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GRANITOIDS OF THE TATRA MTS., WESTERN CARPATHIANS: FIELD RELATIONS AND PETROGENETIC IMPLICATIONS

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Abstract: The granitoids of the Tatra Mts. in the Western Carpathians, form a pluton, composed of several types ranging from leucocratic granite and granodiorite to tonalite and diorite. The sheet-like intrusion is accomodated in the upper tectonic unit of an inverted metamorphic sequence. REE-patterns show low fractionation of magma, as well as low differentiation among several types forming the pluton. Chemical composition and physical properties indicate a heterogeneous supracrustal mantle source. Affinity to high-potassium, calc-alkaline, I-type, together with oxidation of magnetite suggest generation through partial melting of older metaigneous material. Fluid-absent melting of muscovite and biotite are suggested as major melting reactions during decompressional uplift, consistent with clockwise P-T-t path in metamorphic rocks. Intrusion into a dextral shear zone, generated during Variscan collision-transpression is proposed as a preliminary model of magma emplacement.

Key words: Tatra Mts., collisional tectonics, Variscan orogen, geochemistry, granitoid rocks.

Introduction

Granitoid rocks form the major part of the pre-Alpine basement in the Western Carpathians, and are generally considered as products of the Variscan orogeny (Cambel et al. 1985; Hovorka & Petrík 1992; Petrík et al. 1993, 1994 this volume). Abundant granitoid plutons are exposed mainly in the core mountains of the Central Western Carpathians, the Tatra Mts. are one of the best examples.

On the basis of previous investigations (e.g. Michalík 1951; Gorek 1959; Gorek & Veizer 1966; Burchart 1970; Skupiňski 1975; Broska et al. 1993), the granitoids of Tatra Mts. form a pluton, composed of leucocratic granites to biotite and hornblende-bearing tonalites and diorites. Their Variscan age was documented by geochronology (Burchart 1968; Maluski et al. 1993). On the basis of field observations, a sheet-like character for the granitoid intrusion was proposed (Gorek 1959). The tectonic position of the granitoids together with their migmatitic mantle above mica schists was documented in the Western Tatra (Kahan 1969). In recent years inverted metamorphic zonation in the Western Tatra has been observed (Janák 1992a,b, 1993; Janák et al. 1993), supporting the structural position of granitoids within a higher-grade metamorphosed slab of migmatites, thrust above lower-grade mica schists. Structural study in the Western Tatra (Fritz et al. 1992) distinguished the kinematics and conditions of Alpine vs. pre-Alpine tectonics, suggesting generally S and S - E vergent Variscan thrusting involving granitoids in the hanging wall.

The aim of this paper is to present new geochemical and petrophysical data. We discuss possible constrains on the melt source and propose a preliminary model for the emplacement and petrogenesis of the Tatra granitoids.

Geological setting and field relations

The Tatra Mts. are typical core-mountains belonging to the Tatric Unit of the Central Western Carpathians (e.g. Andrusov 1968 ; Mahel' 1986). The crystalline basement of the Tatra is composed of pre-Mesozoic metamorphic rocks and granitoids, overlain by sedimentary Mesozoic and Cenozoic cover sequences and nappes (Fig. 1). Geological investigations concerning granitoids and the crystalline basement have been presented mainly by Sokolowski (1956), Gorek (1959), Jaroszewski (1967), Kahan (1969), Burchart (1970), Skupiňski (1975) and Nemčok et al. (1993).

On the basis of field relations and study of metamorphic zonation, two superimposed tectonic units have been distinguished (Janák 1992a,b; Janák et al. 1993; 1994 this volume):

a - *the lower unit*, composed of staurolite, kyanite and sillimanite-bearing mica schists;

b - *the upper unit* of migmatitic ortho- and paragneisses, amphibolites and rare calc- silicates penetrated by granitoid intrusion.

Both structural units form a nappe pile, exhibiting an inverted metamorphic zonation (Janák 1993; Janák et al. 1993, 1994 this volume), as shown in a schematic profile (Fig. 2) observable in the Western Tatra.

The lower unit shows neither penetration by granitoids, nor migmatization. Mineral assemblages and metamorphic zones (staurolite-kyanite to kyanite-sillimanite) indicate increasing metamorphism towards the thrust contact (Janák et al. 1988, 1993; Janák 1994 this volume).

The upper structural unit shows widespread migmatization (Fig. 3) and accommodation of granitoid melt. The pluton occupies higher structural levels, closely associated with medium - to low-pressure migmatites (Figs. 2, 3), calc-silicates and meta-

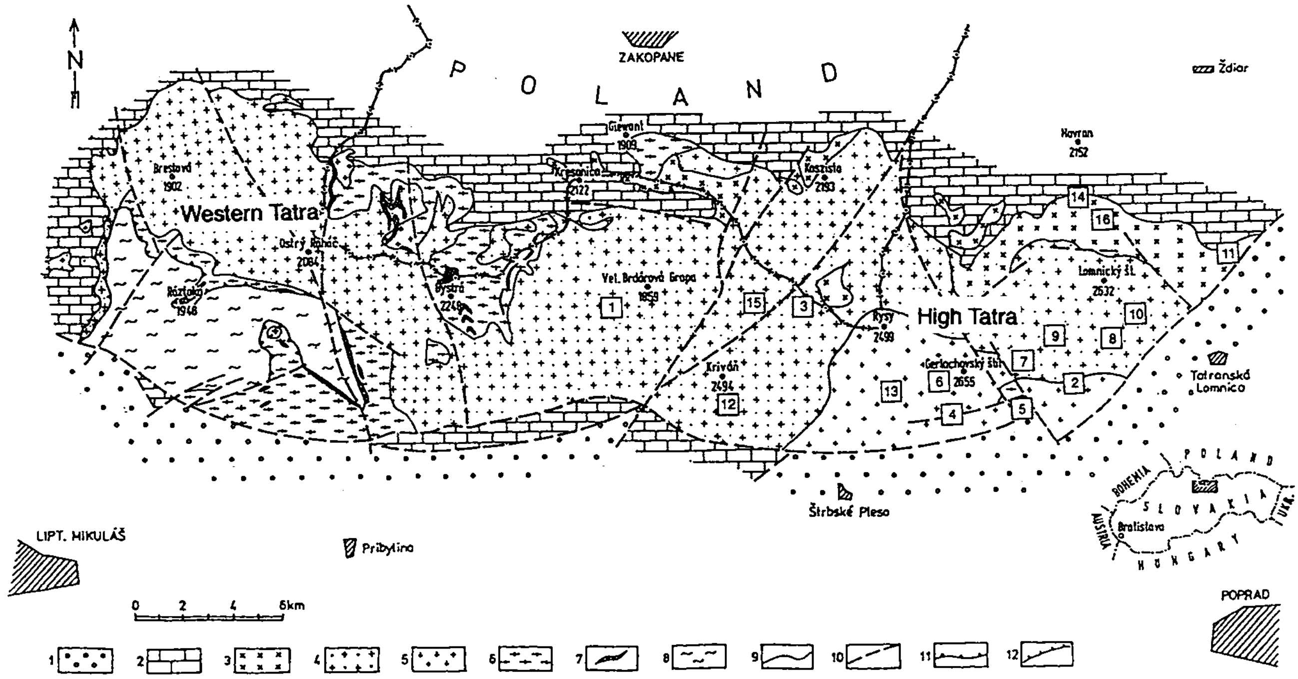

Fig. 1. Simplified geological map of the Tatra Mts., according to Janák et al. (1993). Explanations: **1** - Paleogene; **2** - Mesozoic; **3** - **5** granitoids: 3 - Goryczkowa type, **4** - common Tatra type, 5 - High Tatra type; **6** - migmatites; **7** - amphibolites; **8** - mica schists; **9** - lithological boundaries; **10** -faults; **11** - Variscan thrust fault; **12** - Alpine thrust fault.

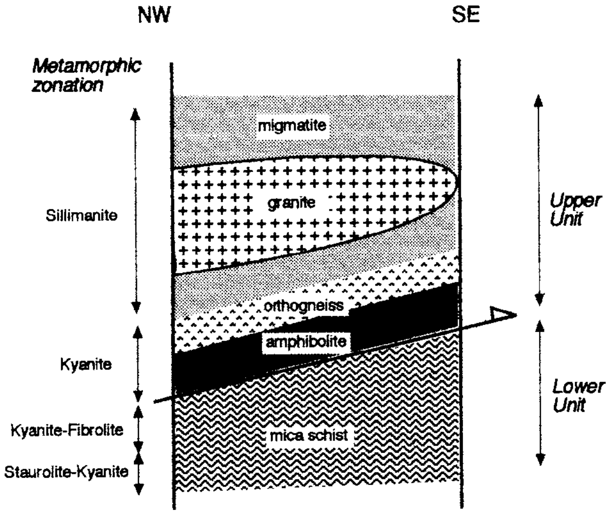

Fig. 2. Schematic profile of inverted metamorphic zonation in the Western Tatra. Structural position of granitoids is shown with respect to major Variscan tectonic units, lithology and metamorphic zones.

basites of the sillimanite zone. The base of the overthrust unit is composed of mylonitic ortho- and paragneisses and amphibolites with relics of high-pressure metamorphism (kyanite, clinopyroxene and garnet), partly overprinted by lower- pressure recrystallization and retrogression. More details about mineral assemblages and metamorphic conditions have been presented in Janák et al. (1988, 1993) and Janák (1994 this volume).

Marginal parts of the pluton exhibit transitional contacts with surrounding migmatites and common preferred orientation of the fabric (Fritz et al. 1992). According to kinematic indicators, mainly feldspars, micas and quartz (Berthé et al. 1979; Simpson & Schmid 1983), the granitoids show a generally dextral E-W shear in ductile conditions of non-coaxial deformation. According to Fritz et al. (1992), oriented fabric in granitoids can be attributed to deformation (D2), related to late-Variscan extension, or extensional segment of strike-slip. An earlier compressional deformation (D1) is preserved only sporadically in the metamorphites, indicating the top to the SE direction of displacement, as a consequence of Variscan thrusting and uplift of the upper unit (Fritz et al. 1992; Janák 1992, 1994 this volume). Where not in contact with a metamorphic mantle, the granitoids exhibit a more homogeneous fabric, suggesting that the magma was less affected by shear strain. Alpine deformation, in contrast to Variscan, is mostly in brittle or brittle-ductile conditions, generally of top to the NW orientation (Fritz et al. 1992), interpreted as a consequence of Alpine thrusting. The most intense Alpine deformation is localised along the major normal faults transsecting the granitoid pluton and in the contact with the Mesozoic and Paleogene (Fig. 1). For further details about tectonics see also Jaroszewski (1967), Kahan (1969), Nemčok et al. (1993), Želazniewicz (1993a, b).

Petrography

The following granitoid types have been distinguished in the Western and High Tatra:

a - biotite-amphibole-quartz diorite;

b - biotite granodiorite to tonalite transitional to muscovite-biotite granodiorite ("High Tatra type" s.s.);

c - biotite and muscovite-biotite granodiorite to granite, slightly porphyric ("common Tatra type");

d - porphyric granites to granodiorites with phenocrysts of pinkish K-feldspar ("Goryczkowa type").

Biotite-amphibole-quartz diorite appears mainly on the eastern ridge of Krížna in the Western Tatra, as well as in the other

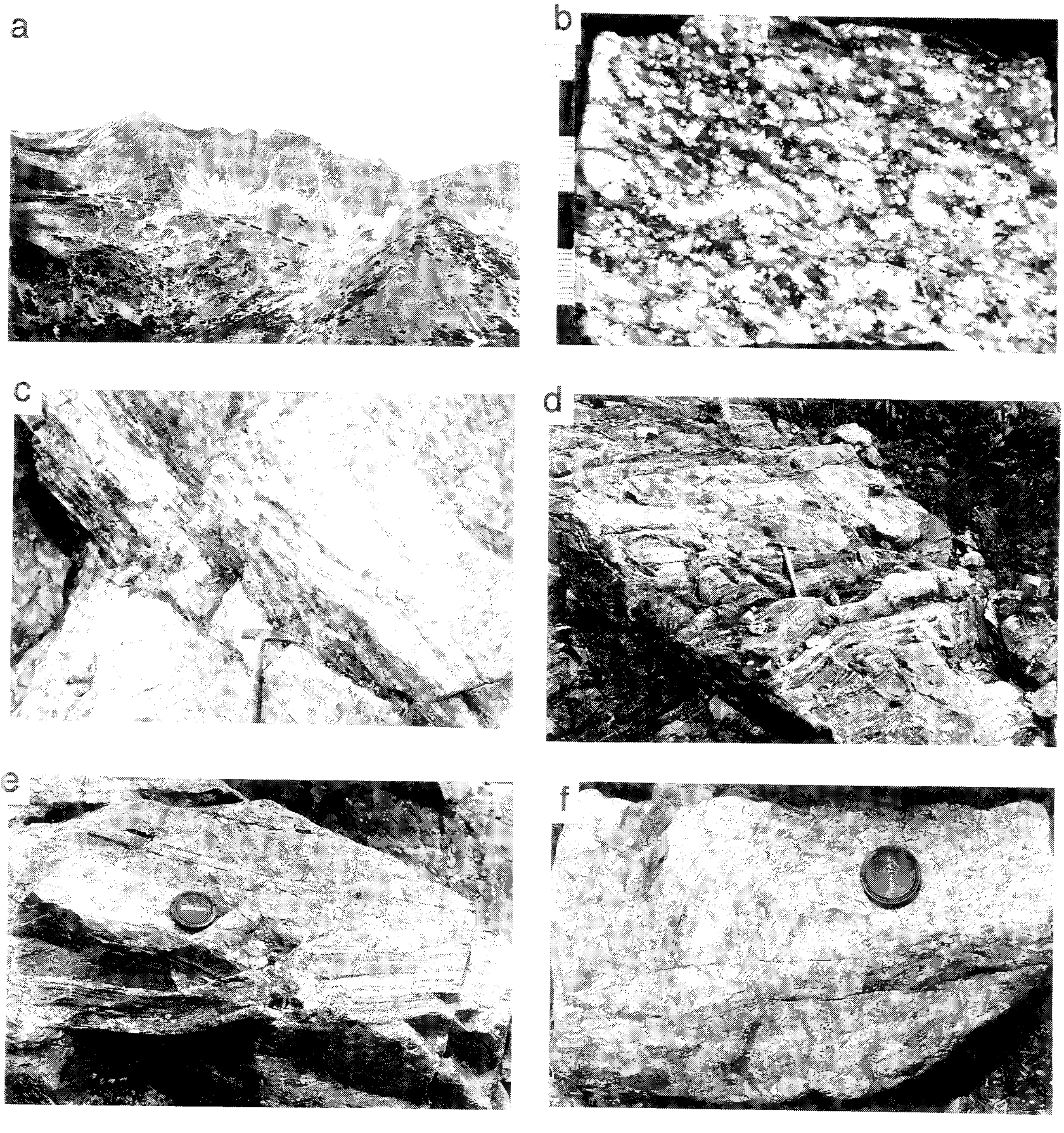

Fig. 3. Phototables a-f. **a** - General view showing the position of granitoids in the Western Tatra with respect to tectonic structure (dashed line) separating the lower and upper tectonic units. The main ridge of Roháče - Tri Kopy above Žiarska Valley. **b** - Deformation of granitoids (common Tatra type) in the marginal zone of the pluton in the Western Tatra. **c** - Metamorphic xenoliths at the contact with granodiorite intrusion (High Tatra type) exhibiting common deformation in ductile conditions. Biotite, sillimanite and garnet-rich mafic "schlieren" and leucocratic granite melt are produced. High Tatra, Velická Valley. **d** - migmatization and partial melting in gneisses at the base of the upper structural unit. Western Tatra, Trnovecká Valley. **e** - Veins of granite composition in partially melted tonalitic gneiss. The melt segregations and pods can be observed in the tensional fractures. Upper structural unit, the Western Tatra, Bystrá Valley. **f** - Granitoid melt, penetrating gneiss, indicating melt-enhanced deformation and shearing.

places not shown on the map, because of forming only small bodies and lenses of several meters to tens of meters within the biotite-muscovite granodiorite of the common Tatra type. The rock is melanocratic, medium-grained with hypidiomorphic to porphyric texture. Mineral composition is : plagioclase, hornblende, quartz, biotite ± K-feldspar, with accessory apatite, sphene, zircon, magnetite, pyrite, ilmenite ± allanite. Hornblende is often altered to biotite, plagioclase is strongly sericitized. The average modal composition is presented in Tab. 1.

Biotite granodiorite to tonalite, transitional to muscovite-biotite granodiorite ("High Tatra type s.s."). This type appears only in the High Tatra (Fig. 1), mostly between Hrebienok and Mengušovská

Table 1: Average modal composition of granitoid types of the Tatra Mts.

	Quartz diorite (n=4)		High Tatra type (n=15)				Tatra (common) type (n=18)				Goryczkowa type (n=13)			
	x	R	x	s	R	V	x	s	R	V	x	s	R	V
Quartz	10.3	3.2-15.1	29.8	4.1	21.5-34.5	13.6	33.1	3.7	27.6-36.6	11.2	32.2	4.8	28.3-38.3	14.9
Plagioclase	37.2	28.5-40.3	50.5	5.9	41.8-63.2	11.7	36.8	4.4	29.8-47.6	12.0	33.4	4.2	25.2-41.2	12.6
Alkali-Feldspar	0.3	0.0-1.2	6.6	2.3	0.4-13.8	34.8	19.5	4.9	9.9-28.6	25.1	25.7	5.0	18.2-34.8	19.5
Biotite	12.1	10.4-15.6	9.7	3.0	3.7-13.5	30.9	5.4	1.1	2.3-7.4	20.4	4.0	1.0	2.5-6.9	25.0
Muscovite	-	-	1.7	0.7	0.0-3.3	41.2	4.0	1.2	2.2-7.0	30.0	3.4	1.1	2.3-5.3	32.3
Amphibole	38.4	35.3-55.0	-	-	-	-	-	-	-	-	-	-	-	-
Access.	1.9	1.4-3.4	1.6	0.4	1.0-2.2	25.0	1.2	0.3	0.7-1.6	25.0	1.3	0.3	0.9-1.9	23.1

Explanations: **n** - number of samples; **x** - arithmetic mean; **s** - standard deviation; **R** - range; **V** - variation coefficient. (Values of x, s, R - are given in volume % and V in %).

Valley. The texture is medium-grained, mostly homogeneous, in contact with xenoliths and screens of metamorphic mantle, the texture shows a preferred orientation of feldspars and biotite, parallel to the foliation in embedded metamorphites. Asymmetric tails of feldspar phenocrysts, mainly plagioclase, indicate ductile deformation with a dextral sense of shearing. Mineral composition of granodiorites and tonalites is: plagioclase, quartz ± K-feldspar, biotite ± muscovite, accessory apatite, zircon, monazite, ilmenite ± magnetite. Plagioclase I with An_{35-45} is enclosed in twinned phenocrystic plagioclases II of An_{18-30} composition. Plagioclase III is albite, commonly interstitial between older plagioclase grains. The modal composition is shown in Tabs. 1 and 3.

In some places (e.g. Velická Valley, Fig. 3), at the contact between biotite granodiorite (tonalite) and garnet and sillimanite-bearing metapelites, leucocratic veins and segregations of nearly eutectic granitic composition can be observed, indicating melting reactions in the metapelite driven by ascending hot granodiorite magma.

In the upper part of the Velická Valley, mafic enclaves in rather homogenous granodiorite to tonalite can be observed (Janák et al. 1993). The enclaves are oval-shaped, with microgranular texture of tonalitic to dioritic composition, indicating their magmatic origin. In contrast to metamorphic xenoliths, mafic enclaves may represent batches of more basic magma, mixing with the surrounding more acid magmas, similar to the situation in the Tribeč Mts. and some other Western Carpathian I-type granitoid plutons (Petrík & Broska 1994; Broska et al. 1993).

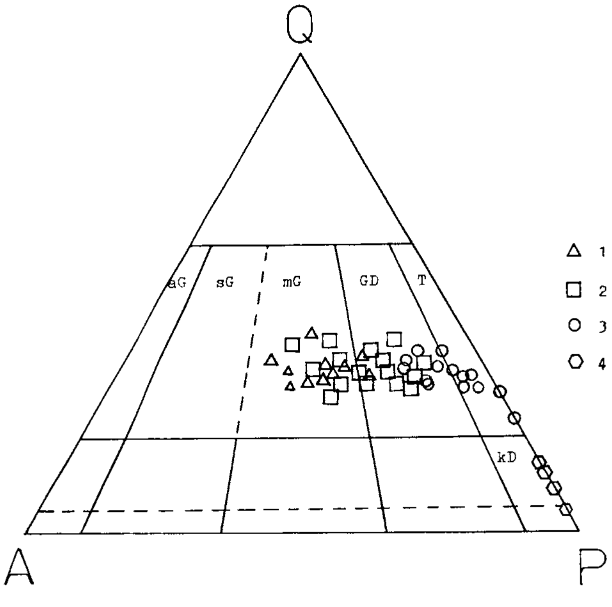

Fig. 4. Classification diagram QAP according to IUGS for investigated granitoids. Symbols: **1** - Goryczkowa type, **2** - common Tatra type, **3** - High Tatra type, **4** - quartz diorite.

Biotite and muscovite-biotite granodiorite to granite, slightly porphyric (the common Tatra type) is very similar to the previous type, except for its more felsic varieties of granite composition. This type is most abundant in the Western Tatra (Fig. 1). Macroscopically, the rock is medium- to coarse-grained, in some parts phenocrysts of white plagioclase or pinkish K-feldspar reach 1 - 1.5 cm size. Muscovite is more abundant, the mineral composition is similar to the previous ("High Tatra type"), as shown in Tabs. 1 and 3, differing only in the modal abundance. In the Western Tatra, in the marginal zone of the pluton, the fabric is mostly oriented, defined by deformation of biotite, feldspars and quartz (Fig. 3).

Porphyric granites to granodiorites ("Goryczkowa type") show abundant phenocrysts of pinkish K-feldspar up to 2 - 3 cm in size. This type is relatively well distinguishable and appears mainly in the northernmost part of the pluton, or as detached tectonic slices of the crystalline basement involved within Mesozoic nappes in the northern part of the High Tatra (Goryczkowa, Giewont, Javorinská, Široká), Fig. 1. Its mineral composition is: K-feldspar, plagioclase, quartz, biotite, muscovite, accessory apatite, zircon, magnetite, allanite, monazite ± ilmenite (Tab. 1).

The modal composition of the above distinguished granitoid types is plotted in the QAP diagram in Fig. 4, exhibiting the classification according to IUGS.

The presence of accessory minerals - monazite, allanite, magnetite and ilmenite (Broska et al. 1993) in some rocks of the same type is in contradiction with the antagonism between monazite-bearing and allanite-bearing granites, observed in some Western Carpathian granitoids (Broska & Gregor 1992).

Geochemistry

The chemical composition of selected representative samples is presented in Tab. 3, the average composition of above distinguished types, including already published analyses, is given in Tab. 2.

The investigated granitoids belong to the calc-alkaline magmatic series, which is documented by diagrams in Fig. 4 and 5. As shown in Fig. 5, most of the analysed samples plot within the medium-potassic field, part of them, mostly porphyric K-feldspar-bearing granites belong to high-potassic, calc-alkaline rocks. However, extrapolated Peacock's index ALI = 62 - 63 corresponds rather to the Ca-series, which is also supported by the high content of CaO, reaching 3.5 wt. % in some samples

Table 2: Average chemical composition of the Tatra Mts. granitoid types. Major elements in wt. %, minor elements and REE in ppm.

	Quartz diorite (n=6)*				High Tatra type (n=13)				Tatra (common) type (n=19)				Goryczkowa type (n=10)			
	x	s	R	V	x	s	R	V	x	s	R	V	x	s	R	V
SiO_2	52.58	3.12	48.79-60.77	5.9	68.16	2.33	63.97-71.57	3.4	70.55	1.89	67.12-73.38	2.7	71.8	1.23	69.54-73.93	1.7
TiO_2	0.98	0.28	0.40-1.30	28.6	0.82	0.20	0.30-1.40	24.4	0.77	0.14	0.21-1.45	18.1	0.46	0.12	0.18-1.12	26.1
Al_2O_3	15.05	0.93	13.07-17.30	6.2	15.32	0.98	13.34-19.70	6.4	14.62	0.79	11.69-16.22	5.4	13.94	0.88	12.6 -15.89	6.3
Fe_2O_3	3.32	1.23	1.33-6.45	37.0	1.36	0.64	0.55-3.12	47.1	1.43	0.53	0.47-3.02	37.1	1.42	0.46	0.27-4.04	32.4
FeO	5.86	0.47	5.48-6.91	5.0	1.56	0.58	0.14-3.50	37.2	1.21	0.48	0.18-2.06	39.7	1.13	0.42	0.18-1.95	37.2
MnO	0.21	0.02	0.18-0.24	9.5	0.05	0.01	0.04-0.06	20.0	0.04	0.01	0.03-0.05	25.0	0.03	0.01	0.02-0.04	33.3
MgO	8.19	2.08	5.43-10.91	25.4	1.03	0.33	0.69-1.60	32.0	0.84	0.26	0.56-1.16	30.9	0.68	0.16	0.31-1.09	23.6
CaO	7.13	1.85	4.31-10.22	25.9	2.72	0.30	2.34-3.50	11.1	2.52	0.62	1.33-3.27	24.6	1.53	0.38	0.64-2.21	24.8
Na_2O	2.65	0.72	1.56-4.19	27.2	4.03	0.41	3.28-4.85	10.2	4.41	0.31	3.96-4.77	7.0	4.06	0.29	3.66-4.61	7.1
K_2O	1.52	0.38	1.05-2.43	25.0	1.81	0.30	1.51-2.74	16.6	2.18	0.40	1.47-3.15	18.3	3.23	0.47	2.23-4.13	14.6
P_2O_5	0.26	0.08	0.09-0.35	30.8	0.26	0.12	0.13-0.46	46.2	0.20	0.07	0.06-0.41	35.0	0.23	0.08	0.13-0.44	34.8
H_2O^+	1.96	0.39	0.42-2.49	19.9	0.88	0.38	0.43-1.54	43.2	1.03	0.33	0.46-2.14	32.0	0.82	0.31	0.28-1.45	34.1
H_2O^-	0.27	0.16	0.06-1.00	59.6	0.58	0.21	0.23-1.39	36.2	0.12	0.10	0.05-0.61	83.3	0.39	0.12	0.08-1.03	30.8
Sr	-				554	86	306-654	15.5	573	92	251-714	16.1	434	35	398-614	8.1
Rb	-				62	10	41-87	16.1	53	14	32-100	26.4	70	8	46-94	11.4
Ba	-				933	285	460-1620	30.5	1042	291	480-1300	27.9	1389	364	810-2280	26.2
Zr	-				182	43	103-255	23.6	167	32	131-231	19.2	123	18	56-179	14.6
Y	-				15.64	4.82	7-26	30.7	11.89	4.53	4-17	38.1	12.70	3.62	6-29	28.3
Nb	-				9.91	1.90	5-15	19.2	8.84	1.25	7-11	14.1	8.00	1.51	5-13	18.9
Ta	-				0.40	0.16	0.26-0.65	40.0	0.33	0.06	0.26-0.48	18.2	0.32	0.09	0.17-0.49	28.1
Hf	-				5.00	0.35	4.00-6.10	7.0	4.45	0.42	3.70-5.40	9.4	3.54	0.35	1.75-4.90	9.9
Th	-				9.39	2.92	5.20-14.8	31.1	7.84	1.51	6.30-12.4	19.3	7.96	0.82	6.10-13.1	10.3
U	-				2.82	1.20	0.50-8.6	42.5	2.20	1.10	0.48-7.80	50.0	2.60	0.66	1.35-4.60	25.4
La	-				31.25	9.58	17.9-43.0	30.7	28.38	6.52	19.8-38.0	23.0	25.44	4.53	19.1-39.0	17.8
Ce	-				74.14	18.61	46.5-102	25.1	66.08	13.50	44.5-91.5	20.4	58.40	6.78	47.5-91.0	11.6
Nd	-				32.07	8.64	22.7-45.5	26.9	27.76	5.95	20.9-38.5	21.4	22.02	2.89	16.9-35.5	13.1
Sm	-				5.34	1.33	3.50-7.70	24.9	4.39	1.02	3.30-6.50	23.2	3.81	0.38	3.10-6.30	10.0
Eu	-				1.20	0.14	0.91-1.45	11.7	1.06	0.19	0.76-1.35	17.9	0.95	0.09	0.61-1.31	9.5
Gd	-				4.53	0.92	2.45-6.70	20.3	3.87	0.77	2.80-6.10	19.9	3.29	0.56	2.50-4.80	17.0
Tb	-				0.53	0.17	0.33-0.72	32.1	0.43	0.10	0.32-0.60	23.3	0.38	0.09	0.27-0.51	23.6
Tm	-				0.22	0.06	0.13-0.31	27.3	0.20	0.05	0.14-0.30	25.0	0.18	0.04	0.12-0.35	22.2
Yb	-				0.96	0.28	0.60-1.80	29.2	0.81	0.12	0.60-1.15	14.8	0.73	0.10	0.43-1.50	13.7
Lu	-				0.17	0.06	0.11-0.29	35.3	0.14	0.04	0.11-0.19	28.6	0.15	0.05	0.08-0.26	33.3

Explanations: **n**, **s**, **R**, **V** - similary as in Tab. 1. * - published analysis from catalogue Hovorka (1972) were used by calculation. Major elements were analysed by classical (wet) methods in the laboratories of the Dionýz Štúr Institute of Geology, minor element and REE were determined by X-ray fluorescence method in the laboratories UNIGEO Brno and INAA method at ČSUP Stráž pod Ralskem.

(Tabs. 2 and 3). The prevalence of Na_2O above K_2O is also documented by chemical composition.

According to Shand's discrimination index given by the ratio A/CNK (Fig. 6), the investigated rocks belong to transitional (subalkalic), peraluminous to metaluminous types. Alumina - rich minerals (e.g. Al_2SiO_5 polymorphs, garnet and cordierite) are lacking, therefore, the peraluminous character of some leucogranites and porphyric types is rather due to secondary alterations than to primary peraluminous character of the protolith.

The chondrite-normalized pattern of the REE (Nakamura 1974), Fig. 7 exhibits uniform trend lacking Eu anomaly, which is suggestive of low magma fractionation, as well as low differentiation among the above distinguished granitoid types (LaN/YbN = 25 - 14 for ”High Tatra type” and ”Goryczkowa type”).

Petrophysical properties

Several physical properties such as magnetic susceptibility, normal remanent magnetic polarization (NRMP) and radioactivity have been investigated (Tab. 4). High magnetic susceptibility of granodiorites to tonalites of the ”High Tatra type” reflects their affinity to the magnetite series (Ishihara 1979), while the ”common Tatra type” granodiorites to granites are transitional between the magnetite and ilmenite series. Only porphyric ”Goryczkova type” shows affinity to the ilmenite series. Study of

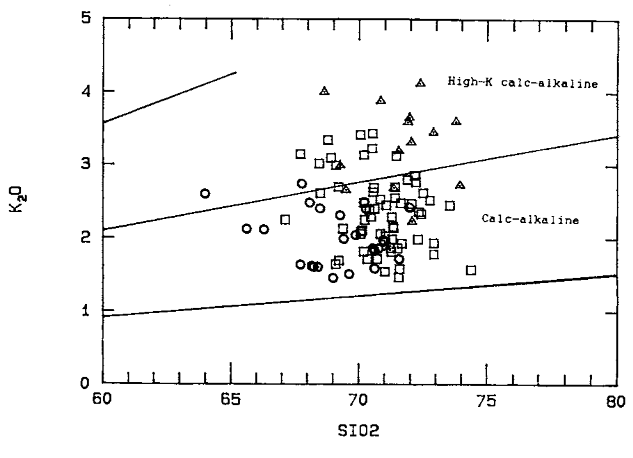

Fig. 5. Plot of K_2O vs.SiO_2 documenting medium to high-potassic calc-alkaline affinity of Tatra granitoids. Symbols as in the Fig. 4.

Table 3: Mineral and chemical composition of selected samples granitoid rocks of the Tatra Mts.

No.	1	2	3	4	5	6	7	8
Quartz	3.2	25.6	34.5	28.4	28.2	27.8	28.9	33.0
Plagioclase	28.5	59.1	46.4	55.9	53.6	49.6	38.3	41.1
Alk. Feldspar	-	0.4	9.5	1.8	4.5	9.7	22.3	15.2
Biotite	11.3	13.3	5.3	10.5	9.8	8.6	5.2	5.5
Muscovite	-	-	3.0	1.5	1.8	2.3	4.2	3.8
Amphibole	55.0	-	-	-	-	-	-	-
Access.	2.0	1.6	1.3	1.9	2.1	2.0	1.1	1.4
SiO_2	48.79	65.60	69.61	67.73	68.17	67.77	68.45	69.22
TiO_2	1.20	0.76	0.38	1.10	0.40	1.30	1.45	0.84
Al_2O_3	17.30	19.70	15.30	15.43	15.87	14.78	14.16	16.00
Fe_2O_3	1.33	0.95	0.77	2.82	0.55	3.12	2.72	1.18
FeO	6.91	2.10	1.73	0.14	2.57	0.20	0.20	1.59
MnO	0.22	0.04	0.05	0.06	0.05	0.04	0.03	0.04
MgO	9.96	0.69	0.80	0.95	1.45	0.98	1.16	0.84
CaO	10.22	2.73	2.71	3.19	3.09	3.50	1.33	3.27
Na_2O	1.57	4.36	4.85	4.84	4.75	4.78	4.68	4.60
K_2O	1.67	2.12	1.51	1.64	1.62	2.74	3.02	1.70
P_2O_5	0.35	0.17	0.46	0.39	0.30	0.42	0.41	0.23
H_2O+	0.42	0.39	0.11	1.54	0.96	0.40	2.14	0.54
H_2O-	0.20	0.02	1.37	0.11	0.03	0.05	0.09	0.17
Total	100.14	99.63	99.65	99.94	99.81	100.08	99.84	100.22
Sr	-	579	654	513	654	499	294	652
Rb	-	41	45	57	87	71	100	53
Ba	-	980	1060	610	460	1070	1300	1170
Zr	-	149	163	233	143	222	186	183
Y	-	20	8	26	23	9	11	14
Nb	-	9	6	15	9	11	9	9
Ta	-	0.38	0.29	0.65	0.28	0.46	0.38	0.32
Hf	-	4.20	4.60	6.10	4.50	5.30	4.90	5.00
Th	-	6.80	7.40	10.90	5.00	9.80	12.40	8.80
U	-	8.10	4.80	5.90	1.65	1.51	0.53	1.20
La	-	25.10	27.70	35.00	17.90	35.00	38.00	33.00
Ce	-	60.00	66.00	87.00	46.50	83.00	91.5	76.50
Nd	-	24.40	26.00	41.00	22.80	37.50	38.00	34.50
Sm	-	4.00	4.20	7.00	4.20	6.00	6.50	4.90
Eu	-	0.99	1.05	1.45	1.20	1.35	1.35	1.20
Gd	-	3.40	3.00	6.30	4.10	6.20	4.80	4.00
Tb	-	0.42	0.36	0.58	0.70	0.55	0.59	0.49
Tm	-	0.13	0.14	0.26	0.30	0.26	0.28	0.30
Yb	-	0.79	0.97	1.05	1.80	0.75	0.79	0.74
Lu	-	0.16	0.14	0.15	0.29	0.14	0.12	0.17

Explanations: **1** - hornblende-biotite diorite, Krížna Valley, (Reichwalder 1964 in Hovorka 1972); (2 - 6 = High Tatra type) **2** - TL-40-biotite tonalite, Prostredný Hrebeň; **3** - TL-104-biotite granodiorite, Mengušovský štít; **4** - TL-10-biotite tonalite, Kostolík, **5** - TL-87-biotite tonalite, Košiar, **6** - TL-11-biotite granodiorite, Batizovská Valley - SE slope Končistá; (7 - 11 = Tatra common type) **7** - TL-14-two-micas granodiorite, Bradavica; **8** - TL-35-biotite granodiorite, Malá Studená Valley; **9** - TL-117-muscovite-biotite granodiorite, Prostredný Vrch; **10** - TL-38-biotite granodiorite, Medená Valley - waterfall; **11** - TL-119-muscovite/biotite granite, Stežky; (12 - 16 = Goryczkowa type) **12** - TL - 24-two-micas granite, Malý Kriváň; **13** - TL-50-two-micas granite Končistá; **14** - TL-97-muscovite-biotite granodiorite, **15** - TL-124-two-micas granite, Nefcerská Veža; **16** - TL-127-biotite-muscovite granite, Zelené Javorové lake.

remanent magnetization brought noteworthy results. Extremely high values document partial loss of primary ferromagnetic properties, possibly due to partial oxidation of magnetite to hematite (Drinkwater et al. 1992). This may have been controlled by the uplift of magma into shallower crustal levels, or due to partial anatexis of the former magmatic protolith, remelted during subduction-collision (Drinkwater et al. 1992). Octahedral marthites, indicating redox changes have been found, often together with original magnetite. Since the investigated rocks show no significant hydrothermal subsolidus alteration, partial melting as the cause of oxidation is suggested. The radioactivity, expressed by the ratio of Th/U varies from 3 - 4 : 1 in more basic types to 2 : 1 and 1 : 1 in more acid granites. Sporadically, the U content prevails above Th, which is typical of anatectic, collisional granites (e.g. France-Lanord & Le Fort 1988).

Petrogenetic and geotectonic classification

Taking into consideration major element composition, as well as initial ratio of Sr isotopes ISr = 0.703 - 0.708 (Burchart 1968), granitoids of the Tatra belong to mixed I/S types according to Chappell & White (1974) and White & Chappell (1983). Discrimination diagrams based on trace and REE elements (Pearce

Table 3 continued

No.	9	10	11	12	13	14	15	16
Quartz	36.6	29.8	31.2	28.3	29.0	34.4	38.3	32.4
Plagioclase	31.2	47.6	33.4	31.2	34.9	38.0	28.2	34.2
Alk. Feldspar	23.7	10.8	26.2	32.5	27.3	18.2	25.9	25.0
Biotite	3.1	7.4	4.2	3.3	3.8	5.9	3.3	2.8
Muscovite	4.2	2.8	3.6	3.8	3.1	2.3	2.9	4.6
Access.	1.2	1.6	1.4	0.9	1.9	1.2	1.4	1.0
SiO_2	71.24	67.12	72.75	72.37	69.54	71.55	73.93	72.06
TiO_2	0.25	1.16	0.21	1.10	1.12	0.46	0.25	0.38
Al_2O_3	14.56	16.22	14.55	12.83	12.84	14.42	12.91	13.70
Fe_2O_3	1.24	1.36	1.07	2.08	4.04	1.28	0.64	1.00
FeO	1.41	1.75	0.98	0.18	1.33	1.22	1.39	1.45
MnO	0.04	0.05	0.03	0.04	0.03	0.03	0.03	0.04
MgO	0.77	1.14	0.56	0.92	0.80	0.67	0.50	0.82
CaO	2.26	2.96	1.88	0.73	0.64	1.84	2.21	1.81
Na_2O	4.48	4.12	4.49	4.08	3.86	3.79	4.31	4.61
K_2O	1.87	2.25	2.52	4.13	4.01	3.20	2.73	2.23
P_2O_5	0.21	0.32	0.15	0.13	0.14	0.28	0.36	0.16
H_2O+	1.10	1.40	0.67	1.18	1.40	0.98	0.51	1.45
H_2O-	0.18	0.04	0.04	0.10	0.02	0.10	0.06	0.06
Total	99.61	99.89	99.90	99.87	99.77	100.10	99.83	99.83
Sr	649	556	533	410	398	415	564	614
Rb	34	45	51	79	88	94	60	55
Ba	880	1000	1250	990	810	1400	1780	1050
Zr	159	174	131	110	113	179	128	132
Y	7	12	7	12	10	11	10	10
Nb	10	9	9	13	9	7	6	9
Ta	0.29	0.38	0.33	0.43	0.49	0.45	0.25	0.38
Hf	4.10	5.00	3.80	3.70	2.95	4.90	3.50	3.70
Th	6.30	8.40	6.40	12.70	7.30	13.00	6.40	6.30
U	2.60	1.10	1.65	1.35	3.70	2.40	1.40	2.55
La	25.40	31.50	23.70	19.10	20.00	39.00	24.00	23.30
Ce	59.00	74.50	54.50	48.50	48.50	91.00	54.50	53.50
Nd	24.40	30.50	21.70	21.10	20.40	35.50	19.00	19.00
Sm	3.80	4.70	3.40	3.20	3.30	6.30	3.60	3.40
Eu	1.00	1.15	0.86	0.61	0.83	1.30	0.93	0.89
Gd	3.50	4.20	3.50	3.00	3.10	4.80	2.90	3.40
Tb	0.37	0.45	0.37	0.35	0.38	0.47	0.37	0.36
Tm	0.21	0.20	0.18	0.12	0.14	0.14	0.18	0.22
Yb	0.76	0.60	1.00	0.43	0.59	0.60	0.63	0.70
Lu	0.19	0.12	0.18	0.13	0.14	0.14	0.08	0.18

et al. 1984; Harris et al. 1986) provide rather ambiguous information about geotectonic setting, as shown by Figs. 8 and 9. A volcanic arc setting is suggested by plot in Fig. 8, but on the other hand, the spidergram in Fig. 9 indicates affinity to late- and post-collisional granitoids. According to the discrimination diagram of de la Roche et al. (1980) and Batchelor & Bowden (1985) in Fig. 10, the investigated granitoids plot within continental arc and collisional granites.

The above presented discrepancies point to the problem of geotectonic classification based on discrimination diagrams. As stressed by Roberts & Clemens (1993 l.c.), "their interpretation must take into consideration that rather than the tectonic settings existing when the granitoid magmas were actually produced, these plots seem to diagnose the settings in which the protoliths were formed". Therefore, a potentially much older protolith may have formed in a setting very different from that in which the granitoid magma was generated by partial melting. The investigated granitoids with affinity to medium-K and high-K, rather metaluminous, I to I/S type, may reflect the generation of melt from a recycled supracrustal source, involving mainly

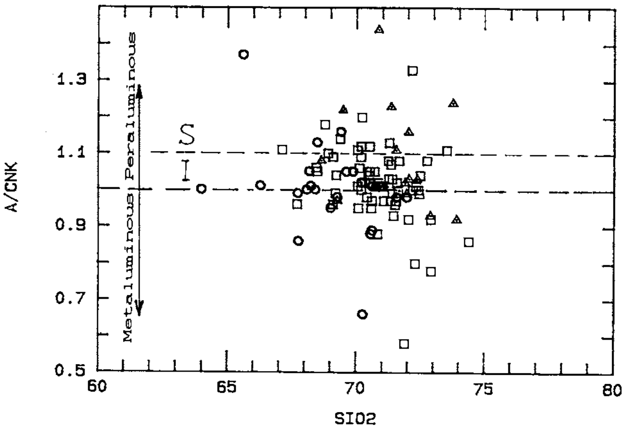

Fig. 6. Diagram showing peraluminous and metaluminous character of granitoids, based on the ratio A/CNK according to Shand (1927), I and S typology is according to Chappel & White (1974).

Table 4: Average values of physical properties of granitoid rocks of the Tatra Mts.

	High Tatra type (n=14)				Tatra (common) type (n=24)				Goryczkowa type (n=7)			
	x	s	R	V	x	s	R	V	x	s	R	V
Specific density (g/cm^3)	2.627	0.013	2.61-2.66	0.5	2.619	0.011	2.58-2.64	0.4	2.604	0.009	2.59-2.63	0.3
Magnetic susceptibility (κ =SI u. x10^{-6})	2357.9	465.4	1178-4883	19.7	1051.7	396.4	100-3404	37.7	867.1	213.7	76.5-2996	24.6
NRMP (nT)	613.9	301.5	49.6-3879	49.1	854.1	418.7	8.5-4661	49.0	543.1	238.2	0.92-2717	43.9
Summary gamma activity (ppm U eqv.)	11.4	2.12	7.8-16.4	18.6	10.7	2.26	8.0-17.9	21.1	13.0	1.79	10.3-16.6	13.8
Thorium (ppm)	8.97	1.87	6.6-16.3	20.8	7.87	1.69	6.2-13.5	21.5	7.45	1.23	5.1-8.9	16.5
Uranium (ppm)	3.91	1.64	1.2-10.7	41.9	3.23	1.25	1.8-10.2	38.7	5.06	2.31	2.6-9.6	45.6
Th/U ratio	3.21	0.78	1.3-6.0	24.3	2.92	0.67	0.7-4.9	22.9	1.70	0.53	0.6-2.9	31.2

Explanations: symbols **n**, **x**, **s**, **R** and **V** are similar as in Tab. 1. Determined in the laboratories GEOFYZIKA Bratislava and GEOFYZIKA Brno.

former plutonic and volcanic (metaigneous) rocks (e.g. Roberts & Clemens 1993).

Discussion

Emplacement model

On the basis of the field relations to the metamorphic mantle, the granitoids of the Tatra are accommodated in the hanging wall of the Variscan nappe (Fig. 2), preserving inverted metamorphic zonation (Janák et al. 1993; Janák 1994 this volume). Therefore, the granitoid pluton may be considered as a sheet-like intrusion, in accordance with previous observations of Gorek (1959) and Kahan (1969). The common ductile deformation of marginal parts of the pluton suggest emplacement of the magma into an extensional shear zone with dextral sense of displacement D2. Strike-slip faulting and extension of an overthickened crust due to the overthrusting D1 is inferred as a mechanism creating the space for ascending magma, similarly to the models of Hutton (1988), Hutton & Reavy (1992) and Brown (1994). Fracture-controlled, rather then diapiric ascent of the melt, collected in the shear zone (e.g. Clemens & Mawer 1992; Petford et al. 1993) is suggested. Despite Alpine overprint, it is inferred that Variscan oblique collision and concomitant orogen-parallel strike-slip faulting and extension may still be manifested by deformational events D1 and D2 recognized by Fritz et al. (1992).

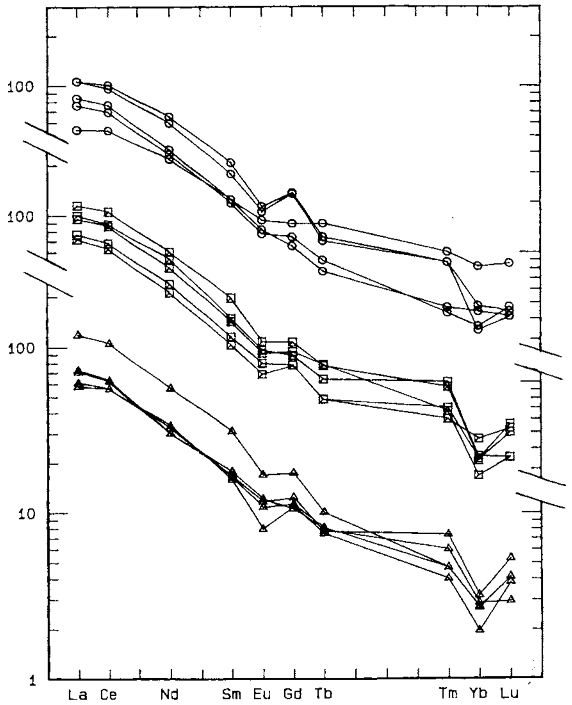

Fig. 7. Plot of REE pattern for the whole series of Tatra granitoids, normalized according to Nakamura (1974).

Metamorphic conditions in the vicinity of the granitoid pluton (about 700 - 750 °C, 4 - 6 kbars, Janák et al. 1988; Janák 1994 this volume), indicate the depth of emplacement and crystallization of the granitoid melt in mid-crustal levels. Emplacement of granitoids was probably syn-kinematic with respect to Variscan uplift of the upper tectonic unit, as shown by the presence of granitoids solely within the overthrust unit. Post-tectonic intrusion relative to Variscan thrusting can be omitted because of a lack of granitoids penetrating the lower structural unit. The available ^{40}Ar/^{39}Ar mineral ages of biotite and muscovite (330 - 300 Ma), using the conventional step-heating method (Maluski et al. 1993) and laser probe (Janák & Onstott 1993; Janák 1994 this volume) record the blocking temperature for diffusion of about 300 - 350 °C during the late-Variscan uplift. The mechanism of granitoid emplacement seems to have been controlled by both - thrusting and contemporary extension, necessary for exhumation, similarly to the

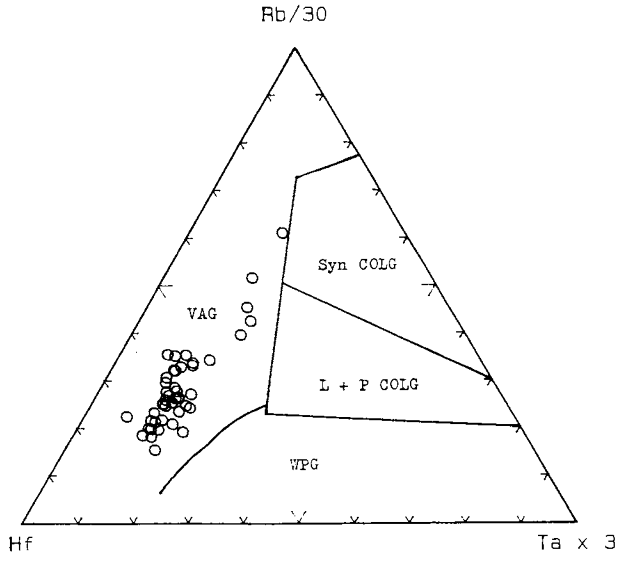

Fig. 8. Discrimination diagram after Harris et al. (1986) for all granitoid types (not distinguished), indicating their volcanic arc (VAC) setting (see the text for discussion).

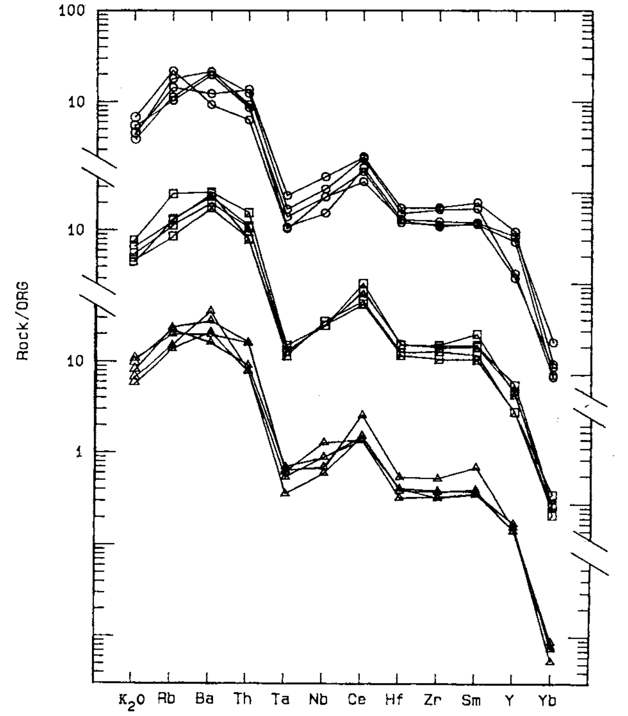

Fig. 9. Spidergram indicating late-collisional setting of granitoids, normalized to ORG according to Pearce et al. (1984).

model proposed by Hollister (1993) and Platt (1993). However, more detailed study is necessary to test this model in the Tatra Mts.

Petrogenetic implications

The heterogeneity of the above distinguished granitoid types seems to be more controlled by melting, than by differentiation of the magma itself. This is supported mainly by the REE pattern, showing a low degree of magma fractionation, as well as low differentiation among several granitoid types. Partial melting of heterogeneous, mostly supracrustal material may explain the variable isotopic ratios of Rb/Sr = 0.05 - 0.3 as well as IRSr = 0.703 - 0.708 (Burchart 1968). Partial melting of a muscovite and biotite-bearing protolith is indicated by the presence of micas and lack of hornblende, except in minor dioritic rocks. A possible source of the melt might have been biotite and muscovite-bearing metapelites and gneisses (e.g. Skjerlie et al. 1993), which can be observed in the upper unit, showing widespread migmatization (Figs. 2 and 3). A plutonic (metaigneous) protolith is also inferred from chemical composition (Chappell & Stephens 1988); I-type affinity, medium to high-potassic and metaluminous) and ferromagnetic properties (oxidation due to partial remelting; Drinkwater et al. 1992). Hence, orthogneiss and tonalitic gneiss of metaigneous origin is a possible source material.

P-T conditions and generally clockwise P-T-t paths inferred from metamorphic rocks (Janák 1994 this volume) record the uplift from the lower crustal levels (about 10 kbars) and nearly isothermal decompression at temperatures exceeding water-saturated granite solidus. Assuming the necessity of melt segregation to generate the pluton, dehydration (fluid absent) melting must be considered, in order to explain the generation of magma capable of ascent (e.g. Wickham 1987; Clemens & Vielzeuf 1987; Thompson 1990; Stevens & Clemens 1993). Taking into consideration the absence of amphibole, dehydration-melting of muscovite and biotite (e.g. Le Breton & Thompson 1988; Vielzeuf & Holloway 1988) seem to be the most important reactions in generation of the investigated granitoids, although partial melting of amphibolites has been also inferred by preliminary study (Janák et al. 1993b). Therefore, granitoids of Tatra probably represent several batches of magma derived by partial melting, which ascended and collected forming the pluton.

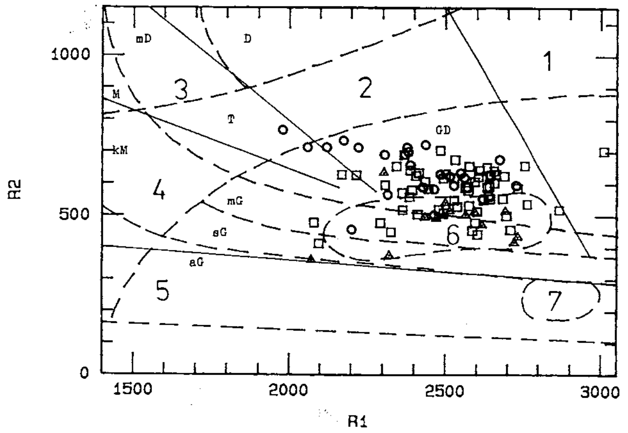

Fig.10. R1R2 diagram of de la Roche et al. (1980), with discriminating fields (1 - 7) according to Batchelor & Bowden (1985), indicating the collisional setting of granitoids.

The heat necessary for melting reactions might have been supplied by internal radiogenic heat production due to crustal thickening (England & Thompson 1984), or by input from the mantle (e.g. Huppert & Sparks 1988). Mafic magmatic enclaves together with low initial Sr isotope ratio (0.703) in some granodiorites and tonalites (High Tatra type) migt indicate a possible mantle influence. However, there is strong evidence for a generally clockwise metamorphic P-T-t path (Janák 1994 this volume), characteristic for overthickened, collisional orogens (Brown 1993).

Summarizing the field observations and data presented, in general, the granitoids of the Tatra may be considered as products of a Variscan collisional orogen, in agreement with the models of granite petrogenesis in the European Variscides (e.g. Matte 1991), as well as in other collisional belts as reviewed by Brown (1994).

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SLOVNAFT AND THE ENVIRONMENT

MONITORING AND PROTECTION OF THE ATMOSPHERE - A FURTHER STEP TOWARDS THE ECOLOGIZATION OF PRODUCTION

SLOVNAFT

Slovnaft Inc. of Bratislava is taking important strategic steps to place itself among world refinery and petro- chemical companies as an equal partner, and not only from the point of view of economic prosperity, but also from the point of view of approach to protection of the environment. In its environment protection programme, the company has started a demanding investment programme amounting to several billion crowns. However specific results and therapeutic steps undertaken to diagnose and treat components of the environment interest the ordinary citizen more than investment expenditure. We have already given you comprehensive information about the protection of underground and surface water by Slovnaft, in the pages of our periodical. In this article we will briefly introduce you to the approach of Slovnaft Inc. to protection of the atmosphere.

In a country with normally functioning market relations and an intellectually and spiritually mature population - the sort of country we want to become - only companies which solve the identification and catching of harmful substances escaping from structures used for technological and energy purposes, in an up to date technological way, have good prospects for survival. This is because a culturally mature society adopts the sort of environmental laws that do not allow a firm to profit at the expense of the health of the present and future generations of the population.

For readers, for whom the processing of oil is a rather distant theme, it is appropriate to say what the source of pollution in Slovnaft is. Refining of oil and oil half finished products mostly consists of distillation processes. Separation by distillation of liquid and gaseous hydro- carbons from crude oil requires heat. This heat is obtained by burning gas or liquid fuel in boilers and furnaces. In boilers the heat is obtained in the form of heated water vapour, in technological furnaces the hydro-carbons are heated directly by direct heat from the products of combustion. It is from such burning facilities, of which there are about 50 at Slovnaft, that emissions arise. They are emissions characteristic of the burning process, that is solid materials, oxides of carbon, sulphur and nitrogen. Hydro-carbons from the burning processes do not escape. The places for putting products into preparatory cisterns, leakage from armatures, reservoirs of oil and oil products, and flowing waste water before it reaches the cleaning facility are the sources of emissions of hydro-carbons. Pollution of the atmosphere, through chimneys with flames - flare stacks - occurs mainly at the beginning or end of production, since otherwise the waste gases are removed and transported by a compressor to the works network of heating gases, that is they serve as fuel for technological furnaces.