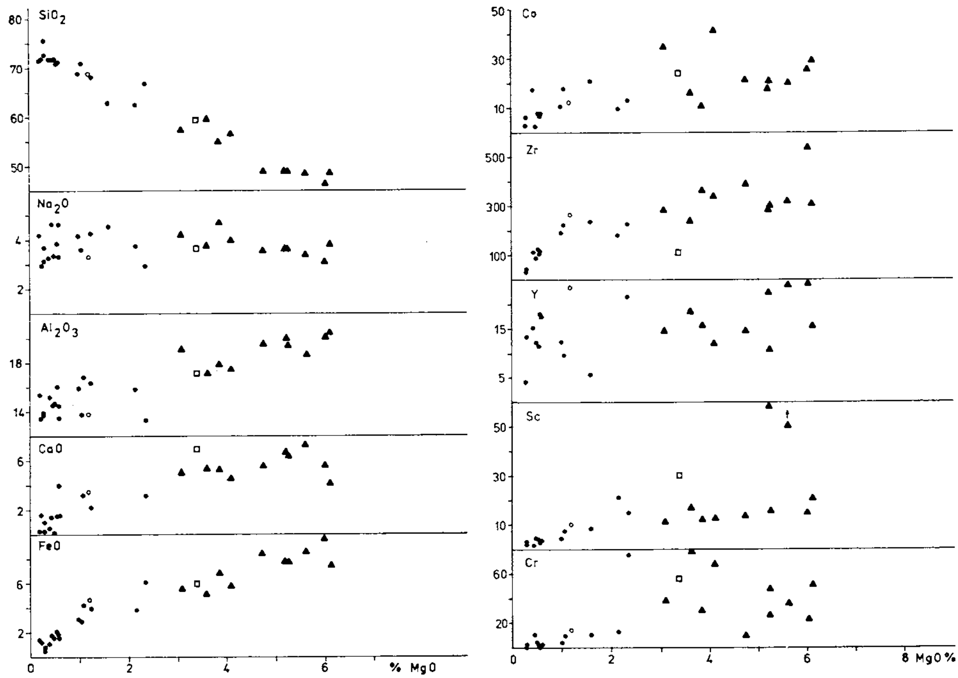
Table 3

Trace element chemistry for Tribeč enclaves (in ppm)

	Ba	Be	B	Pb	Sn	V	Cu	Ni	Zr	Co	Y	Sc	Cr	Sr
T-62	1110	~2.4	~2	23.8	4.2	157	33	18.6	365	10.7	15.7	12	30	870
T-63E	1380	~2.6	<2	19.1	2.8	157	63	29	540	25.7	24.5	15.1	23	690
T-63[1]	1015	~2.3	<2	18.2	~1.7	88	<3	10.7	263	12.1	23.4	9.8	14	810
T-64	269	~2	3.2	19	7.2	209	24	18.2	282	17.6	22.4	58	26	~1200
T-65	980	~2.4	5.9	15.9	3.6	185	32.5	15.5	282	35	14.6	11.2	38	~1170
T-66	1290	~2.2	5.7	12.9	~2.3	135	11.3	27	234	16	18.6	17	78	~1115
GTB-10 E	2400	~2.5	5.2	13.5	~2.8	178	82	25	340	41.5	12	12.5	68	710
GTB-12	1130	~2	4.3	12.9	3.4	251	9.3	15.7	390	21.4	14.5	12.7	10	>1500
GTB-16	1720	~2.3	4.1	21	4.9	242	9.6	21	300	21	10.7	15.9	48	>1500
GTB-17	980	~2.7	4.7	20.9	6.9	270	19.7	20.4	318	20	24	62	36	980
GTB-22	1110	~2.2	3.8	9.3	4.6	219	11.9	26	309	29.5	15.7	21	51	770

[1]Host rock.

Analysts: RNDr. J. Medveď, CSc.
H. Beličková



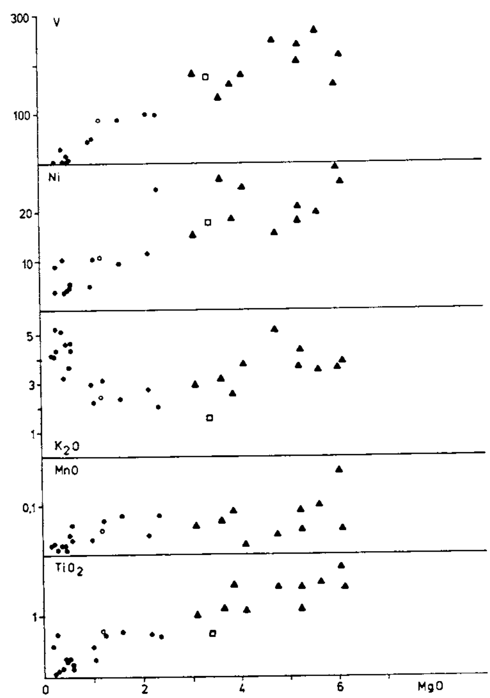


Fig. 6. Variation diagrams of major oxides (wt. %) and trace elements (ppm) against MgO.
Triangles — enclaves studied; solid circles — granitoid rocks of the Tribeč massif (I. Broska, unpublished data); open circle — the host tonalite of T63E enclave. The open square in diagrams refers to average andesite after Taylor et al. (1969), see Tab. 9.

Table 4

INAA analyses of Tribeč enclaves

	La	Ce	Sm	Eu	Tb	Yb	Lu	Au	Rb	Ta	Cs	Hf	Sb	U[2]	Th[2]
T-62	79.8	120.0	6.10	1.75	<1	<1	<0.20	—	107	<1	2.47	11.0	1.69	2.6	11.1
T-63 E	41.2	59.8	3.03	0.85	<1	<1	0.32	—	156	<1	4.45	14.7	<1	n. a.	n. a.
T-63[1]	47.4	82.2	6.45	1.91	<1	1.75	<0.20	0.05	106	<1	2.18	7.23	<1	2.7	9.1

[1]Host rock, [2]U and Th were determined by gamma spectrometry, n.a. not analysed.
Analysts: Ing. Moučka, RNDr. V. Kátlovský, CSc.

derable scatter (Al_2O_3, CaO, Co, Ni, Y). A significant exception is K_2O: the high contents in enclaves disturb the curvilinear trend defined by granitoids. The lack of the correlation MgO vs K_2O suggests that the general coincidence of granitoid and enclave trends is apparent: the granitoids are controlled by their own differentiation mechanism (presumably fractional crystallization, cf. Vilinovič—Petrík, 1984; Cambel et al., 1985, with the crystallizing assemblage dominated by plagioclase). On the other hand, the enclave trend is dominated by the substitution biotite↔quartz (see Tab. 1), plagioclase content being relatively stable.

The two enclaves analysed by INAA for REE are plotted in Fig. 7 and compared with the field of granitoid rocks (I. Broska, unpublished data).

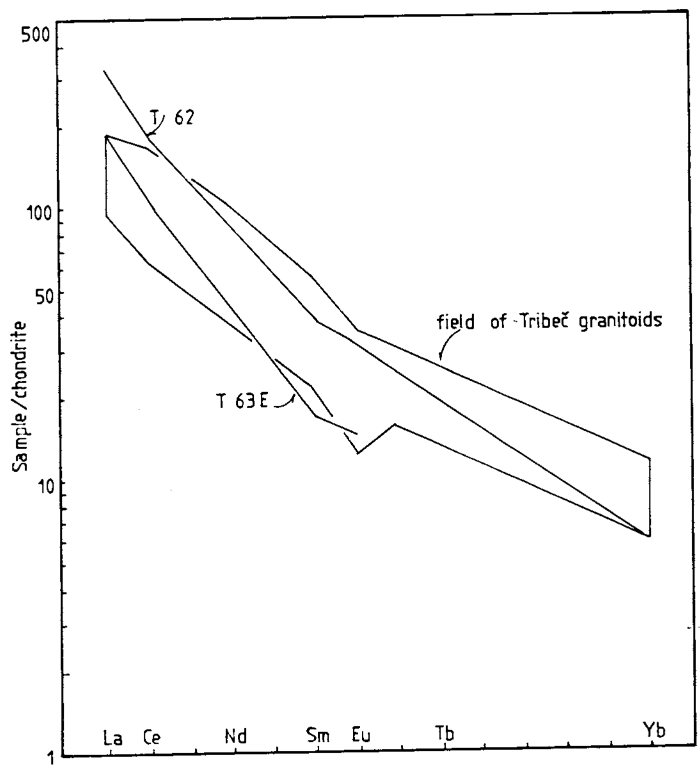


Fig. 7. Chondrite-normalized REE patterns for two enclaves (T62, T63E) compared with the field of Tribeč granitoids.

The curves are incomplete because of high detection limits of Tb and Yb (1 ppm). Both enclaves show a steep REE distribution pattern, the tonalitic one being richer in LREE than granitoids. Middle and heavy REE drop below the granitoid field. The steep pattern is probably a result of the presence of allanite - the major concentrator of LREE (e.g. Gromet—Silver, 1983). The high modal amount of allanite in some other enclaves (Tab. 1) suggests even higher LREE concentration. This feature does not seem to be exceptional: high LREE concentrations in a mafic enclave are reported by S a w k a — C h a p p e l l (1988) and very high contents of Nd, Sm in enclaves from the Criffel and Strontian plutons by H o l d e n et al. (1987).

In comparison with trace element composition of plutonic dioritic enclaves reported by N o y e s et al. (1983), D i d i e r (1987), and of volcanic enclaves (B a c o n — M e t z, 1984) the Tribeč enclaves are markedly enriched in K_2O, Ba, Rb, La, Ce, P, and Zr, Tab. 9. The mafic nature with overwhelming mafic mineral - biotite, and the abundance of zircon, apatite and allanite are responsible for such a distribution. The calcium deficit also reflects the biotite presence at the expence of hornblende, the latter being more common in plutonic enclaves. The low Cr (<80 ppm) and Ni (<30 ppm) contents are significant: in the comparison with average dioritic enclaves from the French Massif Central, as reported by D i d i e r (1987) it is 8 and 4 times lower, respectively.

Mineral chemistry and petrology

Representative microprobe analyses of rockforming and some accessory minerals are given in Tabs. 5—7. The analyses were performed on microanalysers JXA-5a (Tab. 5) and JEOL 733 Superprobe (Tabs. 6, 7) using an acceleration voltage 20 kV. Row data were corrected using ZAF procedure (733 Superprobe) and A l b e e — R a y (1970) (JXA-5A).

Plagioclase. As mentioned in the petrographical section, plagioclase is strongly retrogradely altered. The basicity of the more preserved parts is typically An = 26—31. A profile made across the contact of the T62 enclave and the host tonalite showed the basicity of both enclave and host rock plagioclases to be the same An ≅ 26. It is obvious that the re-equilibration has been attained between both rocks. The fact that the plagioclase is crowded by minute zoisites suggests, however, that the original basicity was higher. Indeed, the CaO balance based on mass fractions of Ca-minerals, their microprobe analyses, and the whole rock CaO content gives the inferred basicity in T62 An = 43, in T63E An = 47, and in T65 An = 34.

Biotite and hornblende. Biotite was analysed in 9 enclaves, in more detail, however, only in T62 and its host rock, Tab. 5. The biotite composition is relatively monotonous and similar in all enclaves, $Fe_t/(Fe_t + Mg)$ ratio ranges typically between 0.4—0.5. The low TiO_2 content, generaly below 2 %, is characteristic (the highest value is 2.57 % in T65, T63E). The profile across the contact T62/host rock showed that $Fe_t/(Fe_t + Mg)$ ratio is the same in both rocks (0.42—0.45). All the features suggest a strong subsolidus re-equilibration. According to F o s t e r's classification (1960) enclave biotites belong to Mg-biotites. They are, however, distinctly more magnesian than granitoid biotites of other West Carpathian mountain ranges (P e t r í k, 1980).

Hornblende, as mentioned in petrographical section, does not occur in all the found enclaves (Tab. 1). Tab. 5 gives the representative analyses of T62 and T64 hornblendes. The Fe^{2+}/Fe^{3+} partitioning was made according to the recommendation of L e a k e 1978). After this classification all the analysed amphiboles are magnesiohornblendes. No tremolitic or actinolitic amphiboles

Table 5

Representative microprobe analyses of rock-forming minerals from Tribeč enclaves (in wt. %)

	Plagioclase		Biotite		Epi	Hornblende		Sphene	
	T-62	T-63	T-62	T-63	T-62	T-62	T-64	T-66[1]	T-62[3]
SiO_2	62.72	60.96	38.38	38.72	39.45	45.62	44.46	33.17	30.45
TiO_2	0.01	—	1.70	2.19	0.06	1.10	1.09	35.23	38.50
Al_2O_3	22.44	25.27	15.14	15.47	21.33	7.88	9.13	2.37	1.16
FeO	0.19	0.11	17.55	19.62	13.69	18.23	17.97	2.54	1.58
MnO	—	—	0.38	0.35	0.13	0.70	0.76	—	0.15
MgO	—	—	12.97	11.15	—	10.75	10.62	0.84	0.03
CaO	5.58	5.80	0.01	0.08	22.50	11.56	11.59	25.99	27.83
Na_2O	8.42	9.09	—	0.07	—	1.28	1.49	—	—
K_2O	0.57	0.18	10.06	10.04	0.03	0.95	0.96	0.29	0.01
Total	99.93	101.41	96.19	97.69	97.19	98.08	98.12	100.43	99.71
O =	8	8	22	22	12.5	23	23	5	5
Si	2.79	2.68	2.88	2.88	3.24	6.77	6.60	1.07	1.00
Al^{IV}	1.18	1.31	1.13	1.12	2.06	1.23	1.40	0.09	0.05
Al^{VI}	—	—	0.21	0.23	—	0.15	0.20	—	—
Fe^{3+}	—	—	—	—	—	0.61[2]	0.66[2]	—	—
Fe^{2+}	0.01	—	1.10	1.22	0.94	1.65	1.58	0.07	0.04
Mn	—	—	0.02	0.02	0.01	0.09	0.10	—	—
Mg	—	—	1.45	1.24	—	2.38	2.35	0.04	0.01
Ti	—	—	0.10	0.12	—	0.12	0.12	0.86	0.95
Ca	0.27	0.27	—	0.01	1.98	1.84	1.84	0.90	0.98
Na	0.73	0.78	—	0.01	—	0.37	0.43	—	—
K	0.03	0.01	0.96	0.95	—	0.18	0.18	0.01	—

[1]Sphene exsolution in biotite, [2]Fe was partitioned after recommendation of Leake (1978), [3]Sphene from a felsic domain.

were found. Analysed hornblendes are similar, although a systematic correlation between the Al_2O_3 content and the quartz occurrence has been found out: the quartz-bearing enclaves have the lower Al hornblendes (average Al_2O_3 = 8.09 %, SiO_2 = 45.22 %). The quartz-free enclaves have hornblendes with lower SiO_2 (44.25 %) and higher Al_2O_3 (8.82 %). The $Fe_t/(Fe_t + Mg)$ ratio of hornblendes is somewhat higher than that of biotites: 0.46—0.52. Cambel — Pitoňák (1980) characterized various amphiboles of West Carpathian metabasites including small dioritic bodies in granitoids. Compared to them, the enclave hornblendes are more Fe, Na, K rich, and Mg, Ti poorer.

Hornblende - biotite interrelations were in more detail studied using $Fe_t/(Fe_t + Mg)$ ratio. Perchuk (1970) defined the temperature dependence of the Fe/Mg partitioning between this mafic pair: with raising temperature (maintaining all other hornblende components and rock composition unchanged) Mg preferably enters hornblende. Sčambos et al. (1986), Czamanske et al. (1977) showed on the data from the Center Pond Pluton and Pliny Range the crossover of biotite and hornblende $Fe_t/(Fe_t + Mg)$ ratio increase trends: in mafic members (diorite) biotite is more Fe-rich mineral, while in porphyritic granite the more Fe-rich is hornblende. This is consistent with the temperature decrease during differentiation. Coexisting hornblendes and biotites in enclaves show very similar range of $Fe_t/(Fe_t + Mg)$ ratios. Several biotites exhibit the increase of Mg/Fe ratio while coexisting hornblendes maintain their composition. The re-equilibration at a lower temperature is preferred for the explanation of this phenomenon. All the analysed biotite-hornblende pairs give the subsolidus temperature 570—600 °C (600—670 °C with correction for Ti) according to the Perchuk's empirical geothermometer (1970).

Accessory minerals. They were studied in detail from heavy fractions of the large enclave T62 and the host tonalite T63. The host biotite-tonalite occurs regionally in the SE part of the Tribeč Mts. where in places changes to hornblende--biotite varietes. Amongst accessory minerals magnetite and zircon were studied in more detail.

Magnetite is the dominant opaque mineral both in enclaves and host rock, the latter being more magnetite-rich (similarly the host rock is richer in ilmenite, apatite, allanite and sphene, Tab. 8). The microprobe analyses of magnetites of both rocks are listed in Tab. 6. X-ray diffraction analysis

Table 6

Representative microprobe analyses of magnetites from enclave (T-62) and host rock (T-63)

	Host rock T-63			Enclave T-62		
	1	2	3	1	2	3
FeO	30.79	30.64	30.19	30.46	30.39	30.42
Fe_2O_3[1]	68.44	68.10	67.10	67.70	67.55	67.58
TiO_2	0.00	0.00	0.05	0.00	0.00	0.04
Cr_2O_3	0.12	0.09	0.11	0.17	0.19	0.09
NiO	0.01	0.03	0.00	0.00	0.00	0.00
CoO	0.06	0.13	0.09	0.10	0.06	0.13
V_2O_5	0.31	0.94	0.22	1.28	1.61	1.11
MnO	0.07	0.12	0.16	0.12	0.16	0.15
Total	99.80	100.05	97.92	99.83	99.96	99.52

[1]FeO/Fe_2O_3 was assumed stoichiometric.

of the magnetic fraction confirmed the pure magnetite in the enclave while some hematite was revealed in the host rock. A characteristic feature of all magnetites are very low titanium contents. In the light of the strong subsolidus re-equilibration recorded e.g. by Fe/Mg partitioning between biotite and hornblende they, however, are not surprising. Magnetites of plutonic rocks are typically low titaniferous (Czamanske—Mihálik, 1972; Czamanske et al., 1977, 1981), a feature believed to be caused by low-temperature oxidation. Tiny sphene rims around some magnetite would suggest titanium exsolution although the sphene might equally well be a product of biotite titanium exsolution.

From Tab. 6 there follows a major difference between the magnetites of enclaves and those of host tonalite: the former are markedly Cr, V, and Co richer. The cobalt content of magnetite is at the high end of the range of granites s.l. reported by Nedashkovsky (1982) and approach the cobalt concentrations of magnetites of gabbro-dioritic rocks (Chernyshov — Plaksenko, 1982). Thus, chromium together with vanadium, and cobalt indicate a different, deeper origin of mafic enclave magma.

Zircon. The morphometrical analysis of zircons after Pupin (1980) place both the tonalitic enclave T62 and host tonalite T63 at the boundary of hybrid and anatectic granite domains, Fig. 8. The concentration maximum of host tonalite zircons falls at the S_{12} type (Fig. 9a) which is characteristic of the basic Tribeč tonalite. The presence of a marked maximum of strongly metamictized zircons (G_1 type) is a remarkable feature of the T62 enclave zircons. Large, non-transparent, white and coloured (orange) crystals (Fig. 9c, d) are not typical for dioritic rocks particularly when we take into account that the host rocks do not contain either G-type or other forms of metamictic zircons.

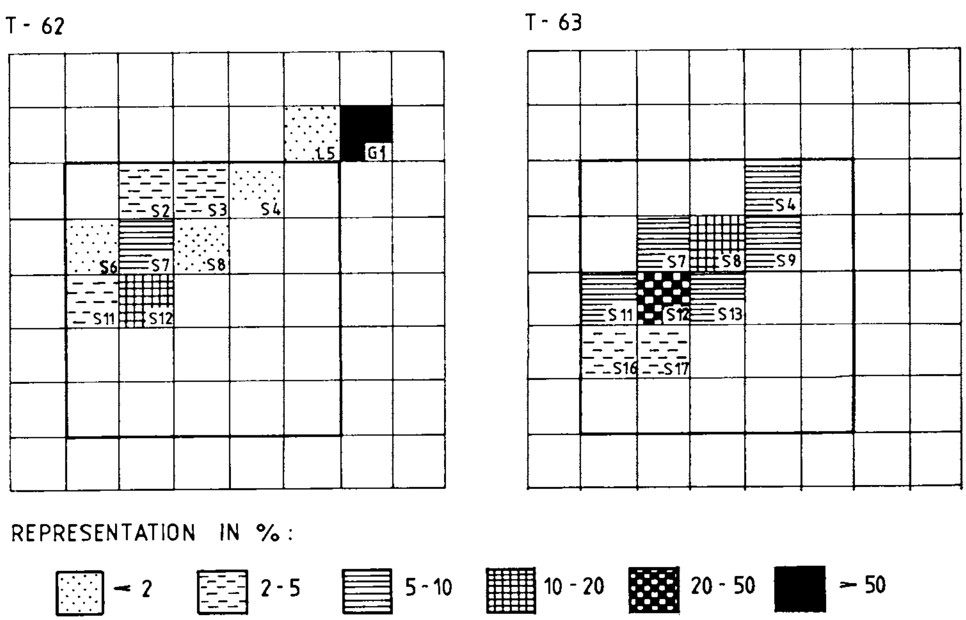


Fig. 8. Distribution of zircon types in enclave (T62) and host tonalite (T63) in typologic classification diagram after Pupin (e.g. 1980).

Microprobe analyses did not show an increased hafnium concentration (Tab. 7), and the mass ratio Zr/Hf is similar to that in non-metamictic host rock zircons. Increased hafnium concentrations are often typical of metamictic zircons (Lyakhovich, 1973; Krasnobayev et al., 1974; Gbelský, 1979).

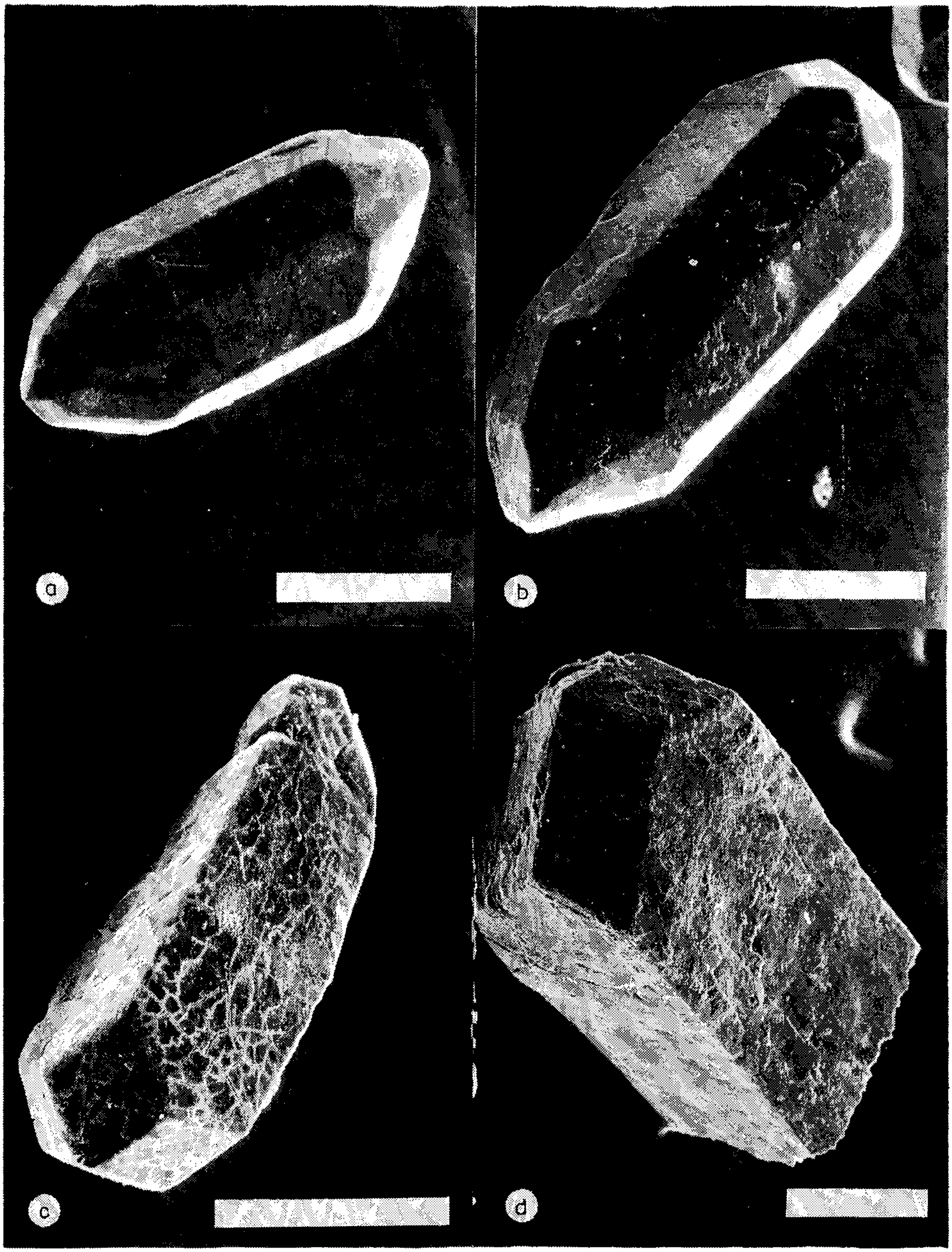


Fig. 9. Scanning electron photomicrographs of enclave and host rock zircons. a) S_{12} type zircon from T63 host tonalite. b) S_{12} type zircon from T62 enclave. c—d) Metamict zircons of G_1 type from T62 enclave. Note slightly damaged surface of metamict zircons. Scale bars represent 100 μm.

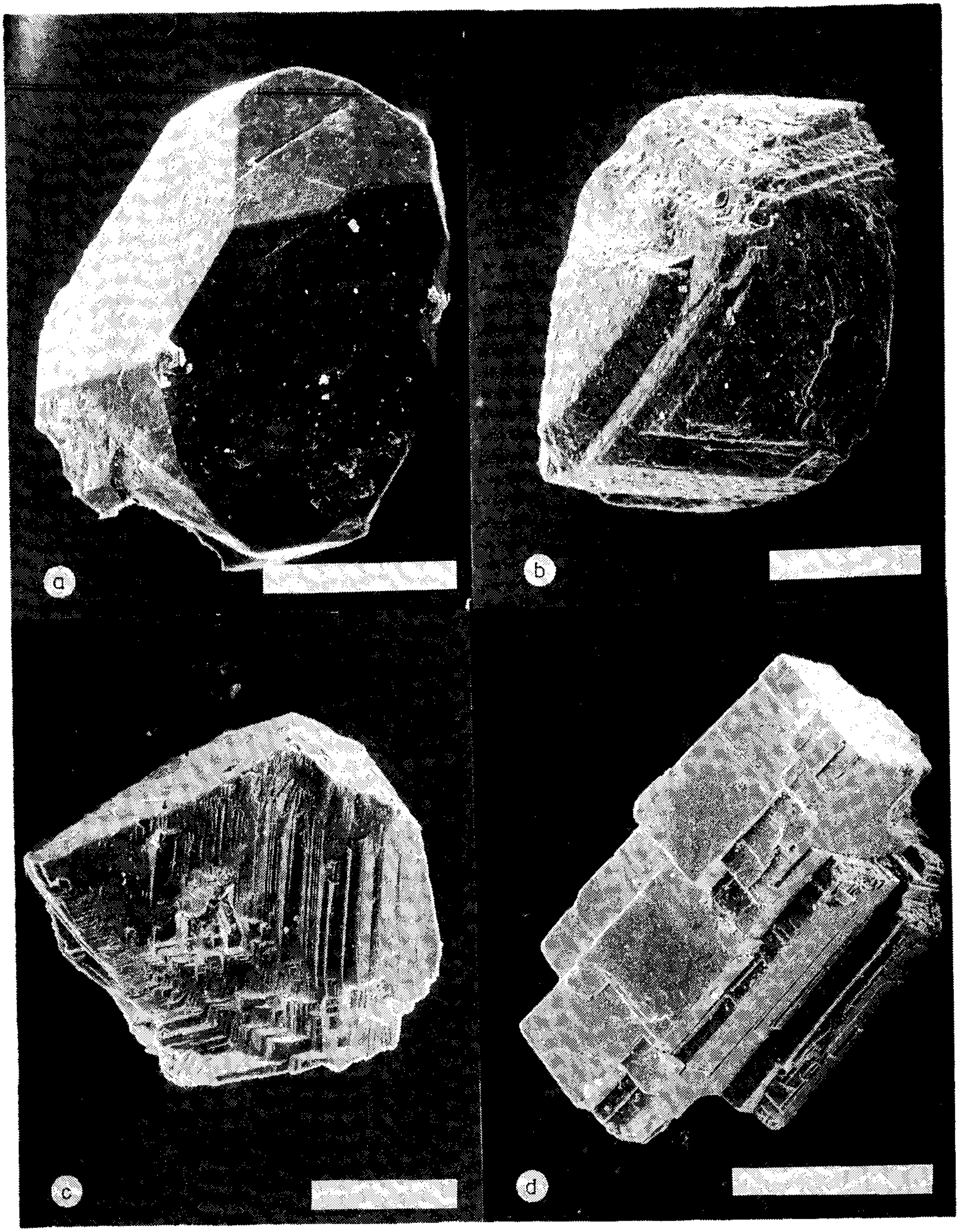


Fig. 10. Scanning electron photomicrographs of enclave (T62) accessory minerals. a) Euhedral sphene. b) Octahedral magnetite (similar magnetites are found also in host tonalite). c) Sphalerite. d) Galena. Scale bars represent 100 μm.

Table 7

Microprobe analyses of reprezentative zircon types from enclave (T-62) and host rock (T-63)

Weight percent	T-62				T-63	
	Metamictic grain (G_1 type)	Metamictic grain (G_1 type)	Nonmetamictic grain (S type)	Nonmetamictic grain (S type)	Nonmetamictic grain (S type)	Nonmetamictic grain (S type)
	core	rim	core	rim	core	rim
SiO_2	34.16	33.11	33.70	33.56	34.53	34.65
ZrO_2	64.40	63.21	65.84	64.60	63.02	62.63
HfO_2	1.76	1.36	1.53	1.65	1.42	1.50
MgO	0.00	0.06	0.00	0.00	0.00	0.01
Al_2O_3	0.00	0.09	0.00	0.00	0.01	0.00
CaO	0.01	0.11	0.01	0.02	0.00	0.00
FeO	0.03	0.36	0.01	0.00	0.00	0.00
Y_2O_3	0.06	0.47	0.37	0.25	0.03	0.21
La_2O_3	0.17	0.15	0.11	0.09	0.19	0.13
Ce_2O_3	0.00	0.02	0.00	0.00	0.05	0.02
Th_2O_3	0.00	0.28	0.00	0.05	0.00	0.10
Total	100.59	99.22	101.57	100.22	99.25	99.25
Zr	47.67	46.79	48.74	47.82	46.65	46.36
Hf	1.49	1.57	1.29	1.40	1.20	1.27
Zr/Hf	31.34	40.42	37.53	34.08	38.74	36.45
Cation percent						
Si	51.50	50.69	50.69	51.10	52.49	52.65
Zr	47.56	47.19	48.28	47.97	46.71	46.40
Hf	0.76	0.59	0.66	0.71	0.61	0.65
Mg	0.00	0.13	0.00	0.00	0.00	0.02
Al	0.00	0.16	0.00	0.00	0.02	0.00
Ca	0.01	0.18	0.02	0.04	0.00	0.00
Fe	0.03	0.46	0.01	0.00	0.00	0.00
Y	0.05	0.39	0.29	0.10	0.02	0.16
La	0.09	0.09	0.05	0.06	0.11	0.07
Ce	0.00	0.02	0.00	0.00	0.04	0.02
Th	0.00	0.10	0.00	0.02	0.00	0.03
$\frac{100 . Hf}{Zr + Hf}$	1.57	1.25	1.34	1.46	1.11	1.38

Analyst: RNDr. F. Caňo

Microprobe analyses did not show either increased Th content, and according to the whole rock analysis for U, nor the increased U content is supposed for the zircons. A strong influence of fluid phase rather than that of radioactivity is, therefore, suggested for the formation of the metamictic zircons, cf. Krasnobayev et al. (1974).

A higher concentrations of ore elements in enclave magma have resulted in more intensive formation of the accessory ore minerals - pyrite, chalcopyrite, arsenopyrite, galena and sphalerite, Fig. 10c, d and Tab. 8.

Table 8

Abundances of accessory minerals (in g/t) from enclave (T-62) and host rock (T-63)

	T-62	T-63
Zircon	734	529
Apatite	3300	5120
Allanite	400	480
Magnetite	3063	5813
Ilmenite	35	120
Rutile	0.5	—
Amphibole	2	—
Garnet	0.5	<0.5
Sphene	700	4903
Pyrite	7	1
Chalcopyrite	<0.5	—
Galena	8	0.5
Sphalerite	3	—
Arsenopyrite	<0.5	—
Leucoxene	80	10
Epidote	890	2708
Scheelite	<0.5	—
Limonite-goethite	10	40

The abundances were calculated using correction factors (due to losses during separation of heavy fractions) of Broska et al. (1989).

Discussion

The Tribeč enclaves have all the characteristic features of microdioritic enclaves so typical of calc-alkaline plutons: fine-grained texture (typically 0.8—0.1 mm), mafic nature (colour index M = 25—50), small size, spherical or ellipsoidal shapes, and a population of acicular apatites (Fig. 3). They do not contain any metamorphic minerals (e.g. sillimanite or staurolite) nor any rounded forms of accessory minerals typical of metasediments. In the field: they were not found in the NE part of the Tribeč Mts. (Krnča, Dolina) where there occur remnants of metamorphic mantle. Enclave occurrences are bound to basic coarse- to medium-grained hornblende-biotite tonalite where they occur in swarms. The Tribeč granitic massif is also typical of its absence of amphibolites. All the features make us for the magmatic interpretation of their origin: we suppose that they have originated by intermingling of hotter mafic magma globules with cooler granitoid magma. Undercooling of the mafic globules due to the thermal contrast has caused the fine-grained texture, gave rise to acicular apatites (Wyllie et al., 1962; Vernon, 1983; Didier, 1987). After Ayrton (1988) the enclave swarms indicate the pluton margin.

The Tribeč enclaves, however, possess several characteristic peculiarities: the occurrence of felsic patches in tonalitic type (T62, T65), the biotite-rich nature causing unusually high potassium (also Rb, Ba) content - up to 5 %, and the signs of strong interaction with fluid phase.

Felsic domains. Vesiculation phenomena are not rare in volcanic enclaves (Eichelberger, 1978; Bacon—Metz, 1984). They occur also in other rock types, particularly from low-pressure environment (e.g. pseudotachylytes, Maddock et al., 1987). The vesicules are a result of vapour exsolution: as rapid crystallization of the undercooled globules proceeds the water content of residual liquid increases until the magma is saturated. It is tempting to consider the felsic domains (Fig. 2) in several samples (T62, T65, T66) as plutonic equivalents of the vesicles occurring in volcanic enclaves. However, their mineralogical composition: (vol. %) plagioclase 70 (An = 26—29, although albite is common also), quartz 15—25, biotite 3—5, sphene 1—10, does not correspond to the vesicle infilling reported e.g. by Maddock et al. (1987). Another complicating factor is the fact that the separation of vapour phase to vesicles results in overpressure preventing the vesicle infilling by differentiated granitic material (e.g. Roedder, 1979). The driving force causing migration of segregated liquid to the vesicles was, as a relevant problem, discussed in detail by Smith (1967) and Anderson et al. (1984). The process of gas-filter pressing suggested by Anderson et al. l.c. supposes the pressure gradient generated by vapour saturated crystallization as the driving force. In their model the vesicles form, however, in still liquid melt (less than 50 % crystals) what is possible only in a low-pressure environment (lavas) where the solubility of fluids is low. In our case, we tend to suppose the formation of felsic domains to be the result of extensive crystallization caused by heat transfer at the interface which is able to rise the water content in remaining differentiated liquid to the saturation boundary. As the water content neccessary for the saturation depends on the load pressure its estimate is critical. The empirical hornblende geobarometer (Hollister et al., 1987) gives the load pressure of the Tribeč intrusion about 300 MPa (3 kb). This estimate is close to the pressures obtained on the basis of metamorphic associations in adjacent massifs (e.g. Korikovsky et al., 1984, 1986). The saturation of basic magma at P = 300 MPa requires approximately 7.5 wt. % H_2O (Jahns — Burnham, 1962 in Carmichael et al., 1974) what exceeds considerably the typical range 2—4 wt. % H_2O which is characteristic of calc-alkaline magmas (Anderson, 1979). Finally, the calculations of Huppert et al. (1982) showed that saturation (and saturation-induced overturning of magmas) is most probable in shallow magma chambers beneath volcanoes (50—150 MPa). Thus, the felsic domains are more probably a part of the post-entrapment history of enclaves and the mechanism of Anderson et al. l.c. is not suitable for them. The felsic domains may rather represent micropegmatites as predicted by Bacon (1986). In this case, they may have separated as more or less well constrained felsic patches (cf. Jahns — Burnham, 1969). The relatively large size of the sphenes (Fig. 4c) growing in the patches (up to 10 mm) indicates the presence of interstitial fluids in the final stages of crystallization and/or after the solidification. Ca-rich plagioclase environment was a suitable barriere for Ti-rich fluids (the source of titanium having been biotite and possibly magnetite) for the sphenes to precipitate, though, their central position in domains is not fully understood.

The rise of water concentration in remaining liquid (Jahns — Burnham, 1969) is sensitive to the composition of crystallizing assemblage: a large proportion of water-bearing minerals may strongly delay or even suppress the water saturation. Indeed, the large amount of biotite (up to 40 vol. %)

in dioritic enclaves fixes about 2 wt. % of water which is a good explanation of micropegmatite absence in small mafic dioritic enclaves.

Biotite nature of mafic enclaves is responsible for high K_2O content. Its concentration reaches the level of K_2O content in differentiated leucogranites. The behaviour of alkalies in coexisting basic and acid melts seems to be relevant for the explanation of this phenomenon (Watson, 1976, 1982; Watson—Jurewicz, 1984). The main results of the experiments (l.c.) may be summarized as follows:

— the components of coexisting acid and basic melts attempt to establish a distribution that resembles two-liquid equilibrium,

— a degree of the equilibrium establishing depends on diffusivity (diffusion coefficients),

— the rate of alkali diffusion is much higher than that of network-forming species (SiO_2, Al_2O_3) which causes a selective transfer of alkalies during the interdiffusion process,

— two-liquid equilibrium is characterized by the strong preference of alkalies for acid melts and of di-valent, and more highly charged cations for basic melts,

— the direction of diffusion may be "uphill" or "downhill" depending on the inicial concentration contrast of alkalies in basic and acid melt: the diffusion approaches the concentrations to the equilibrium value (as expressed by partitioning coefficient).

The bulk composition of coexisting magmas is, however, not only a result of two-liquid equilibrium but also of the process of crystallization (Johnston—Wyllie, 1988). The fast diffusion of potassium to the basic magma is able to stabilize biotite as a mafic mineral. The biotite crystallization, in turn, maintains the K-concentration in the melt at a low value promoting further K-exchange until Fe-Mg components use up. The bulk potassium content may exceed that of acid melt (l.c.). We believe that the process described may be well responsible for the biotite (high K) nature of Tribeč enclaves. Since, in this case, the downhill diffusion is concerned the original K concentration must have been much lower. Table 8 presents the compositions of intermediate rocks and enclaves according to various authors. The Tribeč enclaves are markedly rich in Rb, Li and Ba. Correlation of these elements with potassium anticipates similar diffusion properties to those of potassium.

Both the alkali transfer and the fluid phase activity are supported by *zircon character*. As mentioned in the accessory mineral section, zircon forms two generations: S type and G type with two distinct maxima (Fig. 8). The S type crystallized in the main magmatic phase while G type, proportion of which we cannot determine more precisely, crystallized during final stages of crystallization. This can be explained by the rise of Zr saturation level. According to the experiments of Watson (1979), and Watson—Harrison (1983), there are mainly the changes in alkalinity (besides temperature) which are responsible for the Zr saturation level changes: zircon has long been known for its instability in the alkali environment (Maurice, 1949; Linthout, 1984). As mentioned earlier, an extensive K transfer in the direction: host tonalite→enclave is supposed. It is conceivable that the transfer coud have increased the K activity to such a degree that the alkaline environment be able

Table 9

Average major and trace element compositions of andesite, diorite, magmatic enclaves, and amphibolites

(wt. %)	Andes. aver.	Diorite Modra m. n = 6	Enclaves			Amphibolites	
			Tribeč n = 10	Aigoual n = 5	Mayet n = 2	S.C. n = 27	Tribeč n = 11
SiO_2	59.50	54.59	51.88	59.10	57.90	51.24	50.69
TiO_2	0.70	1.27	1.36	0.90	1.10	1.47	1.37
Al_2O_3	17.20	17.64	18.91	15.80	17.60	16.47	17.27
Fe_2O_3		4.01		1.10	1.40	3.67	2.83
FeO	6.10[1]	3.67	7.26[1]	5.45	4.40	6.24	6.08
MnO		0.15	0.07	0.10	0.10	0.14	0.12
MgO	3.40	4.46	4.77	5.90	3.35	5.93	6.69
CaO	7.00	6.39	5.47	2.75	3.70	8.26	8.39
Na_2O	3.70	3.60	3.77	2.75	5.60	3.19	3.49
K_2O	1.60	1.98	3.67	4.20	2.30	0.95	1.10
H_2O^+		1.78	1.42	1.10	1.85	1.77	1.82
P_2O_5			0.60			0.05	0.14
Total	99.20	99.54	99.18	99.15	99.30	99.38	99.99
(ppm)		n = 6	n = 10	n = 5	n = 2	n = 13	n = 11
Li	10		71.5				
Rb	31		146.5				
Sr	385	1006	1050.5			220	369
Ba	270	1539	1237			155	134
Sn	0.8	10.5	4.3	23	35		
Pb	6.7	22.6	16.8	12	12		
Cu	54	24.1	29.6	50	40	40	58
Zr	110	101	336			113	186
Ni	18	15.7	22.2	114	102	133	112
Co	24	17.3	23.8			43	37
Cr	56	31.6	40.8	582	375	289	291
V	175	196	200.3			285	339
Sc	30	22.5	23.7			40	26
Y		26.6	23.8			34	34

Notes: Average andesite after Taylor (1968) ex Taylor et al. (1969) and Taylor (1972) ex Tauson (1977). Diorite is the average of 6 diorites from the Modra massif of the Small Carpathians (Cambel — Vilinovič, 1987).
Enclave averages: Tribeč — this work, Aigoual and Mayet de Montagne after Didier (1987). Amphibolites: S.C. — Small Carpathians, and Tribeč after Cambel — Kamenický (1982).
[1]All Fe as FeO, missing data are not reported by authors.

to inhibit zircon precipitation. The remaining zirconium may have crystallized later due to the temperature drop (after Pupin's temperature scale, the G type crystallizes at low temperature in late-magmatic or post-magmatic stages) in the vapour-saturated environment in the form of metamict crystals.

Dioritic character of majority of enclaves follows unambiguously from both the modal and chemical composition approaching them to dioritic bodies abundant e.g. in the Small Carpathians, Low Tatras, Vepor pluton and elsewhere. Averages of intermediate rocks and enclaves are compiled in

Tab. 9 and compared with the average composition of Tribeč enclaves and Small Carpathian diorites and amphibolites. The enclave composition is close to that of andesite, particularly in the iron group elements concentrations (Ni, Co, Cr, V). With exception of alkalies (discussed earlier) the enclaves are very similar to dioritic rocks e.g. of the Modra massif (Small Carpathians), Cambel — Vilinovič (1987) including high Ba and Sr contents. The high concentrations of the latter element make the intermediate rocks of the West Carpathians (Tribeč and Small Carpathians) different from island-arc andesites. In accord with Taylor et al. (1969), the low Ni, Cr and Co contents do not support the direct derivation of dioritic magma from the mantle and they require a multistage melting process, or a more complex process involving e.g. the interaction with the crust. The low content of mentioned elements differentiate the enclaves distinctly also from the amphibolites abundant in metamorphic rocks of West Carpathian core mountains which are considered as products of metamorphosis of tholeiitic basalts, i.e. the rocks of direct mantle origin.

Conclusions

We suppose that the small fine-grained mafic enclaves occurring in the basic rock type of the Tribeč granitic massif give evidence for the existence of an intermediate (dioritic) magma coexisting with the host granitoid magma. The dioritic magma could have initiated granitoid plutonism in this area.

According to the trace element contents (mainly the iron group elements) the dioritic magma was not directly derived from the mantle rather it is akin to island-arc andesitic magmas.

The diversity of enclaves (tonalitic vs dioritic) suggests an interaction of the both magmas before enclave formation. The biotitic nature of enclaves, in turn, suggests a strong influence exerted by the host magma upon mafic blobs after entrapment. The rapid solidification of the blobs due to thermal contrast caused the fluid concentration growth and lead into micropegmatite formation in quartz-bearing enclaves. The influence of fluid phase was very strong also in the sub-solidus region where the complete re-equilibration of plagioclase, biotite and hornblende with the host rock occurred together with a partial replacing of primary minerals by secondary associations.

The intensive potassium diffusion into the mafic blobs stabilised biotite, and in the last crystallization stages created the relatively alkalic environment causing a delay in the zircon crystallization. The remaining zirconium precipitated later forming the second metamict zircon generation.

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