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GRANITOID ROCKS OF THE VEĽKÁ FATRA MTS. — Rb/Sr ISOTOPE GEOCHRONOLOGY (WESTERN CARPATHIANS, SLOVAKIA)

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Abstract: Isotope study of granitoid rocks of the Ľubochňa Massif in the Veľká Fatra Mts. has been carried out on whole-rock (WR) samples and separated mineral phases (muscovite, biotite) using the Rb/Sr method. It confirmed the long duration of the granitoid magmatism with "re-cycled" crustal-mantle source material (I_{Sr} = 0.7057). During the main Meso-Hercynian event (350-340 Ma) the crust tectonically thickened. As a result of the collision of the upper overheated unit with the lower, cooler one, the anatectic Ľubochňa leucogranites (LLG) in the middle crust were melted. In the subsequent, extension phase, these leucogranites were emplaced into the upper cover unit, into the block of the "relatively older crystalline complex", composed of the Smrekovica tonalites (ST), Kornietov granodiorites (KGD) and Lipová granites (LG), which were also partly melted and re-magmatised, however, preserving their original composition and zoning. This event is documented by the WR, Bi, Mu isochron (340 Ma) for all rock types. The age of the pre-existing granitoid body (ST, KGD and LG), showing an "inherited isochron" with an apparent age of 420 Ma is problematic. More than 340 Ma ago, this zoned Veľká Fatra pluton, like the Eo-Hercynian crystalline block, was probably already isotopically homogenized and solidified. The presented study confirmed that during the Meso-Hercynian stage there was no isotopic homogenization affecting the whole Veľká Fatra pluton. Only local $^{87}Sr/^{86}Sr$ isotopic homogenization has been recorded.

Key words: Hercynian tectonics, Western Carpathians, Veľká Fatra Mts., granitoid rocks, petrology, Rb/Sr geochronology.

Introduction

Since the times of Zoubek (1936) the opinion has predominated that most of the West-Carpathian (WC) granitoid rocks are Variscan in age. Andrusov (1958) upheld this opinion in his monograph: "Geology of the Czechoslovak Carpathians" (Volume I). He considered the products of the Caledonian orogeny as not proved to occur in Slovakia, but, he did not exclude the possibility of the occurrence of older rocks of the Precambrian stage. In contrast to this, Máška & Zoubek (1961) on the basis of lithological-tectonic signs considered almost all of the WC crystalline complex to be Precambrian. This opinion was opposed by Kantor (1961) — the pioneer of Slovak isotope geology — who, on the basis of his own results (K/Ar) estimated the age of WC granitoids at 250-320 Ma, which is consistent with the earlier opinions of Zoubek (l.c.). Kamenický in Maheľ et al. (1967) admitted the validity of Kantor's isotopic dating, but for a part of the granitoids he still assumed a Precambrian age.

Extensive use of the Rb/Sr method from the end of the sixties (Burchart 1968) to the present times (Bagdasaryan et al. 1990, 1992; summary in Cambel et al. 1990) confirmed the Hercynian age of the majority of WC granitoid rocks (300-393 Ma). Rare U/Pb data (Bibikova et al. 1988, 1990; Broska et al. 1990; summary in Kráľ 1994) have shown that the Hercynian granitoid magmatism had two periods: an older (340-355 Ma) and a younger one (303-306 Ma). The differences between the Rb/Sr (WR) and U/Pb ages have been explained by Kráľ (1992, 1994) as a process of mixing between the crustal and mantle source material of the granitoids and he called it "ageing" of apparent isochron ages.

The aim of the presented work is to provide new whole-rock (WR) and mineral Rb/Sr data from the Veľká Fatra granitoid massif, and to discuss the existence of "inherited isochrons" of granitoid massifs in the Western Carpathians.

Geological setting

The crystalline basement of the Veľká Fatra Mts. is represented by the so called Ľubochňa granitoid massif. This massif is overlain by the autochthonous, or paraautochthonous Mesozoic — Šiprúň envelope sequence. The Upper Mesozoic structure form Krížna and Choč Nappe. The crystalline complex of the Veľká Fatra Mts. is formed absolutely predominantly by four types of granitoid rocks — which create a zoned body. The uppermost part of the pluton forms Smrekovica Tonalite (ST) with residues of older rocks — orthogneiss and paragneiss. Other rocks in vertical structure are: Kornietov Granodiorite (KGD), Lipová Granite (LG) and Ľubochňa Leucogranite (LLG). The leucogranites penetrate the upper granites along tectonic lines, partly interrupting the regular zoned structure (Fig. 1).

The **Smrekovice type**: according to the IUGS classification, this type includes biotite tonalites to granodiorites. They are fine- to medium-grained rocks of dark-grey colour, greyish-green shade, not containing any macroscopically observable K-feldspars. From Fe-Mg silicate minerals it contains

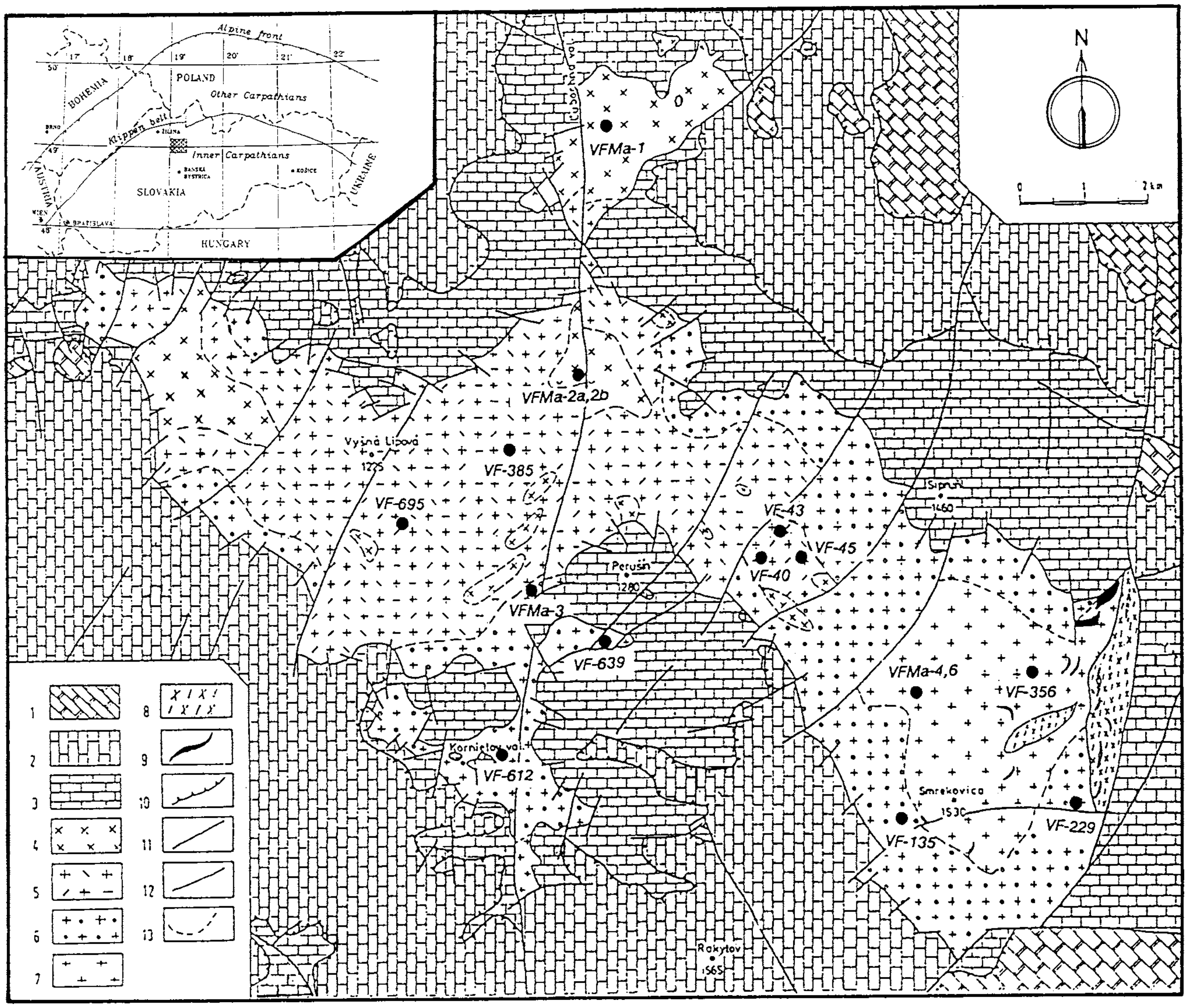

Fig. 1. Geological sketch of the central part of the Veľká Fatra Mts. with detailed presentation of the crystalline complex (Kohút 1992). **1** — Choč Nappe, **2** — Krížna Nappe, **3** — Mesozoic envelope unit, **4** — Ľubochňa Leucogranite, **5** — Lipová Granite, **6** — Kornietov Granodiorite, **7** — Smrekovica Tonalite, **8** — orthogneisses, **9** — paragneisses xenoliths, **10** — nappe lines, **11** — faults, **12** — stratigraphic (normal) boundaries, **13** — gradual transitions (boundaries between granitoid types).

only biotite. Its texture is hypidiomorphic-grained, structure is random, however, sometimes we could observe an oriented distribution of biotite. It represents the most basic rocks and metamorphic xenoliths occur in the Veľká Fatra Mts. practically only in this type. The mineral composition consists of: three generations of plagioclase (Plg I-III), quartz, sometimes interstitial K-feldspar, biotite, sporadically muscovite. Plg I are intensively altered calcic cores enclosed in hypidiomorphic crystals of Plg II with oscillation zoning, with a basicity of An_{25-35}, the youngest Plg III — albite — forms locally rims around older plagioclase generations. From accessory minerals: apatite, monazite, zircon, ilmenite, magnetite are present.

The **Kornietov type** are biotite granodiorites to muscovite-biotite monzogranites with pink K-feldspars. They are mostly medium-grained rocks with slightly porphyric to porphyric structure, greyish-green in colour. The phenocrysts are pink K-feldspars with a size of 1.5-2 cm (locally up to 3 cm). The texture of these granitoids is usually hypidiomorphic-grained and porphyritic-granitic. The mineral composition consists of similar components as in the previous type, however, with different volume contents.

The **Lipová type** is represented by two-mica granites to granodiorites. Macroscopically they are medium- to coarse-grained rocks, very frequently they are irregularly-grained to porphyritic. Their colour depends on the content and proportion of micas and content of feldspars, from light shades to greyish-green colour, in some places with a pinkish-beige hue. The phenocrysts are pinkish K-feldspars with a size of 1-1.5 cm (usually filled with biotite) and greenish plagioclases up to 1 cm in size. A characteristic feature of this granitoid type are also large mica flakes, especially muscovite — up to 5-7 mm. Texture of these rocks is granitic — hypidiomorphic-grained and blastogranitic. They are composed of the same mineral phases as previous types, from accessories: apatite, zircon, monazite, ilmenite ± garnet are present.

It is clear from field observations that ST, KGD and LG form a relative older — zoned granitoid body into which a younger leucogranite was intruded. This is the basis of the working name — "pre-existing granite body" for ST + KGD + LG.

The **Ľubochňa type** is represented by leucocratic muscovite and two-mica granites to granodiorites. They are usually medium- to coarse-grained, even-grained (not porphyritic) rocks of directionless structure. Their colour is predominantly pale-grey. This type is characterized by white feldspars and muscovite flakes with a size of up to 7-9 mm. The plagioclase occurs in the form of an albite twin, albitic and/or acid oligoclase in composition (An_{2-15}). The contents of biotite are variable, it is mostly baueritized. K-feldspar is usually albitized, substituted by various perthites to chess-board albite. Quartz is in some places cataclazed to a fine-grained rubble. The primary texture of these leucogranitoids — hypidiomorphic-grained — bears signs of cataclastic texture. Accessories are zircon, apatite, monazite, garnet. On the basis of field observation we can identify this type as an younger type, which intruded into an already formed zoned body.

Besides the four basic granitoid groups, pegmatites and aplites as well as ortho- and paragneisses also in the formation of the study area.

The boundaries between the types (ST, KGD + LG) are *usually* gradual, intrusive contact can be observed only locally, on the contact of leucogranites with surrounding older granitoid types; pegmatites and aplites have sharp contacts with their surroundings.

The basic mineral and chemical composition is presented in Tab. 1.

The Veľká Fatra Mts. granitoid rocks are low- to moderate-potassium calc-alkaline (trondhjemite-granodiorite) series of magmatic rocks. The prevalence of Na_2O over K_2O is a common geochemical feature, except of LLG in which $K_2O > Na_2O$. The Peacock index for all Veľká Fatra granitoid series has the value of ALI = 59-60. On the basis of Shand's aluminosity index (A/CNK = 0.9-1.5) the studied rocks are peraluminous, but a part of the rocks is projected into the subaluminous to metaluminous domain. Petrography and straight linear trends of the major elements display continual transition and consequently a common — gradual differentiation among individual rock types. This is in contrast to the "en échalon" trends of trace elements distribution (mainly Rb, Sr and Ba), and to the measurement of the physical properties of the VF granitoid rocks: specific density, magnetic susceptibility, normal remanent magnetic polarization (NRMP) as well as summary gamma activity (radioactivity), U and Th (Kohút 1992). Geological setting as well as the above mentioned geochemical and physical character of rocks indicates apparent independence of the three types of granitoid rocks in the Veľká Fatra Mts. c.f. ST, LG and LLG, whereby KGD create "transition" between ST and LG (Kohút l.c.). This facts rather suggest fractional crystallization with a pulse character. The chondrite-normalized records of the REE exhibit uniform, but differentiated distribution trends (La_N/Yb_N = 45-15 for ST and LLG as well) with slight negative Eu anomaly (Eu/Eu^* = 0.5-0.7).

Typology of the Veľká Fatra Mts. is partially problematic. On the basis of a comprehensive evaluation the classic I/S typology of Chappell & White (1974) and White & Chappell (1983), ST, KGD and LG belong to the mixed I-S granite type with an eminent affinity to the I-type of source material. However LLG is a crustal, peraluminous, anatectic S-type of granitoid. Tectonic interpretation of the granitoids according to Pearce et al. (1983), Harris et al. (1986) is also not unambiguous. On the basis of discrimination diagrams, the VF granitoids belong to the VAG type of granites, but according to REE spidergram normalized to ORG, they can be classified as Group III — late- to post-collision calc-alkalic granitoids. The results of the zircon typology (Pupin 1988) show that all types of VF granitoids relate to the first group — crustal anatectic granites (Broska & Kohút in prep.). An application of the classification of Maniar & Piccoli (1989) makes the situation even more confused. Individual VF granitoid types are well discriminated on the basis of chemical and modal composition. The evaluation of this classification also shows that the Smrekovica tonalites belong to the CAG type (Continental arc granites) — formed on continental margin at the end of oceanic plate subduction. The Lipová granites are standard CCG type (Continental collision granites) generated at the late stage of continental collision. The Kornietov granodiorites appear to be transitional between the previous two granite types. The leucocratic Ľubochňa granites have an affinity to post-orogenic-post-collision granites. The analysed VF granites represent H_S-type in sound of Castro et al. (1991) proposal. According to the classification of Barbarin (1990), the VF granites represent a transition between C_{CI} and H_{LO} — Intrusive Crustal Collisional & Late Orogenic Hybrid granites in general.

Methods

Fresh samples were collected from each rock type, weighing of 15-20 kg. One third of each sample was deposited in the original state for further studies. Several thin sections were prepared from each sample, and a macro-sample (0.5-1 kg) for the determination of physical properties. The rest of each sample was crushed and divided into three aliquot parts, from which one was preserved, the second processed by the standard method of mineral separation. The third part was pulverised and it served for analytical purposes (major, trace elements, REE and isotopic determinations).

The analyses of isotopic composition (Rb, Sr) were done in the laboratories of BGR Hannover after methodics Wendt (1986). Approximately 200 mg of pulverised WR sample (for Mu and Bi, an approximately double quantity was used) was, together with a mixture of HNO_3 and HF acids placed into a Teflon pressure vessel and dissolved in a micro-wave oven. After cooling, the addition of several drops of HNO_3 and drying, the sample was definitively dissolved in 6N HCl. The isotope analyses were made on the mass spectrometer Finnigan-MAT 261. In the BGR laboratory in Hannover, the international standard NBS-607 was used, while in the Acad. Sci. laboratory in Jerevan they used the comparable standard SRN-987.

For the calculation of ages, constants recommended by the Sub-Commission for Geochronology in Steiger & Jäger (1977) have been used. The isochrons were calculated using the program created by C. Carl, according to Brooks et al. (1972).

Results

For the purpose of Rb/Sr dating, we had available ten whole-rock samples; one was of the Smrekovica Tonalite (VF-356), four of the Kornietov Granodiorite (VF-135, VF-229, VF-612, VF-639) and five of the Lipová Granite (VF-40, VF-43, VF-45, VF-385, VF-695). The Rb/Sr isotopic ratios were also measured on eight samples of separated mineral phases (four biotite and four muscovites). In three of the samples (VF-43, VF-45 and VF-229) Rb/Sr data from the whole rock (WR) as well as biotite (Bi) and muscovite (Mu) can be used. In the interpretation we also used and evaluated the results of Rb/Sr analyses from the Veľká Fatra crystalline com-

Table 1: Basic modal and chemical composition of the studied granitoid samples from Veľká Fatra Mts. Average composition of the Ľubochňa leucogranites (LLG, n=20 from Kohút (1992) is listed for comparison.

Sample	VF-40 LG	VF-43 LG	VF-45 LG	VF-135 KGD	VF-229 KGD	VF-356 ST	VF-385 LG	VF-612 KGD	VF-639 KGD	VF-695 LG	LLG n=20
Quartz	27.9	33.5	31.4	33.1	31.2	29.8	29.7	33.5	31.0	32.1	33.3
Plagioclase	34.0	31.7	36.6	39.9	35.4	49.8	35.7	37.1	44.0	40.7	32.4
K-Feldspar	31.0	23.3	21.5	17.1	22.1	6.4	22.8	19.1	12.4	16.1	23.2
Biotite	4.0	7.5	6.0	6.4	7.0	13.2	4.6	6.9	8.6	8.1	3.6
Muscovite	3.3	3.0	3.3	1.4	3.4	0.0	6.3	2.3	2.5	1.7	6.7
Access.	0.7	1.0	1.2	1.9	1.0	0.9	0.9	1.1	1.5	1.3	0.8
SiO_2	71.49	72.66	73.31	69.93	72.85	68.76	72.04	67.59	66.33	69.56	73.57
TiO_2	0.21	0.21	0.18	0.37	0.24	0.51	0.24	0.35	0.58	0.16	0.18
Al_2O_3	15.79	14.64	14.52	15.25	14.64	15.59	14.76	16.52	15.70	15.00	14.55
Fe_2O_3	0.18	0.47	0.09	0.72	0.32	0.81	0.27	2.20	1.62	2.09	0.95
FeO	1.52	1.29	1.29	1.65	1.65	2.23	1.44	1.63	1.64	0.21	0.52
MnO	0.04	0.03	0.02	0.03	0.02	0.04	0.03	0.06	0.05	0.04	0.03
MgO	0.50	0.61	0.61	0.92	0.41	1.22	0.41	1.14	1.21	0.77	0.34
CaO	1.38	1.42	1.42	2.41	1.70	2.83	1.98	1.53	2.89	2.30	0.93
Na_2O	3.79	3.74	3.40	3.88	3.64	4.04	3.70	3.50	5.01	5.23	3.90
K_2O	3.89	3.52	3.38	3.14	3.40	2.24	3.56	3.84	2.94	3.28	3.68
P_2O_5	0.29	0.13	0.18	0.17	0.15	0.21	0.18	0.18	0.24	0.15	0.20
H_2O+	0.42	0.75	0.99	0.93	0.58	0.94	0.84	1.02	1.24	0.89	0.94
H_2O-	0.33	0.18	0.16	0.19	0.16	0.14	0.19	0.15	0.13	0.10	0.14
Total	99.83	99.65	99.55	99.59	99.76	99.56	99.64	99.71	99.58	99.80	99.90
Rb	109	110	101	87	118	91	111	104	91	90	121
Sr	224	259	181	438	282	563	294	341	365	357	144
Ba	768	864	917	1060	887	826	832	1180	641	951	728
Zr	84	104	91	147	142	185	110	132	203	135	76
Y	13	11	11	8	7	6	8	9	27	17	15
Nb	7	7	8	5	4	4	8	6	11	11	9
Zn	37	36	34	43	42	53	49	42	81	59	21
Pb	30	25	22	35	41	16	31	27	28	19	23
V	19	18	21	34	16	60	19	40	75	23	13
Cu	4	5	4	5	4	4	6	3	4	3	4
Ni	11	12	7	7	7	7	12	4	4	3	4
Co	1.4	2.1	4.7	2.9	4.0	4.4	1.9	3.1	4.7	5.6	8.2
Be	2.0	2.9	2.4	2.0	2.1	1.7	2.4	1.8	2.6	3.1	2.3
La	16.50	26.10	32.00	33.00	37.30	23.70	23.60	46.90	32.00	23.90	17.03
Ce	25.20	40.60	57.20	56.40	68.30	45.60	38.10	49.60	62.20	34.40	34.50
Nd	10.00	18.00	31.00	24.00	39.00	22.00	15.00	31.00	31.00	16.50	17.98
Sm	2.62	4.04	5.19	5.09	6.30	4.64	3.63	6.66	5.07	3.66	3.11
Eu	0.50	0.71	0.82	0.86	1.07	0.92	0.69	1.19	0.91	0.71	0.62
Tb	0.20	0.40	0.20	0.30	0.90	0.30	0.36	0.30	0.60	0.30	0.34
Yb	0.50	0.60	0.40	1.10	0.40	0.40	0.70	0.70	0.80	0.60	0.78
Lu	0.10	0.08	0.11	0.12	0.11	0.06	0.13	0.10	0.09	0.09	0.13
Th	3.80	6.00	8.00	9.90	9.80	2.30	5.30	7.50	8.90	6.40	6.15
U	0.30	0.50	1.30	1.40	1.30	0.50	0.20	0.30	0.40	1.85	4.50
Hf	1.60	2.80	3.20	4.50	3.60	4.30	2.80	3.20	3.90	2.10	2.18
Sc	2.38	3.78	3.96	5.99	4.27	6.11	2.88	5.04	6.76	3.13	3.16
Cs	1.30	3.50	3.10	2.60	3.00	3.50	2.80	3.60	2.00	2.66	2.66
F/F+M	0.78	0.74	0.69	0.72	0.83	0.71	0.81	0.76	0.72	0.74	0.82
K/Sr	0.49	0.43	0.56	0.20	0.42	0.16	0.38	0.31	0.25	0.25	0.86
K/Rb	296	266	278	300	239	204	266	306	268	302	252
K/Ba	42.0	33.8	30.6	24.6	31.8	22.5	35.5	27.0	38.1	28.6	41.9

plex published by Bagdasaryan et al. (1992). Nine Rb/Sr analyses of WR samples were done from various types of granitoids and ortho-gneisses. The authors calculated for these rocks the isochron with parameters corresponding to the age: t = 361±10 Ma, the initial ratio $^{87}Sr/^{86}Sr$ - I_{Sr} = 0.70627 + 0.00022, with a MSWD = 4.71. The authors (l.c.) interpreted these data as the age of the main pluton intrusion, the protolith being of mantle-palingenic origin. Since the authors (l.c.) used a different rock type classification, we re-classified their rock samples according to the classification scheme used in this work, on the basis of their occurrence in the field and the mineral and chemical composition. These are the whole-rock analyses of samples Nos. 4 (VFMa-4, ST), 3 (VFMa-3, KGD), 6 (VFMa-6, LLG), 1 (VFMa-1, LLG), 2a (VFMa-2a, LLG), 2b (VFMa-2b, LLG). The samples Nos. 5 and 44 (in our opinion, and in the opinion of the above authors, l.c., they are ortho-gneisses) were, because they are not co-magmatic with the rest of the rock types, excluded from further interpretations.

In this way we obtained the basic material for further interpretations, including Rb/Sr data on sixteen whole-rock samples (of them, 2 ST, 5 KGD, 5 LG, 4 LLG) and four biotite and four muscovites, see Tab. 2.

The analytical data were divided into two groups (LLG + "pre-existing body"), according to genetic criteria (see above) and we calculated for them the isochron data listed in Tab. 3. Tab. 4 shows mineral-WR two-point isochrons. Graphic representation of the samples in a $^{87}Sr/^{86}Sr$ vs. $^{87}Rb/^{86}Sr$ diagram is shown in Figs. 2 and 3.

From Table 3 it follows that we obtained relatively ambiguous results. Twelve WR samples of a "pre-existing granitoid body" (ST, KGD + LG) display an "isochron" age of 421 Ma. Mineral isochrons (WR-Bi-Mu) from the same rocks vary in the range 335-342 Ma, which is consistent with the isochron (WR) for all rock types of ST, KGD, LG and LLG. A limited number of samples (n = 5) of a single lithological type (KGD, LG) display "pseudo-isochrons" with ages about 500 Ma.

Discussion

Tab. 2 and Figs. 2 and 4 show that Rb/Sr data are partly dispersed, reflecting genetic aspects of the formation of the "pre-existing, relatively older body", without a perfect homogenization (enabling to preserve the zoned structure), and the age difference between the LLG and the relatively older body. This situation may be interpreted in several ways:

1 — granitoid rocks of the "pre-existing body" were melted and emplaced 420 Ma ago and then 340 Ma ago LLG was intruded into them, causing the heating (300-400 °C) of the older pluton and "opening", or resetting, of the Rb/Sr system in micas, and — subsequently — the massif cooled.

2 — the whole pluton melted and was emplaced into upper parts of the crust 420 Ma ago, it was thermally "conserved", or it cooled only minimally, and it was only 340 Ma ago that it cooled below 400 °C.

3 — the Veľká Fatra granitoid pluton is an imperfectly homogenized mixture of several anatectic melts, with different source composition, mixing and rapid cooling 340 Ma ago. The source of ST, KGD and LG were older magmatic rocks displaying an "inherited" isochron, with an apparent age of

Table 2: Rb/Sr analytical data of whole rock, biotite and muscovite samples from Veľká Fatra Mts. The samples marked with "*" are taken from Bagdasaryan et al. (1992). Using symbols: AS — analysed specimen, WR — whole rock, Bi — biotite, Mu — muscovite, bT — biotite tonalite, bmG — biotite-muscovite granite etc.

No.	Sample	Type	Rock	AS	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
1	VF-356	ST	bT	WR	91	563	0.4330 ± 0.0042	0.70824 ± 0.00021
2	VF-356	ST	bT	Bi	-	-	42.7130 ± 0.4271	0.90749 ± 0.00027
3	VF-135	KGD	bGD	WR	87	438	0.5029 ± 0.0050	0.70923 ± 0.00021
4	VF-639	KGD	bGD	WR	91	365	0.5255 ± 0.0053	0.70882 ± 0.00021
5	VF-612	KGD	bGD	WR	104	341	0.8497 ± 0.0085	0.71014 ± 0.00021
6	VF-695	LG	bGD	WR	90	357	0.8551 ± 0.0086	0.70991 ± 0.00021
7	VF-40	LG	bmG	WR	109	224	1.2636 ± 0.0126	0.71357 ± 0.00021
8	VF-40	LG	bmG	Mu	-	-	48.2620 ± 0.4826	0.94235 ± 0.00028
9	VF-43	LG	mbG	WR	110	259	1.3838 ± 0.0138	0.71359 ± 0.00021
10	VF-43	LG	mbG	Bi	-	-	95.2580 ± 0.9526	1.18164 ± 0.00035
11	VF-43	LG	mbG	Mu	-	-	56.6870 ± 0.5669	0.97631 ± 0.00029
12	VF-45	LG	mbG	WR	101	181	1.3587 ± 0.0136	0.71370 ± 0.00021
13	VF-45	LG	mbG	Bi	-	-	91.9139 ± 0.9191	1.09553 ± 0.00033
14	VF-45	LG	mbG	Mu	-	-	55.3520 ± 0.5532	0.97512 ± 0.00029
15	VF-385	LG	bmG	WR	111	294	1.0580 ± 0.0106	0.71199 ± 0.00021
16	VF-229	KGD	mbG	WR	118	282	1.0317 ± 0.0103	0.71341 ± 0.00021
17	VF-229	KGD	mbG	Bi	-	-	67.8350 ± 0.6783	1.02322 ± 0.00031
18	VF-229	KGD	mbG	Mu	-	-	46.0830 ± 0.4608	0.93515 ± 0.00028
19	VFMa-4*	ST	bT	WR	103	546	0.5450 ± 0.0080	0.70896 ± 0.00006
20	VFMa-3*	KGD	mbG	WR	85	320	0.7680 ± 0.0120	0.71036 ± 0.00007
21	VFMa-6*	LLG	mbG	WR	113	190	1.7290 ± 0.0260	0.71573 ± 0.00013
22	VFMa-1*	LLG	bmG	WR	103	177	1.6920 ± 0.0250	0.71520 ± 0.00016
23	VFMa-2a*	LLG	bmG	WR	100	148	1.9140 ± 0.0290	0.71512 ± 0.00012
24	VFMa-2b*	LLG	bmG	WR	100	154	1.9100 ± 0.0290	0.71499 ± 0.00013

Table 3: Rb/Sr isochron ages for different combinations (WR, Bi, Mu) samples, calculated on the basis of genetic criteria (see in text) from analytical data — Tab. 2.

No.	Isochrone from samples	Age (Ma)	I_{Sr}	ΣCHI^2	MSWD
1	VF-43 WR, Bi, Mu	342.1 ± 2.5	0.70684 ± 0.00023	3.34	5.2
2	VF-45 WR, Bi, Mu	318.0 ± 2.3	0.70761 ± 0.00023	9.57	38.8
3	VF-229 WR, Bi, Mu	335.7 ± 2.5	0.70850 ± 0.00023	4.10	7.4
4	WR: VFMa-3, 4, VF-40, 43, 45, 135, 229, 356, 385, 612, 639, 695 n=12 (All WR samples without LLG type)	421.3 ± 11.2	0.70571 ± 0.00012	2.91	3.3
5	WR: VF-40, 43, 45, 385, 695 n=5 (WR samples LG type only)	502.7 ± 35.7	0.70407 ± 0.00060	1.87	2.1
6	WR: VFMa-3 VF-135, 229, 612, 639 n=5 (WR samples KGD type only)	497.3 ± 34.4	0.70501 ± 0.00037	4.10	5.5
7	WR: VF-40, 43, 45, 135, 229, 356, 385, 612, 639, 695 VFMa-1, 2a, 2b, 3, 4, 6 n=16 (All WR samples)	341.9 ± 4.5	0.70649 ± 0.00007	4.30	4.2
8	WR: VFMa 1, 2a, 2b, 3, 4, 6, VF-135, 385, 612, 639, 695; VF-40 WR, Mu, 43, WR, Bi, Mu, 45 WR, Mu, 229 WR, Bi, Mu, 356 WR, Bi (All mineral and WR samples) n=23	339.7 ± 1.3	0.70652 ± 0.00004	3.77	3.8

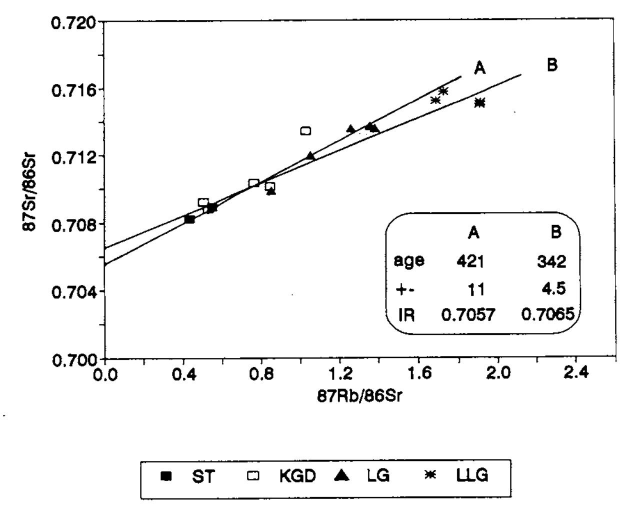

Fig. 2. Whole rock Rb/Sr isochron plot of the Veľká Fatra Mts. Line A calculated for "pre-existing body" (ST-KGD-LG), line B computed from all samples (ST-KGD-LG+LLG). Symbols as are marked in box.

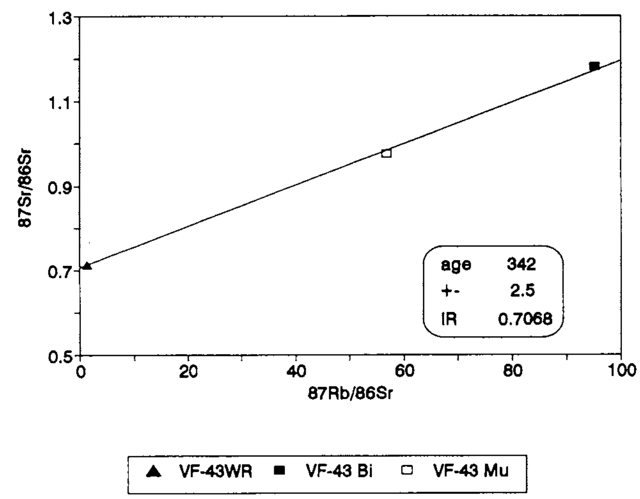

Fig. 3. Mineral isochron plot (WR-Mu-Bi) of the sample VF-43. Isochron from all WR-Mu-Bi analysed samples of Lipová granite type displays identical time relations.

420 Ma. In contrast to this, the source of the leucogranites could have been metamorphosed pelitic rocks.

4 — it is possible to interpret the isotope data in the sense of older opinions on the co-magmatic origin of LLG with other granitoid types of the Veľká Fatra Mts. In this case, the isochrons 7 and 8 would be valid, according to which all WR and mineral fractions are fitting the isochron with the age of 340 Ma, with I_{Sr} = 0.7065. This would mean that this differentiated, but not homogenized pluton cooled to below 300 °C immediately after its emplacement.

Ľubochňa leucogranites

Field observations clearly show that the younger leucocratic granites (LLG) were emplaced along tectonic lines into a relatively older body, composed of ST, KGD and LG. From the petrographic viewpoint these felsic LLG differ from other granitoid types mostly by the absence of altered basic cores of plagioclases Plg I (typical for other 3 types), enclosed in Plg II. Albite is predominant in the leucogranites, together with a slightly sericitised acid oligoclase. On the basis of chemistry, the leucogranites may be compared to the collision granitoids (Kohút 1994), e.g. from southern Armoricum (Vidal et al. 1984), or the Himalayas (France-Lanord & Le Fort 1988). This is supported by the increased Rb, Y, Nb, Ta and U contents, the decreased Sr, Ba, Th contents and the low Sum REE contents, see average LLG values in Tab. 1. LLG also differ considerably from other granitoid types in their physical properties, especially magnetic susceptibility and magnetic polarisation (NRMP). The leucogranites are non-magnetic, while e.g. ST have an increased magnetic susceptibility, up to Kappa κ = 3000 × 10^{-6} SI u., thus representing the transition between the magnetite and ilmenite series after Ishihara (1977). On the basis of these data we assume that LLG are not co-magmatic with the suite of other granitoids of the Veľká Fatra Mts., composing the zoned body. We do not assume that they are the final product of the differentiation of Hercynian calc-alkaline granitoid rocks of the Western Carpathians (and thus the conclusion of a differentiation sequence), as they were usually considered to be in the past. Quite to the con-

Table 4: Two-point isochrons (WR — mineral).

Sample	Age (Ma)	
	Muscovite	Biotite
VF-40	342.0 ± 3.6	-
VF-43	333.8 ± 3.5	350.3 ± 3.6
VF-45	340.3 ± 3.5	296.3 ± 3.0,
VF-229	345.8 ± 3.6	325,8 ± 3.3
VF-356	-	331.0 ± 3.5

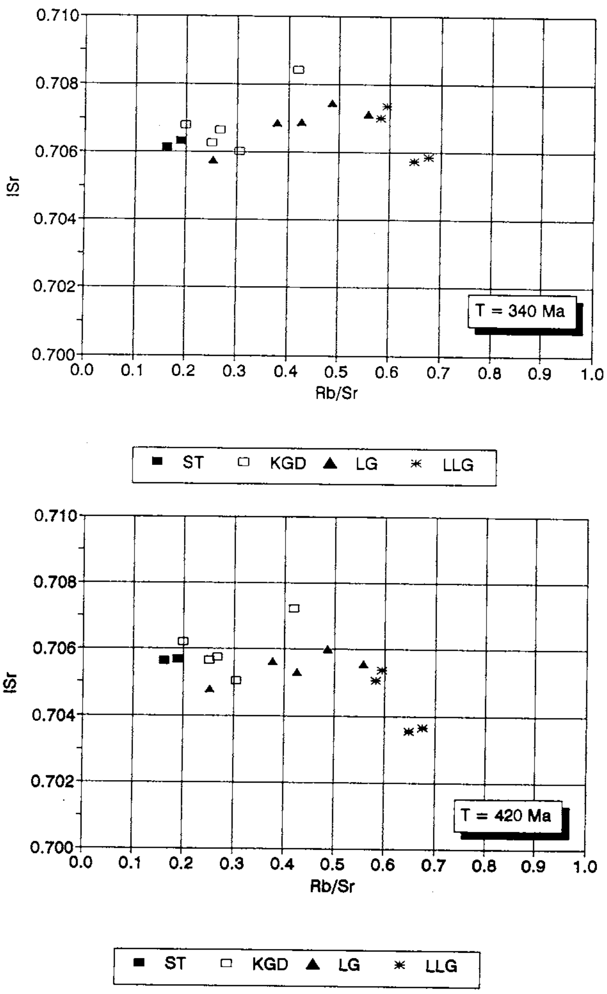

Fig. 4. Diagram I_{Sr} vs. Rb/Sr documenting isotope system conditions: **A** — 340 Ma ago resp. **B** — 420 Ma ago. Studied samples show better correlation in the older time horizon.

trary, we consider them to be typical leucogranites, a product of partial anatexis associated with the tectonic crustal thickening in the transpressive collision orogeny. The melting of leucogranites occurred in the middle crust, between the heated upper and the cooler lower colliding units. The LLG were emplaced into the upper parts of the crust during the extension at the end of the Variscan orogeny.

Isotopic homogenization

Magmatic processes in general are producing initial isotopic homogeneity. However, magmas derived from anatectic melts do not always have a homogeneous Sr-isotope distribution (Hradetzky & Lippolt 1993). The disturbance of isotope homogeneity is caused, among other phenomena, by metamorphism and by post-magmatic alteration (hydrothermal), or by weathering.

The situation in the isotope system 340 Ma and 420 Ma ago is shown by the diagram $^{87}Sr/^{86}Sr$ vs. Rb/Sr in Fig. 4 A, B. The interval of the values $^{87}Sr/^{86}Sr_{(340)}$ = 0.7058-0.7084 is intermediary, it indicates a relatively balanced situation in the crust, without juvenile (new) products of mantle magma. The projection points of the samples are at a slight angle, which may be interpreted as incomplete mixing between the two end members, and in this case all granitoid types would be Variscan. We do not assume total homogenization of the Rb/Sr isotope system for the whole granitoid body, we allow only for the homogenization of the Rb/Sr system on a local scale and re-equilibration for mineral phases, indicated by (WR, Mu, Bi) isochrons.

In the "earlier time — 420 Ma ago" we do not suppose the existence of LLG. Apart from one sample of KGD (VF-229), the values of the $^{87}Sr/^{86}Sr_{(420)}$ lie in a narrow span of 0.7048-0.7062, creating an aclinal sphere, representing the normal accumulation of the radiogenic ^{87}Sr, and thus they form an isochron. Whole-rock samples representing rock types of the "older, pre-existing body" (ST, KGD, LG) form an "isochron" (No. 4, Tab. 3) with the age 421 + 11 Ma, I_{Sr} 0.7057. The studied samples in this time range display the best correlation, leading us to assume isotopic WR homogenization of the pre-existing crystalline block in the time 420 Ma ago, and from the point of view of Hercynian anatectic processes we consider this "isochron" to have been inherited. A problem typical for the Western Carpathians is the "ageing" of isochron ages of granitoid rocks (Kráľ 1992, 1994). This phenomenon has been otherwhere called "inherited isochrons" (Roddick & Compston 1977; Field & Räheim 1979; Pin 1981). The apparent ages of these "isochrons" often do not have a geological meaning and these "inherited isochrons" are explained by the authors as mixing or contamination of granitoid magma with the surrounding rocks. In some cases, when complete regional strontium homogenization did not take place, these "isochrons" indicate thermal events in the earlier times. Similar "inherited isochrons" have been recorded in other core mountain ranges, e.g. in the Strážovské vrchy Mts., and Tatry Mts. In the Strážovské vrchy Mts., WR give an "isochron" age of 393 Ma (Kráľ et al. 1987), while mineral isochrons (WR-Mu-Bi-Plg) show an isochron age of 311 Ma (Kráľ et al. in prep.). Data on the Tatry Mts. recalculated from the work of Burchart (1968) indicate a WR "isochron" age of 370-377 Ma, however, mineral isochron ages vary in the range 306-327 Ma, which is consistent with the Ar/Ar ages of the cooling of the Tatry pluton according to Maluski et al. (1993) — 305-327 Ma.

Source rocks

Initial strontium isotope ratios indicate a source with lower Rb contents and a lower Rb/Sr ratio. At I_{Sr} equal approximately to 0.705 we may consider the more dominant participation of the mantle material in the origin of the "primary" (original) magma, from which the Veľká Fatra granitoids were formed. This situation is also demonstrated by the diagram of strontium isotope evolution (according to Faure & Powell 1972) in Fig. 5. The source of granodiorite-tonalites (Rb/Sr = 0.16-0.30) was rocks which were less differentiated from the

Table 5: $\varepsilon_{Nd(t)}$ data for individual granite types of the Veľká Fatra Mts. (According Kohút et al. in prep.)

CHUR\Time	ST	KGD	LG	LLG
ε^{340}_{CHUR}	-2.45	-2.07	-1.30	-3.98
ε^{420}_{CHUR}	-1.69	-1.22	-0.47	-3.47
ε^{500}_{CHUR}	-0.93	-0.37	0.36	-2.69

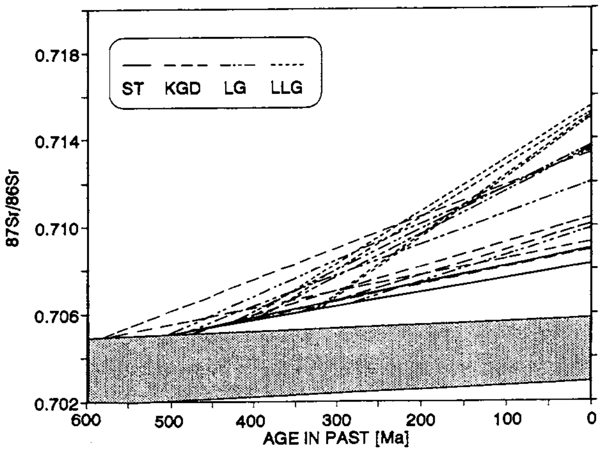

Fig. 5. The strontium evolution diagram for granitoid rocks of the Veľká Fatra Mts. The shaded area represents basalt field t.m. limits of Sr isotope content in the mantle in time dependence.

geochemical point of view and influenced by the mantle composition. Two-mica granites display a higher degree of differentiation (Rb/Sr = 0.4-0.6), but all three types together form a chemically and isotopically zoned body. The parent magma of these granitoids melted from an isotopically inhomogeneous source — a mixture of mantle and crust material, as has been pointed out also by Kráľ (1992). The processes of differentiation and contamination participated in the formation of the various types (the AFC mechanism). The present petrographic-geochemical character of the granites of the pre-existing body (the presence of calcareous cores of plagioclases + primary magmatic muscovites, zircon typology) however indicates that they are an analogue of the "recycled" crustal granitoids and they have an infra-crustal, I-type character after Chappell & Stephens (1988). The resulting mineral, chemical and isotope situation was produced by processes of crustal anatexis, which took place during the main, Hercynian collision event 350-340 Ma ago. These rocks were partially melted (but not completely re-melted!), "without considerable changes in the composition, or during the anatexis they inherited their old composition" (Chappell & Stephens l.c., p. 77). Due to the intra-continental collision, muscovite and two-mica leucogranites (LLG) were also melted, and they were emplaced along the tectonic zones into a partly solidified block (ST+KGD+LG) in the lower part of the overheated unit. However complete isotope and substance homogenization did not take place, as the massif remained zoned. LLG, as the non-fractionated crustal product, represents a migrating granite-minimum melt.

Isotope data of Sm/Nd indicated a long-lasting crustal history of these granitoids, having $\varepsilon_{Nd(0)}$ = -4.7 - -6.4 and model ages T_{DM} = 1.2-1.9 Ga, or T_{DM2} = 1.2-1.4 Ga (Kohút et al. in prep.). The correlation of the ε_{Nd} vs. ε_{Sr} values in the time horizon of 420 Ma is better than with 340 Ma, or 500 Ma (Kohút et al. l.c.). An interesting situation occurs at the age of 500 Ma, indicated by WR samples of KGD or LG, as the more felsic two-mica granodiorite-granites have a more "mantle" character than the more mafic granodiorites-tonalites (I_{Sr} = 0.70407 & 0.70501). The same situation exists in the Sm/Nd system: $\varepsilon_{Nd(500)}$ = +0.36 & -0.37, -0.93 for LG, KGD, ST, respectively, see Tab. 5 (Kohút et al. l.c.). These results indicate a higher degree of contamination by crustal material (the AFC mechanism — DePaolo 1981) at the genesis of more mafic (ST) varieties than in the crystallization of more acid (LG) types of the Veľká Fatra pluton. The problem of the isotope inhomogeneity of the source material of West-Carpathian granitoids has been discussed in detail by Kráľ (1992). This author pointed out that West-Carpathian granitoids may be considered to be the product of mixing of two sources with different $^{87}Sr/^{86}Sr$ ratio and different Sr concentration. This opinion has been confirmed in the case of the Veľká Fatra pluton, where, during the Hercynian orogeny, older magmatic rocks — the products of active continental margins with a VAG geochemical characteristic (or CAG) — were melted ("re-magmatized"), and new leucocratic granitoids were produced. However the mutual mixing of these two magmas was imperfect. Based on a limited number of isotope data we may assume that the source of leucogranites could be older metamorphosed magmatic rocks, but we do not exclude the possibility of melting of pelitic rocks according to the model of Harris & Inger (1992).

Conclusions

During the main phase of the Hercynian continental collision (340-350 Ma), in the middle part of the crust, at the boundary of the upper heated unit with the lower relatively cooler one, crustal material was melted due to partial anatexis and the Ľubochňa leucogranites were produced. In the subsequent extension (transtension), LLG were emplaced into the upper unit — into the relatively older crystalline block, which was also affected by the partial anatexis. As the pluton cooled relatively rapidly, complete substance and isotope homogenization did not occur, and thus the pluton preserved its zoned structure with intrusion of LLG.

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APPENDIX

Sample description and location.	X	Y	Z
VF-40 (LG) — two-mica granite, Vyšná Krivá ridge,	1197622.17	412257.16	1 060.0
VF-43 (LG) — muscovite-biotite granite, Vyšná Krivá hill-side,	1196930.65	412114.31	1 035.0
VF-45 (LG) — muscovite-biotite granite, Krivá Valley,	1196494.17	411500.82	949.0
VF-135 (KGD) — biotite granodiorite, Skalné Valley,	1201973.42	410391.38	1 150.0
VF-229 (KGD) — muscovite-biotite granite, Sekaniny Stream,	1201990.13	407682.18	845.0
VF-356 (ST) — biotite tonalite, Vyšná Matejkova Valley,	1200190.42	408061.99	812.0
VF-385 (LG) — biotite-muscovite granite, Nižná Lipová Valley,	1195789.38	416139.11	820.0
VF-612 (KGD) — muscovite-biotite granodiorite, Kornietov Valley,	1200189.66	416324.11	730.0
VF-639 (KGD) — biotite granodiorite, Blatná Valley,	1198772.91	414769.84	742.0
VF-695 (LG) — biotite granodiorite, Vyšná Lipová hill-side,	1196707.83	417191.15	925.0