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REE geochemistry and petrological model for the generation of Variscan granitoids in the West Carpathians

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(5 fig. and 5 tab. in the text)

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Геохимия элементов редких земель и петрологическая модель возникновения вариских гранитов Западных Карпат

Распределение элементов редких земель в основных типах вариских гранитов центральных гор и вепоридных зон Словацкого рудогория, вместе с известными фактами их геологического положения, минерального и химического состава свидетельствуют о анатектическом происхождении расплавов в коре близко континентального типа. Величина и тип „Eu“ — аномалии, хондритически нормализованный облик и распределение редких земель в основном типе (тип — I), близки по содержанию вычисленному модели анатектического расплава, которая возникла плавлением 20 % состава из секвенции метапелитов и метадроб и смешанием выплавки с избытком в пропорции 6 : 4. Метавулканиты толсиитового типа в основном не повлияли на облик распределения редких земель в генерированных анатектических расплавах.

REE geochemistry and petrological model for the generation of Variscan granitoids in the West Carpathians

REE distribution in main types of Variscan granitoids of the West Carpathian "Core Mountains" and Veporic units, together with the known features of their geological occurrences, mineral and chemical composition point to anatectic origin of melts in a crust approaching the continental type. The magnitude and shape of Eu-anomaly, the chondrite normalized pattern and distribution of rare earth elements in the main type (I) are near to the calculated model composition of the anatectic melt generated by 20 per cent fusion from a metapelite to metagreywacke sequence and by subsequent mixing of this liquid with the residue in 6 : 4 ratio. Metavolcanites of tholeiitic composition did not influence considerably the REE distribution pattern in generated anatectic melts.

The genesis of granitic melts remains a repeatedly and broadly discussed problem: arguments are advanced in favour of granite melt generation by fractional crystallization of basic magmas but also data arguing for the origin of granitic liquids by anatexis processes at the expense of metasediments or older igneous rocks (Bowen, 1924; Tuttle — Bowen, 1958; Winkler, 1965; Wyllie et al., 1976; Clemens — Wall, 1981; Muecke — Clarke, 1981 and others). Views are published now and again in favour of "exotic" ideas on the generation of mineral associations that reached granitic composition through diffusion in solid state and in fact cover the original notion proposed by Perrin — Roubault (1939), Ramberg (1944) or Walton (1960). In the recent years, the problem of origin of granitic massifs is concentrated to relations between ultrametamorphism and the generation of anatexis granitic melts within continental type of crust (Fyfe, 1970; Brown — Fyfe, 1970; Wyllie et al., 1976; White — Chappel, 1977; Nesbitt, 1977 and others). Among the recently broadly discussed questions belongs also the assessment of different geochemical character of two contrasting granitic melts (and igneous rocks consolidated from these) assigned as "I" and "S" types of granite (Chappel — White, 1974; White et al., 1976; Griffin et al., 1976; Hine et al., 1976 and others). Objections may be raised against such, frequently but mechanically meant, classification. Questions arise from the manifold repeated experience on multiple alternation of rocks having different origin in a sequence that underwent partial melting (e. g. alternation of metasediments of various geochemical maturity with volcanite or volcanoclastic layers where their proportion or the rate between the liquid and residue determines also the character of the anatexis melt). Hence the indicated subdivision has, recently, more

only geotectonic meaning.

According to the recent views, the geochemical investigation should give answers to the following questions:

- a) what was the character of the original material subject to fusion,
- b) at which ratio occurred the partial melting of this substratum and,
- c) what was the ratio of mixing (or unmixing) of the originated melt with restite after the partial fusion.

These and some further actual questions will be attempted to answer in this paper.

Main geological and petrological characteristics of Variscan granitoids of the West Carpathians

Granitoid rocks create the backbone of morphostructural units in the so called "Core Mountains" and in the Veporic zones of the Slovak Ore Mts. Their areal extent is from some tens (Považský Inovec and Žiar Mts.) to hundreds of sq. km (the High and Low Tatra Mts., Veľká and Malá Fatra Mts.) whereas the most extensive body, the massif of the Slovak Ore Mts., attains up to 80 km length and up to 30 km breadth on the surface. Recently, the radiometric dating of single massifs has been realized (Kantor, 1959a, b, 1961; Burchart, 1968; Cambel et al., 1977, 1979, 1980) and their geotectonic framework appreciated (Maheľ, 1978) but only some studies were devoted to their genetic problems (Kamenický, 1962, 1968; Hovorka, 1979, 1980, in print; Hovorka — Spišiak, in print; Vilinovič, 1981 etc.).

Several basic petrographic types have been ascertained in the limits of single bodies in the past, assigned mostly by the local name of occurrence (the "High Tatra" type as an equigranular biotite-oligoclase granodiorite, the "Prašivá" type as a porphyritic granite to granodiorite containing

mostly pink K-feldspar phenocrysts and others). Based on spatial relations and mineral composition, four main Variscan granitoid types in the West Carpathians have been distinguished and their basic geochemical and petrogenetic characterization given by Hovorka (in print). For the purposes of REE distributions, we adapt us to this subdivision (with some additions). The basic characteristics of the types distinguished is as follows.

I. *Medium-grained biotite granodiorite to tonalite* (in places with accessory to subordinate amounts of hornblende) represents the most common Variscan plutonite rock in the West Carpathians. Single varieties of it are known under local names (the High Tatra, Ďumbier, Sihla, Smrekovica, Modra and other types). As a remarkable feature, in cases when the whole plutonite body is preserved, this type occurs in central portions of massifs. Towards the margins (laterally) or the top (vertically) of the bodies, this type passes into further types distinguished.

A remarkable homogeneity of grain size and mineral composition is typical feature of this granodiorite to tonalite. Only in some ranges, a transition is observable into hybrid facies towards the margins of bodies (the Malá Fatra and Slovak Ore Mts.). The relation of massifs to their envelope is whether autochthonous or intrusive one (Hovorka, 1980).

II. *Two-mica granodiorite, frequently porphyric*, creates marginal rim facies e. g. in the massif of the Slovak Ore Mts. in its southern parts. This composition reveals, on the whole, also the Bratislava massif of the Little Carpathians.

III. *Leucocratic granite, locally even granodiorite*, occurs in typical development along the northwesternly marginal zone of the Tatra massif. The low amount of mafic minerals (mica) is characteristic feature of rock varieties ranged into the

group. Garnet and Al-silicates coexisting with further silicate minerals are contained in such granite of some mountain ranges (Žiar and Malá Magura Mts.). The rocks are fine- (under 2 mm) to coarse-grained- (over 5 mm).

IV. *Porphyric granite to granodiorite with pink K-feldspar* (the "Prašivá" type) is known from several "Core Mountains" (the High and Low Tatras, Malá and Veľká Fatra Mts.) as well as from the Slovak Ore Mts. In contradiction to former views on extensive potash metasomatism being responsible for the generation of these plutonites, a different explanation, emphasizing late magmatic processes in fact under PT-conditions of the "hypersolidus" domain, has been presented recently (Hovorka, 1979).

We would like to emphasize that there is no primary evidence as yet to distinguish several stages of the Variscan magmatic activity in the West Carpathians. The existing radiometric data, according to which the age of intrusions varies between 360 and 120 m. y., may reflect also different degrees of Alpine metamorphic recrystallization or reheating. Field observations point to gradual transitions between the type distinguished, mostly as the main one (type I) into marginal (porphyric) and, at the same time, more leucocratic types.

Analytical data

For REE analytics the single types distinguished have been chosen. Greatest attention was paid to the archetype (main type I) of granitoids (biotite granodiorite). REE analytics has been made by instrumental neutron activation method at the Institute of Raw Materials in Kutná Hora, the analyst was Dipl. Eng. Lenk. For the purposes of petrogenetic interpretation,

Tab. 1. Sample localization

HG-3 — Veľká Fatra Mts., quarry near to the Podsuchá — Smrekovica route. Fine-grained (2 mm) massive homogenous biotite granodiorite ("Smrekovica" type), H-5 — Slovak Ore Mts., Kráľova Hoľa zone, road-cut above the Podkriváň railway tunnel. Medium-grained biotite granodiorite ("Sihla" type), HG-9 — Low Tatra Mts., Dumbier zone, summit of the Dumbier Mt. Medium-grained biotite granodiorite („Dumbier" type), HG-15 — Malá Fatra Mts., Dubná quarry near Vrútky. Moderately porphyric (plagioclase), medium-grained biotite granodiorite, HG-18 — Malá Fatra Mts., northwesternly from Sútovo village. Medium-grained biotite granodiorite, GH-6 — Slovak Ore Mts., Kohút zone, quarry 1 km northernly from České Brezovo village. Medium-grained biotite-muscovite granodiorite, HG-10 — Žiar Mts., northwesternly from Malá Čausa village. Porphyric biotite-muscovite granite (white feldspar), HG-2 — Slovak Ore Mts., main range, outcrop near the route in Upper Ipeľ valley, northwestern slope of the Bykov vrch hill. Moderately porphyric muscovite leucogranite, HG-7 — Veľká Fatra Mts., Vyšná Lipová valley. Porphyric granite with red K-feldspar phenocrysts, HG-4 — Low Fatra Mts., Dumbier zone, Križianky valley. Porphyric muscovite-biotite granodiorite with porphyric K-feldspar (pink to yellowish, the "Prašivá" type), HG-14 — Slovak Ore Mts., Kráľova hoľa zone, cut on the Klenovec — Klenovský Vepor hill road, some 2 km northernly from Ráztočno settlement. Porphyric (pink K-feldspar) muscovite-biotite granite, HG-12 — Low Tatra Mts., Dumbier zone, Trangoška locality, small quarry near the road. Muscovite leucogranite from a strongly migmatized belt, HG-17 — Low Tatra Mts., Dumbier zone, Magurka settlement. Pink coarse-grained pegmatitic granite to pegmatite with low content of mica, HG-13 — Slovak Ore Mts., Kohút zone, Chorepa locality, quarry near the Kokava nad Rimavicou — Hnúšťa road. Nebulitic migmatite with palimpsestic preferred orientation of biotite. The composition is that granite (white feldspar).

Tab. 1. Lokalizácia vzoriek

HG-3 — Veľká Fatra, lom pri ceste Podsuchá — Smrekovica. Jemnozrnný (2 mm) masívny homogénny biotitický granodiorit (typ Smrekovica), HG-5 — Slovenské rudohorie, kráľovohoľské pásmo — zárez cesty nad železničným tunelom pri Podkriváňi. Strednozrnný biotitický granodiorit (typ Sihla), HG-9 — Nízke Tatry, dumbierske pásmo — vrchol Ďumbiera. Strednozrnný biotitický granodiorit (typ Ďumbier), HG-15 — Malá Fatra — lom Dubná Skala pri Vrútkach. Nevýrazne porfyrikový (plagioklas) strednozrnný biotitický granodiorit, HG-18 — Malá Fatra — na SZ od Sútova. Strednozrnný biotitický granodiorit, HG-6 — Slovenské rudohorie, kohútske pásmo. Lom 1 km na S od Českého Brezova. Biotiticko-muskovitický strednozrnný granit HG-10 — Žiar, na SV od Malej Čausy. Porfyrikový biotiticko-muskovitický granit (biele živce), HG-2 — Slovenské rudohorie, hlavný hrebeň, východ pri ceste v dol. horného Ipeľa, severovýchodný svah Bykovho vrchu. Nevýrazne porfyrikový muskovitický leukogranit, HG-7 — Veľká Fatra — dol. Vyšná Lipová. Porfyrikový granit s červenými porfyrikými K-živcami, HG-4 — Nízke Tatry, dumbierske pásmo, dol. Križianky. Porfyrikový muskoviticko-biotitický granodiorit s porf. K-živcami (ružové, resp. žltkasté, typ Prašivá), HG-14 — Slovenské rudohorie, kráľovohoľské pásmo, zárez cesty Klenovec — Klenovský Vepor, asi 2 km na S od osady Ráztočné. Porfyrikový (ružové K-živce) muskoviticko-biotitický granit, HG-12 — Nízke Tatry, dumbierske pásmo, Trangoška, malý lom pri ceste. Muskovitický leukogranit zo zóny intenzívnej migmatizácie, HG-17 — Nízke Tatry, dumbierske pásmo, Magurka. Hrubozrnný pegmatitický granit až granitický pegmatit ružovej farby s nízkym obsahom sfly, HG-13 — Slovenské rudohorie, kohútske pásmo, lom pri kóte 555 (Chorepa) na ceste Kokava nad Rimavicou — Hnúšťa. Nebulitický migmatit s palimpsestnou prednostnou orientáciou biotitu. Zložením zodpovedá biotitickému granitu (biele živce)

Tab. 2.

Sample locality and description as in Tab. 1. Eu/Eu⁺ — chondrite normalized Eu content divided by the value of Eu obtained by extrapolation between Sm and Gd (Eu⁺).

Opis a lokalizácia vzoriek ako v tab. 1. Eu/Eu⁺ = chondriticky normalizovaná hodnota Eu delená hodnotou pre Eu/Eu⁺ získanou extrapoláciou medzi Sm a Gd (príp. Tb)

Chemical composition of West Carpathian granitoids
Chemické zloženie granitoidov Západných Karpát

Tab. 1

	HG-3	HG-5	HG-9	HG-15	HG-18	HG-6	HG-10	HG-14	HG-2	HG-4	HG-7	HG-12	HG-17	HG-13
SiO ₂	66,25	66,33	67,71	68,86	68,64	72,39	70,85	73,92	72,44	68,53	72,10	74,71	74,61	73,88
TiO ₂	0,93	0,62	0,49	0,48	0,35	st.	0,20	0,39	0,25	0,33	0,35	0,06	0,11	0,26
Al ₂ O ₃	16,19	15,88	15,14	15,03	17,62	16,17	15,55	13,11	14,04	16,18	13,77	14,28	13,05	13,42
Fe ₂ O ₃	1,28	3,00	0,03	1,35	1,60	0,11	1,41	1,54	0,59	1,12	2,24	0,65	0,70	1,66
FeO	2,98	1,43	4,42	1,86	1,79	1,29	0,81	0,16	0,75	1,62	0,14	0,13	0,12	0,86
MnO	0,04	0,08	0,09	0,17	0,22	0,03	0,02	0,04	0,09	0,06	0,03	0,03	0,02	0,03
MgO	1,48	2,74	2,00	1,22	0,97	0,39	0,49	0,79	0,75	0,97	0,66	0,31	0,31	0,72
CaO	3,16	1,09	2,77	3,42	3,10	1,36	1,79	1,98	2,24	1,94	1,32	0,49	0,78	2,17
Na ₂ O	4,14	5,67	3,37	3,77	2,95	3,68	4,29	3,51	3,76	3,60	3,65	3,34	3,71	3,29
K ₂ O	2,57	2,05	2,95	2,63	1,59	4,73	2,89	3,19	3,03	4,42	4,50	4,39	5,58	2,18
P ₂ O ₅	0,12	0,17	0,46	0,09	0,55	0,11	0,12	0,06	0,15	0,31	0,13	0,09	0,05	0,18
H ₂ O ⁻	0,04	0,10	0,10	0,02	0,02	0,05	0,11	0,15	0,04	0,20	0,10	0,17	0,09	0,21
H ₂ O ⁺	1,10	1,07	0,63	0,61	0,78	0,57	0,72	0,86	1,40	0,31	0,91	0,99	0,53	0,80
total:	100,33	100,23	100,20	99,51	100,18	100,93	99,25	99,70	99,75	99,95	99,90	99,64	99,66	99,66
type:	I	I	I	I	I	II	II	III	III	IV	IV	V	V	VI

REE content of West Carpathian granitoids
Obsah vzácnych zemin v granitoidoch Západných Karpát

Tab. 2

	HG-3	HG-5	HG-9	HG-15	HG-18	HG-6	HG-10	HG-2	HG-7	HG-4	HG-14	HG-12	HG-17	HG-13
La	25	33	51	38	27	25	28	15	13	29	32	8	4,4	37
Ce	68	83	120	83	68	59	65	41	29	73	77	14	10	90
Nd	33	46	62	45	43	33	19	25	18	38	36	—	6,5	45
Sm	5	6	8,9	6,1	5,1	5,7	4,2	3	2,7	7	6,4	0,91	1,17	8
Eu	1,5	1,8	1,8	1,26	1,21	0,75	1,11	1	0,78	1,3	0,89	0,97	0,66	0,95
Gd	5,5	7,0	—	10	—	4	4	—	3,2	—	5	—	—	10
Tb	0,6	0,65	2,2	0,67	0,4	0,8	0,61	0,1	0,22	1,2	0,71	0,44	0,18	0,37
Tm	0,1	0,2	—	0,34	0,10	0,06	0,15	0,05	0,09	—	0,18	—	0,10	0,2
Yb	0,75	1,45	3,00	2,1	0,92	1,14	0,94	0,5	0,49	1,0	1,47	2,12	0,56	1,25
Lu	0,1	0,14	0,30	0,26	—	0,12	0,11	—	0,05	—	0,17	—	—	—
Suma TR	139,55	179,24	249,20	186,73	145,78	129,57	123,12	85,65	67,53	150,50	159,82	26,44	23,57	192,77
Eu/Eu ⁺	0,84	0,84	0,55	0,70	0,89	0,46	0,80	1,30	0,80	0,58	0,48	2,39	1,78	0,48
Type	I	I	I	I	I	II	II	III	III	IV	IV	V	V	VI

also the hitherto published analytical data on main and trace elements in West Carpathian granitoids (data from Cambel — Medved' 1981, Hovorka in print) have been utilized together with REE concentrations in metabasites and dioritic rocks of the West Carpathians given by Cambel — Spišiak (1979), Hovorka — Spišiak (unpublished data).

Interpretation of results and discussion

The sample set investigated has been divided into six groups according to petrographic and geochemical criterions. Over the four groups of granitoid types distinguished and characterized by Hovorka (in print), a further group (type V) of leucogranites has been discerned that did not originate by differentiation processes and, by its composition, represents probably a metatect (?). Such rock types are usually assigned as "granitic vein" (Price — Taylor 1977). A further particular group investigated are the migmatite to migmatitic granite samples (group VI). The main element composition together with selected trace element contents are in Tab. 1 and 2. For a genetic interpretation, the normalized REE distribution pattern of single analyses (figs. 1a — d) or the normalized pattern for average composition of types distinguished (fig. 2) were used. Analytical data are normalized according to Nakamura (1974) and Masuda (1975). Single curves from the whole set and also within partial groups reveal certain variations. These may be induced namely by

- different mineral composition,
- different degree of differentiation (frac-

- tional crystallization),
- different degree of alteration, or,
- heterogeneity of the source material.

The evaluation of the normalized REE distribution patterns allows the following deductions.

1. Out of the group V, a pronounced light REE enrichment in relation to chondrite contents is detectable in all groups of Variscan granitoids distinguished in the West Carpathians. The heavy REE enrichment in relation to contents in chondrites is less remarkable.

2. The size of the negative Eu-anomaly is different for single groups. Unlike is the position of the group V where a pronounced positive Eu-anomaly appears quite well ($\text{Eu}/\text{Eu}^+ = 2.1$).

3. A well expressed tendency of decreasing REE content was proved for the groups I—IV depending on increasing acidity of rocks (tab. 1, 2 and 3).

4. Due to conventional limits between single types (facies) also the differences in REE contents are not well expressed however unambiguously discernible.

5. The normalized REE distribution pattern in the main (I) and "autometamorphic" (IV) type of granitoids are very similar what points to their generation from a common melt at different stages of development.

6. The chondrite normalized REE distribution pattern of the group V is completely different from other groups and conforms the pattern in "granitic veins" (Price — Taylor, 1977) or in metatects composing, together with complementary biotite "schlieren" (selvage), the migmatites.

The REE distribution pattern of the main type of granitoids (type I) has been

Fig. 1b. Normalized REE distribution pattern in West Carpathian two-mica granodiorites (type II). Numbers of analyses as in tab. 2

Obr. 1b. Normalizovaný diagram distribúcie vzácnych zemín v dvojsľudných grano-dioritoch (typ II) Západných Karpát; čísla analýz zodpovedajú označeniu v tab. 2

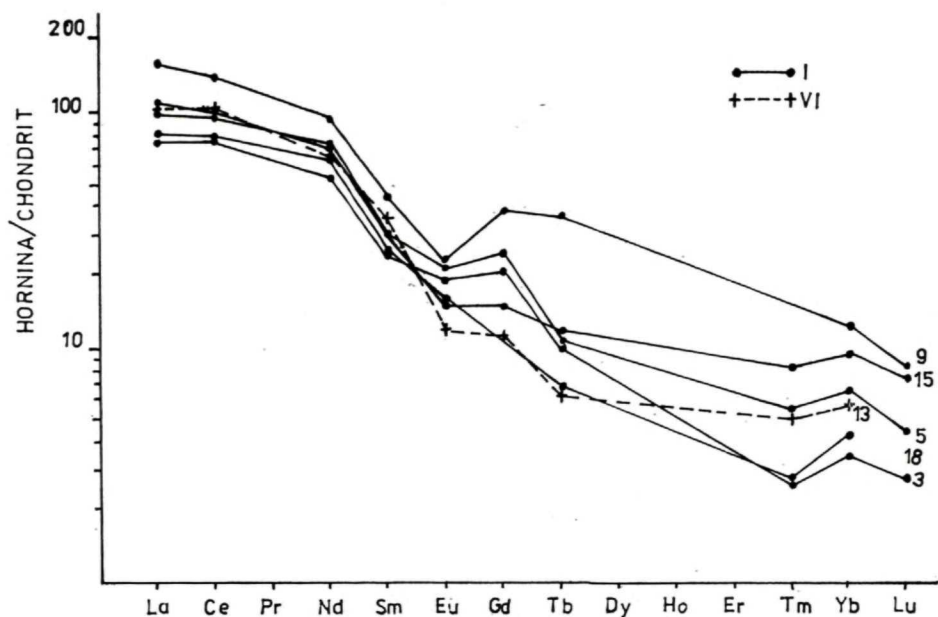
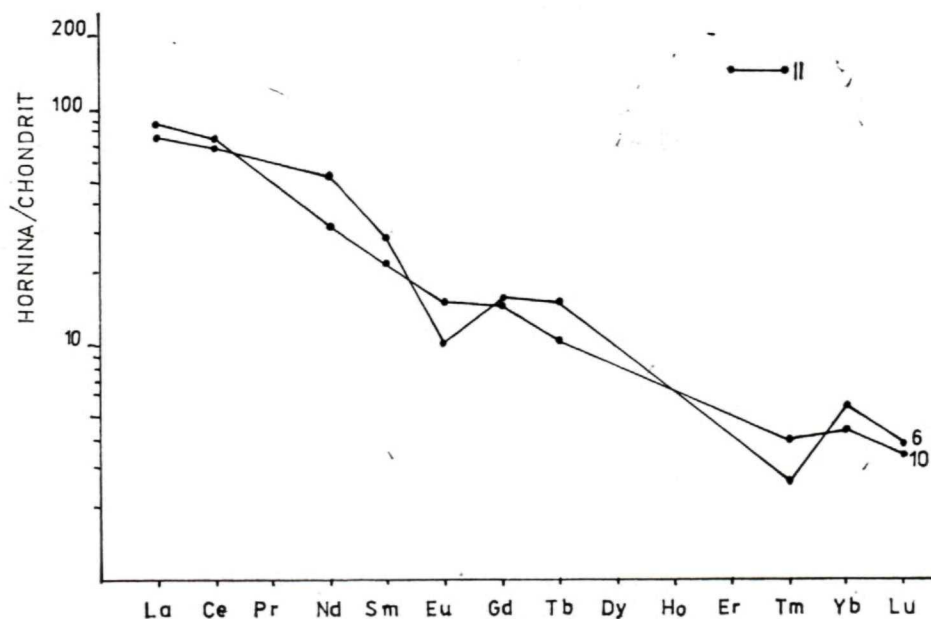


Fig. 1a. Normalized REE distribution pattern in the main type of West Carpathian granitoids (type I) and in migmatites (type VI). Numbers of analyses as in tab. 2

Obr. 1a. Normalizovaný diagram distribúcie vzácnych zemín v základnom type granitoidov Západných Karpát (typ I) a migmatitoch (typ VI); čísla analýz zodpovedajú označeniu v tab. 2



compared with patterns obtained for different granitoid types and also with the REE distribution in sedimentary rocks (fig. 3, 4). According to the normalized REE distribution, the West Carpathian Variscan granitoids have patterns similar to calc-alkaline magmatites of the granite series. In the case of light REEs, the normalized distribution pattern is similar to that in various granitoid types compared or also to the pattern in European Paleozoic Shales (Haskin — Haskin 1966). The distribution curve deviates but in the domain of heavy REEs where the European Paleozoic Shales and the peraluminous granitoids of the South Mountain Batholith (Nova Scotia) are enriched whereas the unaltered granites of SE England are depleted in relation to the West Carpathian granitoids (type I). A very similar normalized REE distribution appears in "Koetong" granites of Southwestern Australia which, according to very detailed geochemical investigations by Price — Taylor (1977), were assigned as S-type according to the Chappel — White's (1974) classification.

For the sake to better emphasize the differences in REE distribution, a normalized REE distribution path was plotted using the REE content in European Paleozoic Shales (Haskin — Haskin, 1966) and in "Koetong" granites as the normalizing factor (fig. 5a, b). It must be emphasized that the European Shales have REE distributions very similar to that of the North American Shale Complex of Lower Paleozoic age (Haskin et al., 1968) considered usually to represent the prototype of REE distribution in evolved (mature) continen-

tal crust. The plot points to similarity of REE contents in European Paleozoic Shales when only the heavy REEs are somewhat enriched in the latter. The heavy REE depletion in West Carpathian granitoids (if compared with the European Shales) may signalize partial fusion of a source material where the refractory residue contains higher amounts of heavy REEs (garnet, pyroxene, apatite etc.) and has been left behind as a restite in the zone of anatexis.

Based on petrography, main element geochemistry and REE distribution pattern in Variscan granitoids of the West Carpathians but also assuming the hitherto published REE concentrations in silicates and accessories of the respective rocks, the genesis of granitoids may be interpreted as the result of, mainly, following processes.

a) Partial melting of metamorphosed supercrustal sequences in the zone of anatexis. Simultaneously, this model supposes a subsequent contamination of the anatectic melt by restite.

b) Anatexis of basic rocks as garnetiferous amphibolite, eclogite etc.

Despite to the first model assumed formerly to represent the leading process that creates crustal melts of granite composition, yet the pronounced Eu-anomaly proved in most of granitoids generated in continental crustal conditions makes intricate this simple model. Such origin is possible only in case of fractional crystallization of feldspars (as main carriers of Eu) and their separation from the (further evolving) melt. The presence of at least two generations of some accessory minerals

Fig. 1d. Normalized REE distribution pattern in leucogranites of group V. Numbers of analyses as in tab. 2, GV — normalized REE distribution curve in granitic veins (Price — Taylor 1977)

Obr. 1d. Normalizovaný diagram distribúcie vzácnych zemin v leucogranitoch skupiny V; čísla analýz zodpovedajú označeniu v tab. 2. GV — normalizovaná krivka distribúcie TR v tzv. granitovej žile (Price — Taylor, 1977)

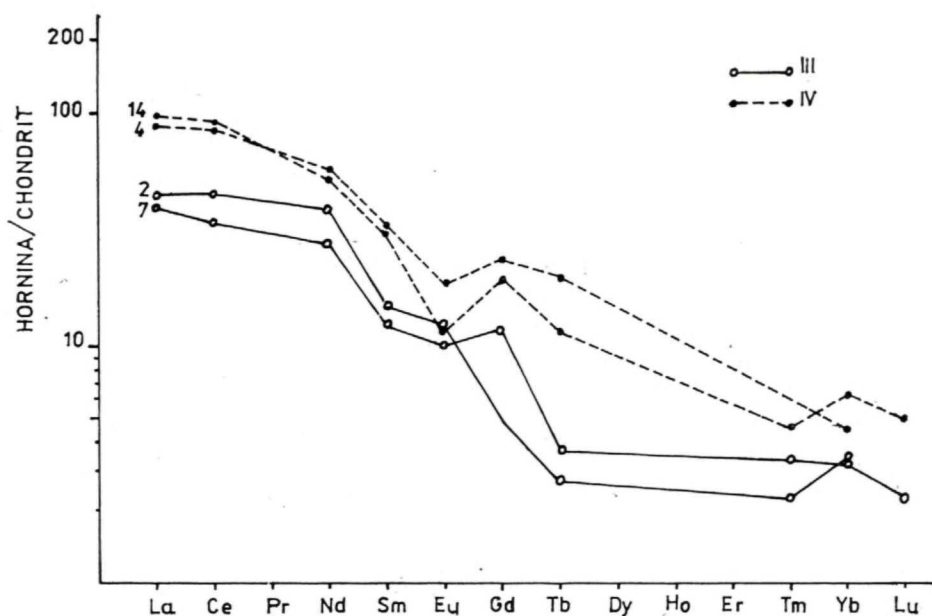
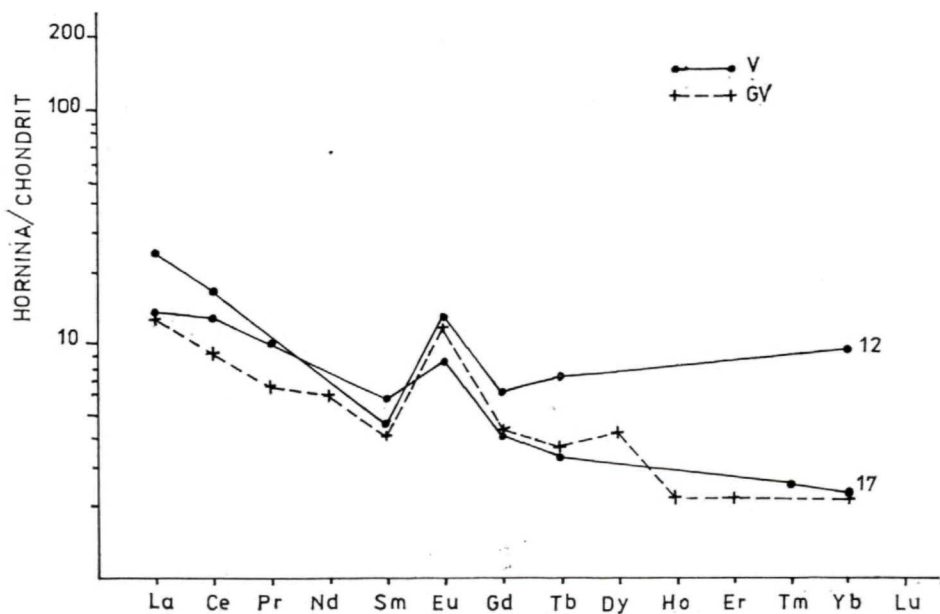


Fig. 1c. Normalized REE distribution pattern in leucocratic (type III) and the so called "autometamorphosed" granitoids (type IV) of the West Carpathians. Numbers as in tab. 2

Obr. 1c. Normalizovaný diagram distribúcie vzácnych zemín v leukokratických (typ III) a tzv. autometamorfovaných (typ IV) granitoidoch Západných Karpát; čísla analýz zodpovedajú označeniu v tab. 2



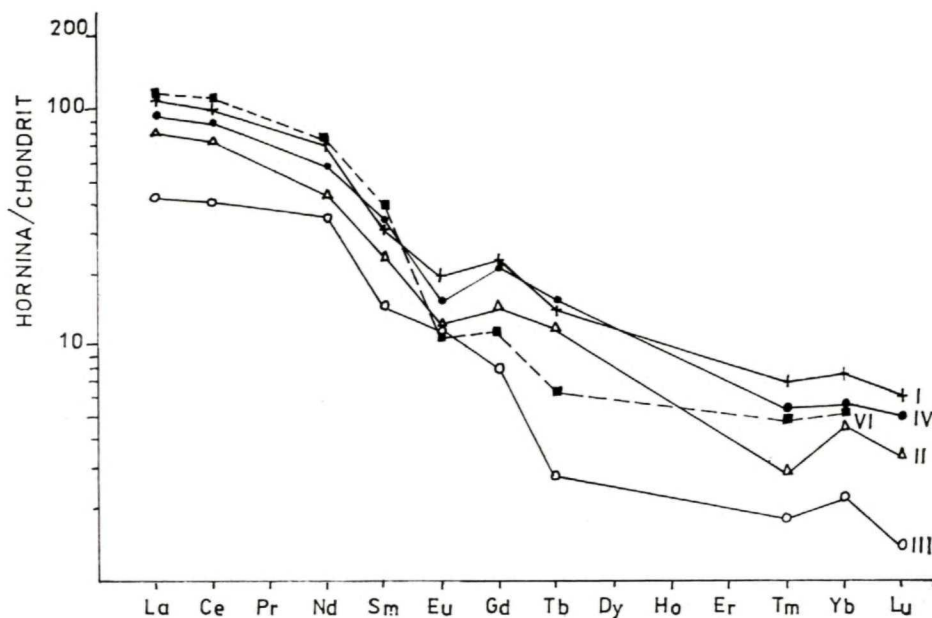


Fig. 2. Normalized REE distribution pattern in main types of granitoids of the West Carpathians (I — type I, II — type II, III — type III, IV — type IV, VI — type VI)

Obr. 2. Normalizovaný diagram distribúcie vzácnych zemin v základných typoch granitoidov Západných Karpát. I — typ I, II — typ II, III — typ III, IV — typ IV, VI — typ VI

otherwise typical for metapsammities or basic metavolcanites points to processes of this kind. Relics of metamorphites containing high amounts of biotite, biotite chambers or even two generations of biotite (Fejdi — Fejdiová, 1981) are recently known from West Carpathian granitoids. These features support the assumption that anatexic melts originated from rocks of gneissose nature. On the other hand, no facies of West Carpathian granitoids may be explained as to represent the segregated and deposited facies, composed mainly of feldspars, nor xenoliths of anchimonomineral feldspathic rocks as e. g. in the case of Mesozoic plutonites of Nigeria (Bowden et al., 1979).

For the verification of this assumption, the REE distribution in the main (I) type

of Variscan granitoids has been compared with the calculated model composition (tab. 4, fig. 4). REE contents in melts generated at different degrees of partial melting were calculated according to the method proposed by Gast (1968) and modified by Shaw (1970). The following preconditions were applied:

1) The presumed main element composition of the source material equals to the average shale (Pettijohn, 1957). There are but insignificant differences in contents of petrogenous elements between shales and greywackes recalculated to anhydrous state. The REE pattern is similar to the average one of Australian Early Paleozoic Shales (Nancy — Taylor, 1976), otherwise low geochemical maturity, and also to the average of European Paleozoic Shales

(there are no data for different kinds of West Carpathian sedimentary rocks).

2) The mineral association present immediately before the fusion was that of quartz + K-feldspar + plagioclase + biotite + garnet $\pm$ Al-silicates + accessory apatite. This precondition is substantiated by the knowledge of high-grade metasedi-

ments in the "Core Mountains" and the Slovak Ore Mts.

3) The melt originated has composition near to the ternary eutectic one in the SiO_2 — $\text{NaAlSi}_3\text{O}_8$ — KAlSi_3O_8 system (Tuttle — Bowen, 1958).

4) Distribution coefficients (Gast, 1968; Schnetzler — Philpotts, 1970; Haskin et al.,

Average composition of main West Carpathian granitoid types
Priemerné zloženie základných typov granitoidov Západných Karpát

Tab. 3

	I		II		III		IV	
	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
SiO_2	67,34	2,66	71,33	1,78	73,37	2,13	70,32	2,23
TiO_2	0,53	0,27	0,29	0,16	0,19	0,21	0,36	0,19
Al_2O_3	15,78	1,39	14,59	1,39	14,14	1,49	14,79	1,13
Fe_2O_3	1,47	0,89	1,31	0,73	0,99	0,58	1,47	0,87
FeO	2,10	0,86	1,27	0,56	0,67	0,46	1,43	0,68
MnO	0,08	0,08	0,06	0,07	0,05	0,05	0,06	0,08
MgO	1,58	0,66	1,00	0,65	0,79	0,81	1,15	0,72
CaO	3,12	0,87	1,88	0,82	1,47	0,91	2,13	0,77
Na_2O	4,01	0,89	3,65	0,71	3,69	1,36	3,61	0,65
K_2O	2,47	1,15	3,52	1,22	3,52	1,27	3,55	0,84
P_2O_5	0,26		0,16		0,14		0,15	
n =	(171)		(86)		(65)		(100)	
B	12,5		14,2		20,2		21	
Ba	1032,5		533		673		780	
Co	8,8		3		3		3	
Cr	16,5		11,4		8		16,6	
Cu	6,8		4,8		6,4		6,6	
Ni	8,4		4,1		3		4,5	
Sc	8,9		4,5		3		4,3	
Sn	5		5		5,1		5,4	
Sr	663,5		231		208		428	
V	69,3		12,6		12		36,5	
Y	21,7		15,6		7,6		10,4	
Zr	182,4		104		73,3		111	
Pb	17,5		17,9		—		—	
n =	(77)		(67)		(8)		(14)	

Contents of main element oxides taken from Hovorka (in print), that of trace elements from Cambel — Medveď (1981). The group I corresponds to the weighted arithmetic mean of diorite and gabbrodiorite, the group II to granite, the group III to values indicated for leucocratic granite whereas the group IV to autometasomatic and autometamorphic granite (all data tab. 7, p. 18 in Hovorka l. c.).

Obsah kyslíčnikov hlavných prvkov z práce D. Hovorku (v tlači). Obsah stopových prvkov z práce Cambel — Medveď (1981). Obsah v skupine I zodpovedá váženému aritmetickému priemeru skupiny dioritov a gabrodioritov, skupina II zodpovedá hodnotám granitov, skupina III hodnotám uvedeným pre leukokratické granity a skupina IV zodpovedá hodnotám uvedeným pre autometasomatické — autometamorfované granity (všetky údaje tab. 7 na s. 18, l. c.).

1980) did not change during the fusion.

5) The operation of "batch melting" (Shaw, 1970) is supposed.

In the limits of these preconditions (the same as used by Price — Taylor, 1977) we attempted to draw up models of REE and petrogenous element contents in rocks at different degrees of fusion and at various rates of liquid and residue that enter subsequently into mixtures.

Analytical data of West Carpathian granitoids (tab. 4) were compared with model compositions obtained by 20 per cent partial fusion and mixing of the liquid with residue in 6 : 4 ratio (model A) as well as

by 5 per cent partial melting of the original substratum and subsequent mixing of the liquid with residue in 3 : 7 ratio (model B). Results reveal relatively good agreement between contents of petrogenous elements and REE content for the model A (fig. 4).

It must be stressed out that even low modal quantities of accessories (e. g. 1—2 per cent of apatite or 4—5 per cent of garnet) have considerable impact on the REE distribution whereas the size of Eu-anomaly is controlled by the amount of plagioclase left in the residue (Price — Taylor, 1977).

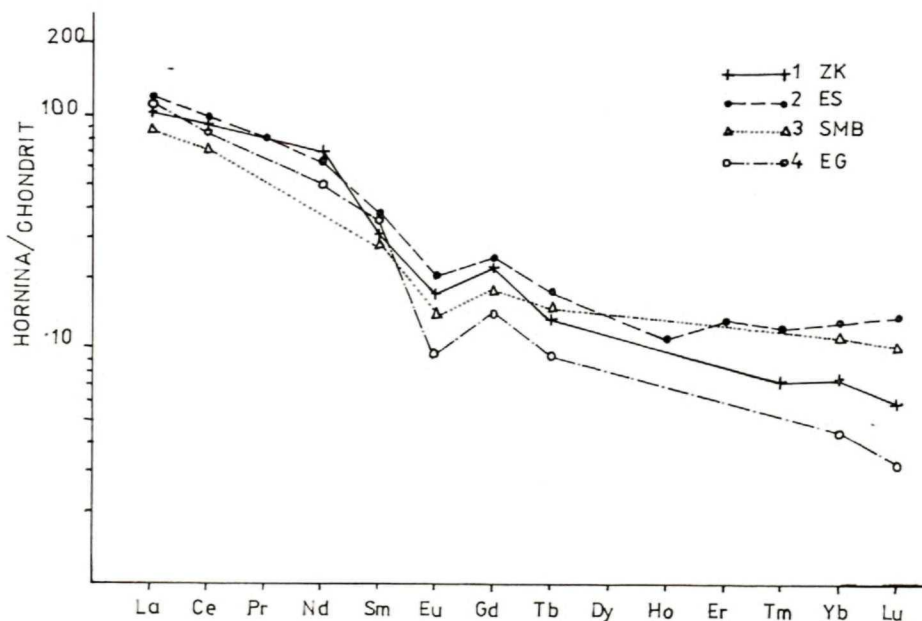


Fig. 3. Normalized REE distribution pattern in granitoids and metasediments. ZK — the main type (type I) of granitoids in the West Carpathians, ES — European Paleozoic Shales (Haskin — Haskin 1966), SMB — granitoids of the South Mountain Batholit, Lower Carboniferous, peraluminous type (Muecke — Clarke 1981), EG — unaltered granites of South-Western England (Alderton et al., 1981)
Obr. 3. Normalizovaný diagram distribúcie vzácnych zemín v granitoidoch a metasedimentoch; ZK — základný typ granitoidov (typ I) Západných Karpát, ES — európske paleozoické bridlice (Haskin — Haskin, 1966), SMB — granodiority batolitu South Mountain, spodný karbón, peraluminózne (Muecke — Clarke, 1981), EG — granity juhozápadného Anglicka, nepremenené (Alderton et al., 1980)

The verification of these models needs detailed knowledge on mineral composition and geochemistry of metamorphic complexes which may have served as source material for West Carpathian granitoids. The assessment of lithology and geochemistry of the volcanosedimentary complex within the West Carpathian crystalline may become the key to the solution of the granitoid genesis. The hitherto but sporadic data on lithology of metasediments in the West Carpathian crystalline may become key to the

original sediments were geochemically "immature" rocks of greywacke composition.

In the limits of indicated knowledge on REE contents and distribution in Variscan granitoids of the West Carpathians, their genesis (relative to the I type) is as follows. The respective rocks originated by partial anatexis of a sedimentary-volcanogenous complex containing, besides overwhelming metasediments of clastic to argillaceous nature, also metavolcanites of tholeiitic composition. The presence of the latter in

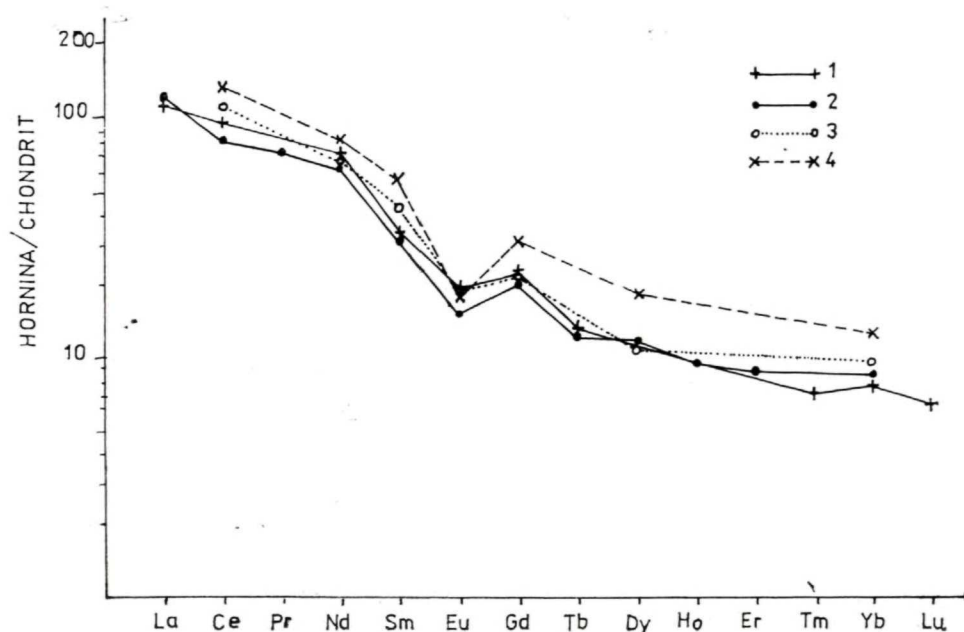


Fig. 4. Comparison between the normalized REE distribution pattern in granitoids and different models of anatectic melt composition. 1 — the main type of granitoids in the West Carpathians (type I), 2 — the "Koetong" granites of Australia, S-type (Price — Taylor 1977), 3 — model composition calculated from 20 per cent of partial melting and mixing of the liquid with residue in 6:4 ratio, 4 — model composition calculated from 5 per cent partial melting and mixing of the liquid with residue in 3:7 ratio, data for 3 and 4 in tab. 4

Obr. 4. Porovnanie normalizovaného obrazu distribúcie vzácnych zemín v granitoidoch a v rozličných modeloch zloženia anatektickej taveniny, 1 — základný typ granitoidov (typ I) Západných Karpát; 2 — granity Koetong, Austrália (S — typ, Price — Taylor, 1977), 3 — model zloženia vypočítaný 20 % parciálnym tavením priemernej bridlice pri zmiešaní výtavku so zvyškom v pomere 6:4; 4 — model zloženia vypočítaný 5 % parciálnym tavením priemernej bridlice a pri zmiešaní výtavku so zvyškom v pomere 3:7; 3, 4 — údaje v tab. 4

the anatectic zone is substantiated by occurrences of metadolerites to hornblendites transformed to various degrees by anatexis within imperfectly homogenized (mostly

marginal) portions of granitoid massifs. However, data point only to lesser influence of metabasites on the final composition of granitoids.

Calculated models of granitoid composition
Vypočítané modely zloženia granitoidov

Tab. 4

	ZK-I	model A	model B	GV
SiO ₂	68,50	71,10	67,50	89,40
TiO ₂	0,50	0,40	0,70	0,02
Al ₂ O ₃	16,00	15,20	16,50	6,00
FeO+	3,50	3,40	5,00	0,21
MnO	0,08	0,06	0,08	0,24
MgO	1,60	1,40	2,00	0,14
CaO	3,20	1,20	1,80	0,29
Na ₂ O	4,10	3,20	2,50	0,77
K ₂ O	2,50	4,00	4,00	2,91
Ce	84,40	92,30	117,40	7,70
Nd	45,80	41,60	52,80	3,70
Sm	6,20	9,10	12,00	0,90
Eu	1,51	1,5	1,40	1,00
Gd	6,25	5,70	8,60	1,10
Dy	3,60**	3,50	6,30	1,40
Yb	1,64	2,30	3,60	0,50

ZK-1 — average composition of the main type of West Carpathian granitoids, model A — calculated composition obtained by 20 per cent partial fusion of an average shale and mixing of the liquid with residue in 6:4 ratio, model B — calculated composition obtained by 5 per cent partial fusion of an average shale and mixing the liquid with residue in 3:7 ratio. The liquid corresponds, in all cases, to the minimum in the Q-Or-Ab system (Tuttle — Bowen 1958), GV — composition of granitic veins (Price — Taylor 1977), FeO+ — total iron as FeO, ** — values obtained by interpolation. All analyses recalculated to anhydrous state.

ZK-I — priemerné zloženie základného typu (typ I) granitoidov Západných Karpát; model A — model zloženia vypočítaný 20 % parciálnym tavením priemernej bridlice pri zmiešaní výtavku so zvyškom v pomere 6:4; model B — model zloženia vypočítaný 5 % parciálnym tavením priemernej bridlice pri zmiešaní výtavku so zvyškom v pomere 3:7; tavenina v obidvoch prípadoch zodpovedá minimu v systéme Q-Or-Ab (Tuttle — Bowen, 1958); GV — zloženie granitových žíl (granitic vein, Price — Taylor, 1977); FeO+ = celkové železo ako FeO; ** = hodnoty získané interpoláciou; všetky analýzy prepočítané na bezvodnú formu

Further types of granitoids (type II to IV) originated by differentiation and fractionization processes from the type I. In the case of leucogranites however other ways of their generation may be assumed relying on results presented here:

a) Leucogranites *sensu stricto* were produced by differentiation and fractionation from the main (I) type. This mode of origin is partly ascribed to rock types (bodies) ranged among the III type.

b) Leucogranites do not represent differentiation products but, probably, we are dealing with a separated phase produced at early stages of melting and producing a pronounced leucocratic metatect at the expense of substratum. The complementary type would be the biotite "schlieren" and "layers" (biotite selvage of Price — Taylor, 1977).

Rocks of this group (discerned as type V) occur mostly in marginal parts of granitoid massifs near to contacts with their mantle. Granitoids of this type have not been described hitherto in the West Carpathian literature. Their presence is, at the same time, one of proofs for the generation of granitoids by partial anatexis. To the contrary, differentiation processes may not explain the generation of such rock types.

A broadly discussed and ambiguously explained problem of West Carpathian Variscan granitoids is the genesis of granite to granodiorite of the "Prašivá" i. e. "autometamorphosed" type (type IV). As it was shown, the normalized REE distribution patterns of the type I and IV are planparallel (fig. 2). Both types are also characterized by a negative Eu-anomaly.

It has been proved recently that alkaline metals migrating in the domain of sub-

solidus autometamorphic or hydrothermal alteration are followed also by rare earths of granitoids (Bowden et al., 1979; Alderton et al., 1980 etc.). Applying this knowledge to the genesis of discussed West Carpathian granitoids one may deduce that granitoids did not generate by extensive alkaline (mostly potash) metasomatism as,

in this case, the normalized REE pattern of type IV should be completely different from that of type I. Extensive investigations of REE mobility at various kinds of alteration in granites of SW England (Alderton et al. 1980) prove the depletion of all REEs, except of Eu proved by slight or no Eu-anomaly, during the potash-sili-

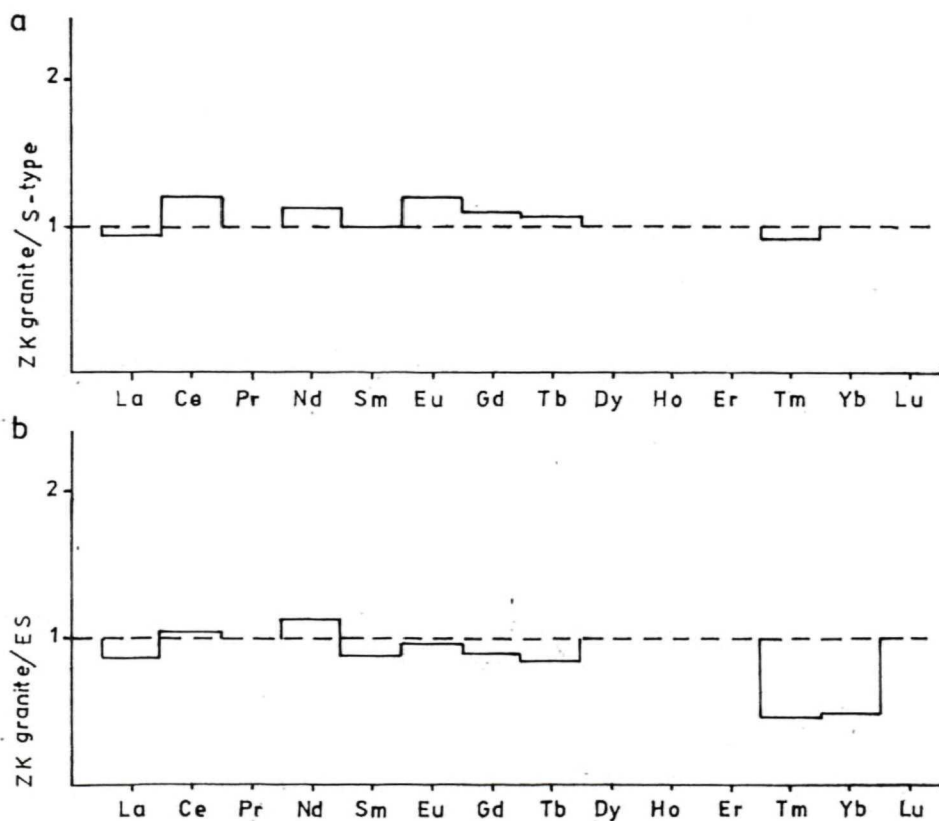


Fig. 5a. Normalized REE distribution pattern in the main type of West Carpathian granitoids (type I). The composition of "Koetong" granite, Australia (Price — Taylor 1977) taken as normalizing factor

Fig. 5b. Normalized REE distribution pattern in the main type of West Carpathian granitoids (type I). The composition of European Paleozoic Shales (Haskin — Haskin 1966) taken as normalizing factor

Obr. 5a. Normalizovaný diagram zloženia základného typu granitoidov (typ I) Západných Karpát. Ako normalizačný faktor použité zloženie granitov Koetong, Austrália. S — typ (Price — Taylor, 1977)

Obr. 5b. Normalizovaný diagram zloženia základného typu granitoidov (typ I) Západných Karpát. Ako normalizačný faktor použité zloženie „európskych paleozoických bridlíc“ (Haskin — Haskin, 1966)

cate alteration (crystallization of orthoclase at the expense of plagioclase and biotite).

Considerations on the source material for the petrogenesis of West Carpathian granitoids are hitherto based on few data. Nevertheless, setting out from the ascertained negative Eu-anomaly in their main type (I), we may conclude partly on the age of this substratum. Data from meta-sediments of various age (Archaic to Pa-

leozoic) allow the postulation of generally accepted deductions on the enrichment of archaic sediments by Eu (positive Eu-anomaly; Jakeš — Taylor, 1974; Nancy — Taylor, 1976; Lennan et al., 1980). Contents of further elements (e. g. that of K, Rb, U, Th, tab. 5) are different, too. These data support the probability that this substratum, in the case of West Carpathian granitoids, was of Early Paleozoic age.

Composition of metapsammites and granitoids of various age
Zloženie metapsamitov a granitoidov rozličného veku

Tab. 5

	ACC	PACC	ES	NASC	KG	ZK
La	12,60	30,00	41,10	32 00	36,30	34,80
Ce	26,80	64,00	81,30	73,00	69,20	84,40
Pr	3,13	7,10	10,40	7,90	10,10	—
Nd	13,00	26,00	40,10	33,00	38,60	45,80
Sm	2,78	4,50	7,30	5,70	6,20	6,20
Eu	0,92	0,88	1,52	1,24	1,20	1,51
Gd	2,85	3,80	6,03	5,20	5,40	6,25
Tb	0,48	0,64	1,05	0,85	0,80	0,90
Dy	2,93	3,50	—	5,80	4,40	—
Ho	0,63	0,80	1,20	1,04	0,80	—
Tm	0,26	0,33	0,56	0,50	—	0,19
Yb	1,79	2,20	3,29	3,10	1,80	1,64
Lu	0,27	0,32	0,58	0,48	—	0,20
TR _{total}	70,30	146,40	203,50	174,20	174,80	181,90
Eu/Eu ⁺	1,00	0,65	0,70	0,70	0,60	0,72
La _N /Yb _N	4,80	9,20	8,40	7,00	13,50	14,10
Th	3,50	11,1	—	—	20,00	13,00
U	0,92	2,90	—	—	4,00	1,80
Rb	30,00	115,00	—	—	239,00	82,50**
K ₂ O	1,10	3,50	—	—	4,40	2,47

ACC — Archaic continental crust (Taylor — Lennan 1980), PACC — Paleozoic continental crust (Taylor — Lennan 1980), ES — composition of European Paleozoic Shales (Haskin — Haskin 1966), NASC — composition of North American Shale Complex (Haskin — Paster 1979), KG — average of the "Koetong" granite, Australia (Price — Taylor 1977), ZK — composition of the main type (type I) of the West Carpathian granitoids (n = 6), Eu⁺ — theoretic value obtained through non-anomalous normalized value, N — normalized value, ** — taken from Cambel et al. (1981), n = 10, average of granodiorites in the Bratislava massif)

ACC — archaická kontinentálna kôra (Taylor — Lennan, 1980), PACC — paleozoická kontinentálna kôra (Taylor — Lennan, 1980), ES — zloženie „európskych paleozoických bridlíc“ (Haskin — Haskin, 1966), NASC — zloženie paleozoických severoamerických bridlíc (Haskin — Paster, 1979), KG — zloženie granitov Koetong, Austrália (Price — Taylor, 1977), ZK — zloženie základného typu (typ I) granitoidov Západných Karpát (n = 6); Eu⁺ — teoretická hodnota získaná na základe neanomálnej normalizovanej hodnoty; N — normalizované hodnoty; ** — prevzaté z práce Cambel et al., 1981 (n = 10, priemer granodioritov bratislavského masívu)

Conclusions

The partly preserved "complete" development (including the types I to IV) of Variscan massifs in the West Carpathian "Core Mountains" and Slovak Ore Mts. point to their isolated generation. In accordance with such assumption and with arguments summarized recently (Hovorka, 1979), the magma of granitoid massifs in Early Paleozoic near-to-continental type of crust created no continuous "layer". To the sites of higher heat flow (?). The emplacement of granitic melts sensu lato into higher crustal levels occurred but after the culmination of the Variscan orogeny (late-orogenic to postkinematic massifs) in places of tectonic predisposition within the Early Paleozoic substratum.

Processes of fractional fusion and crystallization produced generally only a less differentiated rock suite in which biotite is the main mafic mineral. In the case of complete preservation, massifs have the following generalized rock content: the central part is composed of medium-grained biotite granodiorite to tonalite passing towards the margins (both laterally and vertically) into two-mica, frequently porphyritic, granodiorite. The marginal zone is composed of whether porphyritic type with pink potash feldspar (Prašivá type) or of leucocratic granodiorite to granite (both types). The chondrite normalized REE distribution pattern and its comparison with model types points to the generation of granitic rocks at the expense of a supra-crustal metamorphic sequence consisting of metaclastics, metapelites and tholeiitic metabasite intercalations.

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Geochémia prvkov vzácnych zemín a petrologický model vzniku variských granitov Západných Karpát

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Variské plutonické horniny granitového radu sú základom morfoštruktúrnych jednotiek — jadrových horstiev aj veporických zón Slovenského rudohoria. Na povrchu majú plochu niekoľko desiatok km² (Považský Inovec, Žiar), stoviek km² (Tatry, Veľká a Malá Fatra a i.). Najrozsiahlejší je masív Slovenského rudohoria (v dĺžke 80 a šírke 30 km). V rámci jednotlivých telies sa v minulosti vyčlenili viaceré základné petrografické typy a spravidla sa označovali podľa miesta výstupu („vysokotatranský“ typ a pod.).

Podľa priestorových vzťahov a minerálneho zloženia vyčlenil D. Hovorka (v tlači) štyri typy granitoidov variscika Západných Karpát a podal ich základnú geochemickú a petrogenetickú charakteristiku.

I. *Strednozrnné biotitické granodiority (tonality)*, miestami s akcesorickým až vedľajším podielom amfibolu, sú najrozšírenejším typom variských plutonitov Západných Karpát. Sú známe pod rozličným označením (vysokotatranský, Ľumbiersky, Sihliansky, Smrekovický, modranský a i.). Charakteristické je, že v prípade zachovania celých masívov plutonitov tento typ vždy tvorí centrálnu časť masívu. Smerom na okraj (laterálne) a vrchnú časť (vertikálne) telies prechádzajú do ďalších vyčlenených typov.

II. *Dvojsludné (často porfyritické) typy granodioritov* tvoria okrajový lem napr. masívu Slovenského rudohoria v jeho južnej časti.

III. *Leukokratné granity, lokálne granodiority*, sú typicky vyvinuté v severozápadnej okrajovej zóne masívu Tatier. Pre typy tejto

skupiny je charakteristický prevažne nízky obsah tmavých minerálov — sfudy.

IV. *Porfyritické granodiority* (granity s ružovými K-živcami, typ Prašivá) sú známe z niekoľkých jadrových horstiev (Tatry, Malá a Veľká Fatra a i.) a zo Slovenského rudohoria. Na rozdiel od starších predstáv o rozsiahlej káliovej metasomatóze ako vedúcom procese vzniku týchto typov sa v posledných rokoch predkladajú náhľady o ich neskoromagmatickom vývoji, t. j. v PT podmienkach v „nadsolidovej“ oblasti (Hovorka, 1979).

Okrem základných skupín granitoidov sme vyčlenili skupinu leukogranitov, ktoré nie sú produktom diferenciálnych procesov a svojím zložením pravdepodobne zodpovedajú „metatektu“ (skupina V). Samostatne sme bádali aj skupinu migmatitov (skupina VI). Na genetickú interpretáciu sme použili analýzy hornín na petrogénne a stopové prvky skupiny vzácnych zemín.

Podľa pozorovaní a údajov o obsahu a distribúcii prvkov vzácnych zemín v granitoidoch variscika Západných Karpát sa ich genéza (vzťahovaná na typ I) javí takto: taveniny vznikli parciálnou anatexiou sedimentárno-vulkanického komplexu, v ktorom okrem výrazne objemovo prevládajúcich metasedimentov klasticko-ílovitej sekvencie boli zastúpené aj metavulkanity tholeiitového typu. O prítomnosti takýchto metavulkanitov v zóne anatexie svedčia výskyty anatekticky rozlične intenzívne transformovaných metabazitov typu metadioritov až hornblenditov vystupujúcich v nedokonale homogenizovaných (pre-

važne okrajových) častiach granitových masívov. Na základe výskumov možno predpokladať, že metabazity výsledné zloženie granitoidov podstatne neovplyvnili. Ďalšie typy granitov (typ II, III) vznikli diferenciáciou z typu I. Ale v prípade leukogranitov treba podľa novších údajov uvažovať o ich rozličnej genéze: a) leukogranity s. s. ako produkt diferenciácie a frakcionácie, b) leukogranity, ktoré nepredstavujú produkt diferenciálnych procesov, ale sú pravdepodobne separovanou fázou generovanou pri málo pokročilej anatexii a pri súčasnom oddelení výrazne leukokratného metatektu od substrátu. Takéto typy sa označujú ako „granitic vein“ (Price — Taylor, 1977). Komplementárne k uvedeným typom hornín by mali byť biotitové „šmuhy“ (biotite selvage).

Nejednoznačne interpretovaným problémom variských granitoidov Západných Karpát je genéza „autometamorfných“ (prašivských) granitov (granodioritov; typ IV). Priebeh normalizovaných kriviek vzácnych zemín v základnom a autometamorfovanom type granitoidov je zhodný. Pre obidva typy je charakteristická negatívna Eu-anomália. V ostatnom čase sa dokázalo, že alkalické kovy migru-

júce v oblasti subsolidových, autometamorfných či hydrotermálnych premien granitoidov sú sprevádzané prvkami vzácnych zemín (Bowden et al., 1979, Alderton et al., 1980 atď.). Z aplikácie tohto zistenia na genézu predmetného typu granitov Západných Karpát vychodí, že tieto typy nevznikli procesmi rozsiahlej alkalickej (prevažne kálievej) metasomatózy, lebo v takom prípade by normalizovaný obraz prvkov vzácnych zemín v type IV musel byť výrazne odlišný od typu I.

Miestami zachovaný „kompletný“ vývoj (t. j. typ I—IV) variských masívov granitovej série jadrových horstiev a Slovenského rudohoria svedčí o ich izolovanom formovaní sa. V súlade s touto predstavou a dôvodmi zhrnutými v minulosti (Hovorka, 1979) magma granitových masívov v ranopaleozoickej kôre blízkej kontinentálnemu typu netvorila súvislú „vrstvu“, ale vznikla anatektonickými procesmi v miestach zvýšeného tepelného toku (?). Preniknutie granitických tavenín s. l. do vyšších úrovní kôry prebehlo po kulminácii variského orogénu (neskorokinematické až postkinematické masívy) v miestach tektonického predisponovania ranopaleozoického substrátu.