GEOLOGICA CARPATHICA, 50, 6, BRATISLAVA, DECEMBER 1999
477–487

Sr AND Nd ISOTOPE GEOCHEMISTRY OF HERCYNIAN GRANITIC ROCKS FROM THE WESTERN CARPATHIANS — IMPLICATIONS FOR GRANITE GENESIS AND CRUSTAL EVOLUTION

MILAN KOHÚT[1], VIKTOR P. KOVACH[2], ALEXANDER B. KOTOV[2], EKATHERINA B. SALNIKOVA[2] and VALERIY M. SAVATENKOV[2]

Project No 373

[1]Geological Survey of Slovakia, Mlynská dolina 1, 817 04 Bratislava, Slovak Republic; milan@gssr.sk
[2]Institute of Precambrian Geology and Geochronology, Russian Academy of Sci., Makarova Emb. 2, 199034 St. Petersburg, Russia

(Manuscript received February 23, 1999; accepted in revised form September 28, 1999)

Abstract: Combined Sr-Nd isotopic study of the Hercynian granitoid rocks from the Western Carpathians has been carried out on whole rock (WR) samples from typical representatives of each granitic body in the Carpathians. The results presented here reveal the dominance of heterogeneous crustal sources for the majority of the studied granitic rocks, which have a neodymium crustal index NCI = 0.4–1 (majority 0.6–0.8). Initial isotopic data $^{87}Sr/^{86}Sr_{(350)}$ = 0.7053–0.7078 ($\varepsilon_{Sr}^{(350)}$ = 16.7–52.6) and $\varepsilon_{Nd}^{(350)}$ = –0.6 to –6.9 preclude a simple mantle and/or crustal origin for most of the West-Carpathian granites and suggest more complex sources, such as an enriched source in the subcontinental lithosphere, or amphibolitic lower crust, with crustal-sedimentary addition. We cannot exclude, from the presented data, a hypothetical depleted mantle source, at least as heat flux during crustal anatexis processes. Apparent crustal residence ages, indicated by Nd model age — $t_{(DM2st)}$ = 1.1 ~ 1.6 Ga, are comparable with other segments of the European Hercynian belt. Petrographically, these granites are representative of common crustal anatectic rocks with magmatic muscovite, however, their isotopic signature reflects an I-type granitic character, usually related to subduction processes at active continental margins. Recent metamorphic, sedimentary and/or structural knowledge from the Hercynian basement of the Western Carpathians suggests a continental collisional, rather than a volcanic arc setting. The West-Carpathian granitic rocks were generated by partial melting of mainly crustal Proterozoic material during subduction-collisional processes of the Hercynian orogeny.

Key words: Western Carpathians, granitoid rocks, Rb-Sr, Sm-Nd, isotope geochemistry, granite genesis, crustal evolution.

Introduction

The isotopic composition of Sr and Nd are correlated and have been widely used to study the origin of igneous rocks. The values of radiogenic isotope ratios at the time of granite magma formation, coupled with other geochemical data, may indicate the nature of sources contributing to granite magmas. Granitic plutons are an important constituent of the continental crust, making up to one half of the upper crust; bulk continental crust has a tonalitic composition (Wedepohl 1995). The continental crust developed by repeated orogenic and anorogenetic events, during which old crustal material has been recycled and new material extracted from the mantle has been added to the continents. Magmas formed by crustal anatexis will contain information on the history of the crust and its composition at the time of formation, reflecting their isotopic evolution (Sr, Nd). Numerous papers have been published discussing the source of granite rocks using radiogenic isotopes, for example McCulloch & Chappell (1982), Ben Othman et al. (1984), Liew & Hofmann (1988), Pin & Duthou (1990), Moreno-Ventas et al. (1995), Keay et al. (1997). According to these authors granites are a) derived from the melting of discrete crustal sources, b) produced by crust-mantle mixing, or reflect a three component mixture such as c) melting of old greenstone (mafic crustal component) together with metapelites and addition of young mantle-derived magma, and/or d) melting of upper crustal sediments together with lower crustal granulites and mixed/mingled with young mantle magma.

Though the genetic implications from Sm-Nd study of the Carpathian granites were published by Kohút et al. (1995), the primary data of this research have never been presented in written form. The relation of mafic enclaves (MME) to the Cretaceous Rochovce Granite with help of Sm/Nd isotopic characteristics has been discussed by Hraško et al. (1998). The main purpose of this paper is to present Sr-Nd isotopic results from the West-Carpathian granite rocks, constrain their sources and petrogenesis as well as discuss the implications for crustal evolution.

Geological setting

Like the Pyrenees, Alps and/or Himalayas, the Carpathian mountain chain is a typical Alpine collisional fold belt. Their pre-Mesozoic complexes, however, belong to the Hercynian basement within the Alpine-Carpathian orogenic belt. During the Alpine tectonism, the Carpathian part of the Hercynian belt was disrupted and sliced into blocks, which were incorporated into the Alpine (nappe and/or terrane) complexes and subsequently variously uplifted. This polyorogenic history makes the reconstruction of Hercynian structures rather

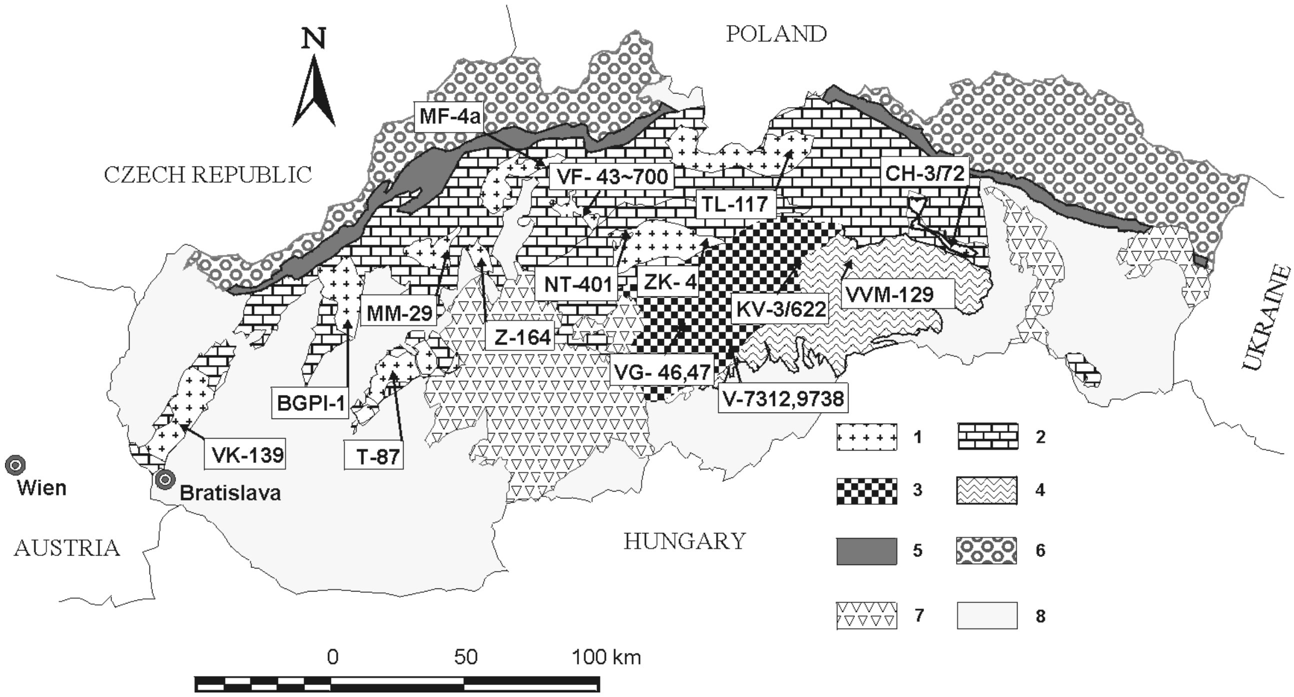

Fig. 1. Simplified tectonic-geological sketch of the Western Carpathians (Slovak part), with location of investigated samples. **1** — Pre-Alpine crystalline basement, Tatric Superunit, **2** — Mesozoic sedimentary cover and nappe structures of the Tatric Superunit, **3** — Veporic Superunit, **4** — Gemeric Superunit, **5** — Klippen Belt, **6** — Flysch zone, **7** — Neogene to Quarternary Central and East Slovak neovulcanites, **8** — Neogene to Quarternary basins.

difficult, but provides excellent exposure of various levels of the Hercynian crust. The Western Carpathians form a direct eastern continuation of the Eastern Alps. The pre-Alpine crystalline basement crops out mainly in the Central Western Carpathians (CWC), the heart of the Western Carpathians, consisting of three principal crustal-scale superunits: the Tatric, Veporic and Gemeric and several cover-nappe systems — the Fatric, Hronic and Silicic (generally from N to S), see Plašienka (1995), Plašienka et al. (1997). The Hercynian granitoid rocks occur in all three superunits of the CWC in various positions (Fig. 1). In the Tatric Superunit, these rocks form backbones of the so-called core mountains. A grand composite granodiorite-tonalite massif, strongly affected by the Alpine tectonics, dominates the Veporic Superunit. A large hidden granitoid body penetrating the overlying Early Paleozoic rocks in the form of apophyses is observed in the Gemeric Superunit. The core mountains of the Tatric Superunit are composed of pre-Mesozoic metamorphic rocks and granitoids, both overlain by Mesozoic cover sediments, and/or nappe structures. Basement rocks were only weakly affected by Alpine metamorphism (Krist et al. 1992). The Veporic crystalline basement consists of high- to low-grade metamorphic rocks, various types of granitoids including hybrid ones, and their Upper Paleozoic and Mesozoic cover. Due to complex Hercynian and Alpine tectonic phenomena this unit has a very complicated — imbricate structure at present. Penetrative brittle-ductile deformation is weakened from SE to NW. The basement of the Gemeric Superunit is composed of Early Paleozoic (Silurian) to Late Carboniferous, mostly low-grade flyshoid metasediments and metavolcanics with remnants of an ophiolite complex. This volcano-sedimentary sequence was intruded by small granite apophyses from a huge underlying postorogenic body. (A more detailed geological map of the Western Carpathians can be find at address — http://www.gssr.sk).

Granitoid magmatism dominated the Hercynian orogen in the Western Carpathians over the time interval of 100 million years (360–250 Ma). In response to varying geotectonic settings different genetic types of granite formed: lower Carboniferous crustal thickening, an upper Carboniferous thermal event, and Permian transtension resulted in S-, I- and A-type granite forming events respectively (Petrík & Kohút 1997). This review lists all relevant geochronological data and discusses all the important geochemical and petrological aspects of the West-Carpathian granitic rocks. Available isotope data (U-Pb, Rb-Sr and Ar-Ar) indicate main phase of granite magmatism between 360 and 340 Ma; therefore we adopted the age 350 Ma for calculation of initial isotopic compositions. The HT/MP metamorphism with concomitant widespread granite magmatism was responsible for resetting (Rb-Sr) of the potential source rocks during this period.

Analytical methods

Geochemical analyses were done at the University of Ottawa using the XRF technique and at the Dionýz Štúr Institute of Geology — Bratislava using classical wet technique. REE were analysed at the University of Newfoundland, St. John's and by MEGA Inc. Stráž pod Ralskem both using INAA. The measurements were checked against international standards. The analyses of isotopic composition were performed at the

Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences, St. Petersburg and partly (Rb/Sr) in the laboratories of BGR Hannover on the mass spectrometers Finnigan MAT 261. The powdered rocks samples (WR) for Sm-Nd studies were analysed following the method of Richards et al. (1976), Rb-Sr analyses were done according to the method of Wendt (1986). Pulverized WR samples were totally spiked with ^{149}Sm-^{146}Nd mixed solution (respectively ^{85}Rb-^{84}Sr), and dissolved in a mixture of $HF+HNO_3+HClO_4$. Separation of Sm and Nd (Rb-Sr) were done using conventional cation-exchange chromatography and then extraction chromatography on HDEHP covered teflon powder. Total blanks during the measurements were 0.1–0.2 ng for Sm, 0.1–0.5 ng for Nd and 0.03–0.07 ng for Rb, 0.5–0.8 ng for Sr. The accuracy of the measurements of Sm and Nd contents was ±0.5 %, $^{147}Sm/^{144}Nd$ — ±0.5 %, $^{143}Nd/^{144}Nd$ — ± 0.005 % (2σ), $^{87}Rb/^{86}Sr$ — ±0.5 % and $^{87}Sr/^{86}Sr$ — 0.005 % (2σ). During these works the weighted average (n = 31) of the La Jolla Nd-standard yielded 0.511845 ± 4 (2σ) for $^{143}Nd/^{144}Nd$, normalized to $^{146}Nd/^{144}Nd$ = 0.7219 for Rb-Sr measurements were used internal standards NBS-987 and NBS-607 respectively. The εNd(0) values were calculated with $^{147}Sm/^{144}Nd$ = 0.1967 and $^{143}Nd/^{144}Nd$ = 0.512638 for the chondritic uniform reservoir (CHUR) according to Jacobsen & Wasserburg (1980). A linear model with parameters $^{147}Sm/^{144}Nd$ = 0.2136 and $^{143}Nd/^{144}Nd$ = 0.513151 was used for depleted mantle (DM) — Goldstein & Jacobsen (1988). The two-stages of apparent crustal residence ages were calculated with correction for crustal component $^{147}Sm/^{144}Nd_{(CC)}$ = 0.12 and $^{143}Nd/^{144}Nd_{(DM)}$ = 0.513151, $^{147}Sm/^{144}Nd_{(DM)}$ = 0.219 according to the model of Liew & Hofmann (1988). The εSr(0) values were calculated with $^{87}Sr/^{86}Sr$ = 0.7045 for present bulk earth composition (DePaolo & Wasserburg 1976). The values NCI (Neodymium Crustal Index) are computed according to the model of DePaolo et al. (1992). More details of the analytical technique are described in Neymark et al. (1993) and Kohút et al. (1996).

Results

The basic chemical composition (major + trace element and REE) of the studied samples is given in Table 1. Since our research was limited, we selected more or less representative samples from each West-Carpathian granite massif. The broad sample set, covering all principle granite types, including hybrid ones from the Veporic Superunit, is complemented by one sample of gabbro (Sm-Nd data, Kotov in Hraško 1993), used for genetic implication. The dominance of common granodiorite-granite types is shown in Fig. 2. The chondrite normalized patterns in this Fig. 2, give a good reflection of all the fractionation/assimilation processes, which operated during the origin of these granites. Generally, the majority of Carpathian granitoid plutons are metaluminous to peraluminous (subaluminous) and are composed of several rock types ranging from tonalite to leucocratic granite. The silica contents of granitic rocks vary in a range of ca. 60–75 wt. %, documenting the increase of alkalinity from the more basic to the most acid ones. The prevalence of Na_2O over K_2O is a common feature (K_2O/Na_2O = 0.25–1.15), except in the porphyritic granite of „Prašivá“ type in which this ratio is equal. The CWC granitoids represent low- to high-potassium calc-alkaline (throndhjemite –monzonite) series of magmatic rocks, with ASI = 0.7–1.4. Biotite is the dominant Fe-Mg mafic mineral, whereas hornblende occurs only rarely in the dioritic enclaves. Accessory minerals (magnetite + allanite and monazite + ilmenite) show dichotomy and/or antagonism in some plutons, which permits the distinction between the two principal granite groups (Petrík & Broska 1994). The occurrence of the mafic microgranular enclaves (MME) in the magnetite-bearing granites and presence of the host (metamorphic) rocks xenolithes in the magnetite-free granites support this division in the Western Carpathians.

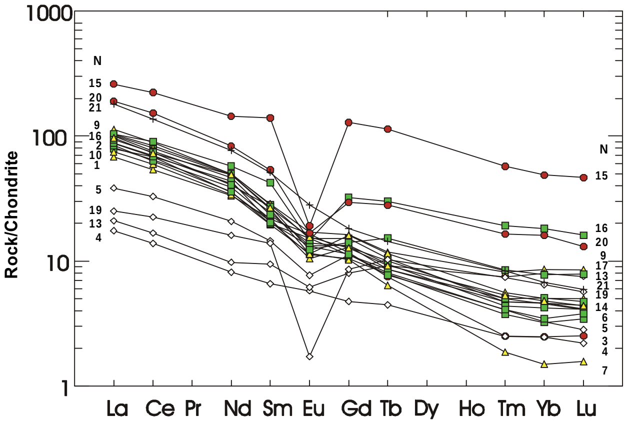

Fig. 2. Chondrite-normalized REE plots of the studied samples from the West-Carpathian granite rocks. Chondrite composition according to Boynton (1984). *Symbols:* circle — tonalites, box — granodiorites, triangle — granites, diamond — leucogranites, cross — gabbro. N — numbers of samples according to Table 1.

The Sm-Nd isotopic data together with Rb-Sr isotopic analyses are listed in Table 2. Measured ratios in the rocks are corrected for decay since the time of crystallization (t = 350 Ma). The ε values relative to CHUR and UR were recalculated in a similar way (see above).

The situation in the Rb-Sr isotopic system is documented by Figs. 3 and 4. Although the samples come from various plutons, a linear correlation of studied samples with the exception of two leucocratic samples (ZK-4 and VVM-129 is clearly observed in the Nicolaysen plot). The linear array of these samples is in good concordance with the reference line for an age of 365 Ma. This leads to an assumption that metamorphic/magmatic processes operated with P-T conditions over stability for this isotopic system, throughout a wide area during the early Carboniferous period. The initial strontium ratios (I_{sr}) in granitoid rocks of the Tatric and Veporic superunits are low (0.705–0.708) suggesting a mixed lower crustal and mantle component and/or Rb-poor crustal source (Fig. 4). This ratio is higher only in the Kralička leucogranites (our sample ZK-4), which show some genetic relations with surrounding metamorphic rocks, migmatites and gneisses (Siegl 1976; Dupej & Siegl 1984). The I_{Sr} of this leucogranite (0.7116 — Bagdasaryan et al. 1985) is comparable with that of gneisses from the Malé Karpaty Mts. and Tatra Mts. (0.710–0.711 — Burchart 1968; Bagdasaryan et al. 1983). Generally the two principal granitoid groups, S-type

Table 1: Chemical composition (major + trace elements and REE) of the studied Carpathian granite samples. *Explanation:* bT — biotite tonalite, mbGD — muscovite-biotite granodiorite, mG — muscovite granite, Gabb — gabbro, etc.

Number	1	2	3	4	5	6	7	8	9	10
Sample	**VF-43**	**VF-639**	**VF-356**	**VF-700**	**VF-298**	**VK-139**	**BGPI-1**	**T-87**	**MM-29**	**Z-164**
Type	mbG	bGD	bT	mG	mbG	mbGD	mbG	bGD	mbG	bmG
SiO_2	72.66	66.33	68.76	73.94	72.74	72.51	72.38	70.01	72.47	74.19
TiO_2	0.21	0.58	0.51	0.16	0.16	0.41	0.17	0.37	0.18	0.19
Al_2O_3	14.64	15.70	15.59	13.27	15.12	14.31	14.86	15.61	14.55	14.24
Fe_2O_3	0.47	1.62	0.81	0.94	0.33	1.00	0.59	1.31	0.37	0.70
FeO	1.43	1.93	2.33	1.25	0.72	1.53	1.60	1.41	1.50	1.04
MnO	0.03	0.05	0.04	0.02	0.02	0.04	0.05	0.04	0.07	0.02
MgO	0.61	1.21	1.22	0.15	0.37	0.81	0.67	0.95	0.60	0.39
CaO	1.42	2.89	2.83	0.69	1.44	1.96	2.88	2.29	2.09	1.66
Na_2O	3.74	5.01	4.04	4.39	4.24	3.23	4.51	3.22	4.14	4.10
K_2O	3.52	2.94	2.24	3.98	3.83	3.19	1.11	2.88	2.57	2.47
P_2O_5	0.13	0.24	0.21	0.21	0.22	0.09	0.17	0.31	0.12	0.08
H2O+	0.75	1.24	0.94	0.76	0.83	0.64	0.82	1.60	0.68	0.51
H2O-	0.18	0.13	0.14	0.08	0.06	0.22	0.26	0.22	0.29	0.19
Total	99.79	99.87	99.66	99.84	100.08	99.94	100.07	100.22	99.63	99.78
Sr	259	365	563	103	146	285	284	482	327	305
Rb	110	91	91	177	108	99	61	92	56	80
Ba	864	641	826	405	534	1550	145	575	957	1200
Zr	112	203	185	40	52	316	86	156	128	134
Y	12.36	11.50	6.98	6.36	11.10	16.00	4.69	11.62	15.23	19.00
Nb	8.79	8.34	8.56	6.00	4.85	7.98	9.06	7.41	5.30	9.00
Ta	0.79	0.44	0.62	0.33	0.46	0.63	0.83	0.84	0.29	0.26
Hf	2.96	4.62	4.30	1.21	1.88	3.38	2.27	3.92	3.53	3.30
Th	6.40	8.90	6.26	2.95	6.52	15.40	8.16	8.73	12.80	10.30
U	2.50	2.20	2.10	3.80	3.70	1.70	2.42	2.51	10.30	3.20
La	20.79	31.20	24.56	5.36	11.82	24.20	22.85	25.52	34.56	31.08
Ce	42.99	66.34	51.11	11.04	26.26	54.50	47.47	49.94	70.83	64.22
Nd	19.73	29.52	23.07	4.84	12.31	21.00	20.18	21.15	29.32	29.10
Sm	4.20	5.41	4.17	1.27	2.80	4.00	3.78	3.80	5.51	5.04
Eu	0.76	1.09	1.19	0.42	0.56	0.82	0.84	1.10	1.24	0.83
Gd	3.32	3.85	2.98	1.22	2.87	2.62	2.63	2.84	4.13	4.12
Tb	0.47	0.49	0.35	0.21	0.38	0.37	0.30	0.40	0.55	0.54
Tm	0.16	0.15	0.08	0.08	0.13	0.12	0.06	0.15	0.26	0.18
Yb	0.94	0.95	0.51	0.51	0.68	0.67	0.31	0.95	1.76	1.04
Lu	0.13	0.13	0.08	0.07	0.09	0.11	0.05	0.14	0.27	0.16

Number	11	12	13	14	15	16	17	18	19	20	21
Sample	**MF-4a**	**NT-401**	**ZK-4**	**TL-117**	**VG-46**	**VG-47**	**V-7312**	**V-9738**	**VVM-129**	**CH-3/72**	**KV-3/622**
Type	mbGD	bGD	mG	mbGD	bT	mbGD	bmG	mbG	bmG	bT	Gabb
SiO_2	71.40	69.40	73.31	71.24	68.87	68.95	73.01	71.02	76.09	61.90	48.78
TiO_2	0.27	0.49	0.08	0.25	0.46	0.46	0.21	0.32	0.11	0.91	0.78
Al_2O_3	14.80	15.16	14.07	14.56	15.64	15.06	14.18	14.45	12.75	16.70	11.22
Fe_2O_3	0.40	1.22	0.73	1.24	1.36	1.17	0.56	0.87	0.41	2.69	5.16
FeO	1.50	1.50	1.35	1.56	2.21	2.13	0.65	1.82	0.98	5.39	6.12
MnO	0.03	0.05	0.06	0.04	0.09	0.04	0.02	0.03	0.03	0.07	0.16
MgO	0.59	1.61	0.55	0.77	1.58	1.10	0.44	1.01	0.13	1.94	15.21
CaO	1.90	1.96	1.10	2.26	2.37	1.79	1.29	1.97	0.49	2.36	7.44
Na_2O	4.15	3.48	4.00	4.48	2.35	3.66	3.60	3.24	2.99	2.16	1.74
K_2O	3.49	3.45	3.70	1.87	2.72	3.80	4.52	3.92	4.76	3.06	2.76
P_2O_5	0.08	0.23	0.16	0.21	0.18	0.22	0.14	0.17	0.18	0.23	0.34
H2O+	1.10	1.14	1.32	1.10	1.56	1.31	1.02	0.75	0.78	1.96	0.19
H2O-	0.14	0.10	0.04	0.18	0.22	0.20	0.16	0.13	0.11	0.16	0.25
Total	99.85	99.79	100.47	99.76	99.61	99.89	99.80	99.70	99.81	99.53	100.15
Sr	473	600	122	449	344	210	120	320	21	464	638
Rb	65	125	158	88	89	131	240	72	448	102	139
Ba	1030	730	316	880	871	851	713	956	60	1040	635
Zr	124	129	31	159	179	215	96	150	66	268	123
Y	10.29	8.75	14.99	7.00	157.59	44.20	24.00	12.00	17.73	40.50	18.00
Nb	5.19	12.50	9.19	10.00	17.06	14.35	5.00	7.00	19.65	12.25	4.80
Ta	0.37	0.98	1.24	0.29	0.66	0.80	1.10	0.50	5.46	0.59	0.50
Hf	3.12	4.46	0.91	4.10	4.44	5.32	3.80	6.80	2.08	4.83	5.10
Th	7.20	11.40	5.50	6.30	52.00	14.00	16.90	22.50	9.55	12.05	8.80
U	2.80	3.80	3.40	2.60	8.00	3.20	4.80	1.70	6.40	4.30	4.00
La	26.87	30.47	6.45	26.67	78.84	31.46	28.52	30.48	7.67	57.20	55.58
Ce	55.63	60.26	13.40	54.56	175.60	71.73	58.90	58.14	17.99	120.00	109.70
Nd	24.59	27.37	5.81	25.67	84.29	33.97	24.00	29.12	9.51	48.61	45.84
Sm	4.72	4.51	1.82	3.91	26.57	8.10	5.23	5.13	2.68	10.20	9.90
Eu	0.96	1.01	0.45	0.95	1.37	1.06	0.89	1.13	0.13	1.20	2.05
Gd	3.41	3.36	2.05	2.89	32.46	8.22	3.60	3.26	2.20	7.42	4.69
Tb	0.44	0.40	0.43	0.36	5.26	1.40	0.71	0.43	0.48	1.27	0.68
Tm	0.14	0.16	0.24	0.13	1.81	0.61	0.27	0.17	0.24	0.52	0.27
Yb	0.87	1.04	1.65	0.71	9.94	3.74	1.60	0.99	1.34	3.25	1.40
Lu	0.13	0.15	0.24	0.12	1.46	0.51	0.25	0.14	0.18	0.41	0.19

Table 2: Radiogenic isotope data and calculated parameters of the investigated samples from the West-Carpathian granite rocks.

Sample	Rb	Sr	1/Sr	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr(2\sigma)$	$\varepsilon_{Sr(0)}$	$^{87}Sr/^{86}Sr_{(350)}$	$\varepsilon_{Sr(350)}$
VF-43	110	259	0.0039	0.42	1.3838	0.71359 ± 21	129.03	0.706695	36.95
VF-639	91	365	0.0027	0.25	0.5255	0.70882 ± 20	61.32	0.706202	29.94
VF-356	91	563	0.0018	0.16	0.4330	0.70824 ± 21	53.09	0.706083	28.25
VF-700	103	177	0.0056	0.58	1.6920	0.71521 ± 16	152.02	0.706780	38.15
VF-298	108	146	0.0068	0.74	3.0970	0.72220 ± 20	251.24	0.706770	38.01
VK-139	99	285	0.0035	0.35	0.9891	0.71240 ± 34	112.14	0.707472	47.98
BGPI-1	61	284	0.0035	0.21	1.6198	0.71492 ± 22	147.91	0.706850	39.15
T-87	92	482	0.0021	0.19	0.3500	0.70768 ± 28	45.14	0.705936	26.17
MM-29	56	327	0.0031	0.17	1.7590	0.71496 ± 24	148.47	0.706196	29.86
Z-164	80	305	0.0033	0.26	1.5696	0.71403 ± 16	135.27	0.706210	30.05
MF-4a	65	473	0.0021	0.14	0.4390	0.70848 ± 18	56.49	0.706293	31.24
NT-401	125	600	0.0017	0.21	0.5644	0.71010 ± 30	79.49	0.707288	45.37
ZK-4	158	122	0.0082	1.30	3.4260	0.73700 ± 28	461.32	0.719930	224.93
TL-117	88	449	0.0022	0.20	0.6092	0.70920 ± 20	66.71	0.706165	29.42
VG-46	89	344	0.0029	0.26	0.5480	0.70800 ± 40	49.68	0.705270	16.71
VG-47	131	210	0.0048	0.62	1.4660	0.71510 ± 30	150.46	0.707796	52.58
V-7312	240	120	0.0083	2.00	0.9727	0.71123 ± 28	95.53	0.706384	32.53
V-9738	72	320	0.0031	0.23	0.7440	0.71005 ± 24	78.78	0.706343	31.95
VVM-129	448	21	0.0476	21.33	17.4520	0.87094 ± 36	2362.5	0.783988	1134.71
CH-3/72	102	464	0.0022	0.22	1.0252	0.71110 ± 22	93.68	0.705992	26.97
KV-3/622	139	638	0.0016	0.22	0.1965	0.70330 ± 20	-17.03	0.702321	-25.17

Sample	Sm	Nd	Sm/Nd	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd(2\sigma)$	$\varepsilon_{Nd(0)}$	$^{143}Nd/^{144}Nd_{(350)}$	$\varepsilon_{Nd(350)}$	$t_{(DM)}$	$t_{(DM2st)}$	NCI
VF-43	3.05	15.93	0.19	0.11602	0.512391 ± 5	-4.82	0.512125	-1.21	1186	1155	0.58
VF-639	4.72	25.19	0.19	0.11364	0.512347 ± 7	-5.68	0.512087	-1.97	1225	1214	0.66
VF-356	4.73	23.44	0.20	0.12241	0.512346 ± 6	-5.70	0.512065	-2.38	1344	1247	0.66
VF-700	2.07	8.39	0.25	0.14990	0.512330 ±13	-6.01	0.511986	-3.92	1958	1368	0.69
VF-298	3.25	15.45	0.21	0.12768	0.512306 ±11	-6.48	0.512013	-3.39	1496	1327	0.73
VK-139	5.66	30.80	0.18	0.11135	0.512302 ± 6	-6.55	0.512047	-2.74	1264	1275	0.74
BGPI-1	3.52	18.50	0.19	0.11551	0.512235 ± 9	-7.86	0.511970	-4.24	1421	1393	0.86
T-87	4.82	27.70	0.17	0.10548	0.512397 ± 7	-4.70	0.512155	-0.62	1063	1109	0.57
MM-29	5.72	30.60	0.19	0.11346	0.512278 ±11	-7.02	0.512018	-3.30	1327	1319	0.78
Z-164	5.77	31.99	0.18	0.10947	0.512298 ±10	-6.63	0.512047	-2.74	1247	1275	0.75
MF-4a	4.19	22.30	0.19	0.11362	0.512307 ±11	-6.46	0.512047	-2.75	1285	1276	0.73
NT-401	4.19	22.66	0.18	0.11216	0.512396 ± 9	-4.72	0.512139	-0.94	1134	1134	0.57
ZK-4	3.57	15.40	0.23	0.14044	0.512156 ± 8	-9.40	0.511834	-6.89	2066	1601	1.00
TL-117	3.75	21.50	0.17	0.10597	0.512343 ± 4	-5.75	0.512100	-1.70	1144	1194	0.67
VG-46	25.50	82.10	0.31	0.18865	0.512516 ± 5	-2.38	0.512084	-2.02	3843	1219	0.36
VG-47	7.96	33.91	0.23	0.14237	0.512354 ±11	-5.54	0.512028	-3.11	1701	1305	0.65
V-7312	5.00	22.50	0.22	0.13498	0.512333 ±14	-5.95	0.512024	-3.19	1583	1311	0.68
V-9738	5.04	28.50	0.18	0.10717	0.512332 ±12	-5.97	0.512086	-1.97	1172	1215	0.69
VVM-129	2.58	8.93	0.29	0.17537	0.512364 ± 9	-5.34	0.511962	-4.40	3116	1405	0.63
CH-3/72	11.83	52.04	0.23	0.13787	0.512343 ± 9	-5.68	0.512031	-3.05	1615	1299	0.66
KV-3/622	11.39	65.68	0.17	0.10515	0.512715 ± 6	1.50	0.512474	5.60	613	620	0.00

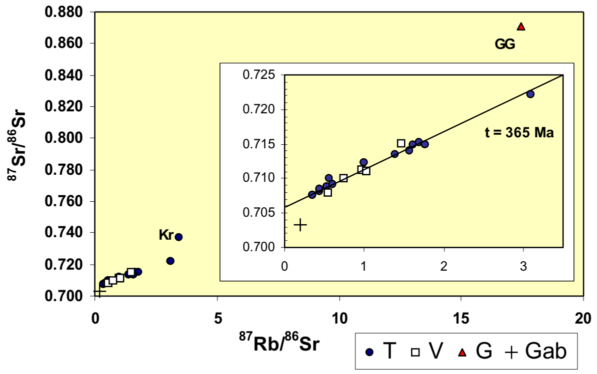

Fig. 3. Whole rock Rb/Sr isotope plot. Insert — eighteen investigated samples are lying around reference line with age t = 365 Ma in the Nicolaysen plot. Symbols according to position of samples within tectonic unit: T — Tatric, V — Veporic, G — Gemeric, Gab — gabbro.

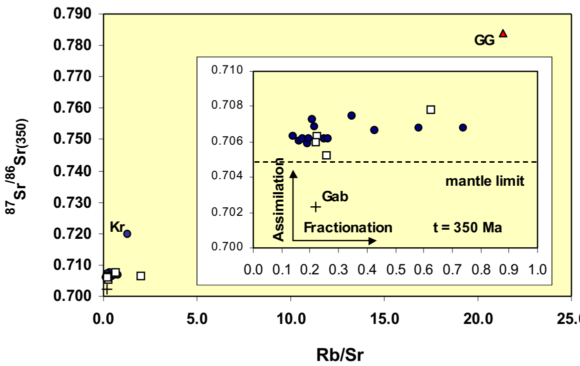

Fig. 4. Diagram I_{sr} versus Rb/Sr documenting nearly balanced and quasi-homogenized isotope conditions during genesis of the Hercynian granites in the Western Carpathians. Symbols as in Fig. 3; Kr = ZK-4, GG = VVM-129, Gab = KV-3/622.

and I-type are distinguished on the basis of their I_{Sr} values, according to Kráľ (1992, 1994). The S-type granitoids have this initial ratio higher than 0.707, in contrast to the I-type where it does not exceed 0.706, with the exceptions of the Tatra Mts. and Veľká Fatra Mts. (Petrík & Kohút 1997). Granitoids from the Gemeric Superunit (VVM-129) have extremely high I_{Sr} (Kovach et al. 1986), suggesting a pure (supra) crustal source. Since, the projection points in Fig. 4 plot over the mantle/basalt limit — 0.705, there is no isotopic proof for a direct input of juvenile mantle-derived magmas which could possibly have triggered anatexis and subsequent differentiation processes. The observed gabbroic rocks within the migmatite and/or anatectic granite rocks in the Branisko Mts., would indicate some genetic relations and thus they

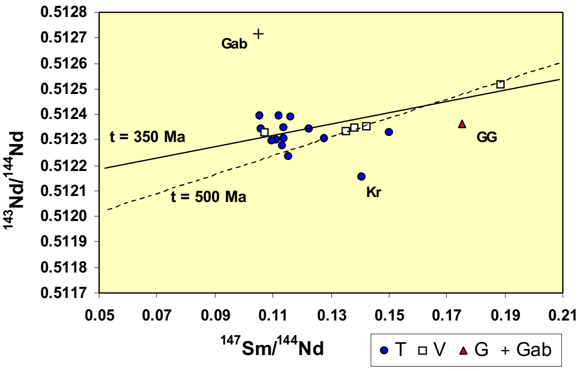

Fig. 5. $^{143}Nd/^{144}Nd$ versus $^{147}Sm/^{144}Nd$ correlation diagram for the West-Carpathian granite rocks. As can be observed, no isochron dependence reflecting lack of the regional scale homogenization. Symbols as in Fig. 3.

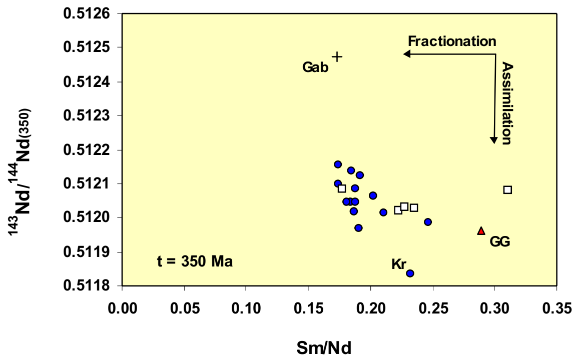

Fig. 6. Initial Nd isotopic ratio at 350 Ma versus Sm/Nd ratio diagram. The lack of a linear array rule out simple two-component source mixing and reflect rather heterogeneous sources and/or open system during genesis of the Carpathian granites.

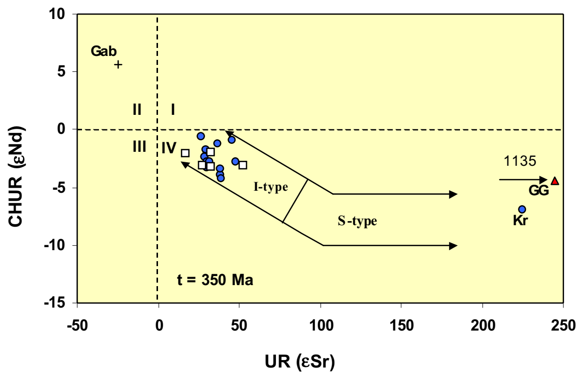

Fig. 7. Initial Nd and Sr isotopic compositions (in relation to CHUR & UR ε values) of the West-Carpathian granite rocks. Due to extremely high content of radiogenic ^{87}Sr of Gemeric granites the projection point falls beyond the diagram. I–IV quadrants scheduled on Faure (1986). I- S-type granite fields are modified from McCulloch & Chappell (1982).

could have been a potential source of heat. The projection points of the samples (Fig. 4) are at a slight angle, which may be interpreted as incomplete mixing between the two end members, but we can not exclude a slight country rocks assimilation for part of the granodiorites-granites.

In the Sm-Nd (WR) system no isochron relationship was observed indicating a lack of the regional scale homogenization, this is common for anatectic granite rocks (Kohút et al. 1995). This relative isotopic heterogeneity (Fig. 5) may have been caused by a) melting of a priori isotopically heterogeneous protoliths, b) a limited hybridization of two crustal anatectic magmas, and/or c) limited contamination by country-rocks. The isotopic variations within the Carpathian granites reflect rather open system processes (mixing of magmas from heterogeneous sources, and/or crustal contamination). On the Sm-Nd diagram a 350 Ma (Fig. 5) reference line is shown and the dashed line on this plot represents an errorchron from six tonalite–granite samples, which is consistent with initial $\varepsilon Nd_{(CHUR)} = -1.9$ and the age 508 Ma. However, Sm-Nd isotopic data are less susceptible to alteration by crustal processes such as metamorphism than Rb-Sr data, the situation in Fig. 6 is rather ambiguous. The lack of a linear array shows that simple two-component source mixing cannot explain the variations in the Sm and Nd concentrations and isotopic compositions within the West-Carpathian granite samples, albeit our limited research is deficient from end members. The $\varepsilon_{Nd}(0)$ values (Table 2) varying from –2.3 to –9.4 are comparable with data from the Hercynian fold belt of central Europe (Liew & Hofmann 1988), Massif Central (Pin & Duthou 1990), Bohemian Massif (Janoušek et al. 1995) and Tauern Window (Finger et al. 1992, 1993). Most of the West-Carpathian granitoid samples create a well defined field, in $\varepsilon_{Sr}^{(350)}$ vs. $\varepsilon_{Nd}^{(350)}$ plot (Fig. 7), falling more or less on the mixing line between crustal and mantle sources and situated in the I-type granitoid domain (McCulloch & Chappell 1982). In contrast, the isotopic characteristics of the Kraličká and the Gemer granites are comparable with the purely crustal (sedimentary) granites of SE Australia. One sample of the gabbro from the Veporic Superunit, falling on the mantle array in II quadrant, shows an obviously mantle origin. Although all the granite samples lie in quadrant IV, is their slight Sm enrichment and affinity to quadrant I is noteworthy. The magma source with both positive value enrichment parameters ($f_{Sm} > 0$ and $f_{Rb} > 0$) indicating a position within quadrant I, is untypical for ordinary felsic igneous rocks (Faure 1986), but common for old mafic lower crust — amphibolite/greenstone composition (Keay et al. 1997; Poller et al. 1998). The apparent crustal residence ages, indicated by Nd model age — $t_{(DM2st)}$ = 1.6 ~ 1.1 Ga, mostly 1.4–1.1 Ga are comparable with others from the Hercynian belt of Europe. For example, t_{DM2st} in the Bohemian Massif varies between 1.7 ~ 1.1 Ga (Liew & Hofmann 1988; Janoušek et al. 1995), Massif Central 1.8 ~ 0.9 Ga (Pin & Duthou 1990; Shaw et al. 1993). Table 2 also listed single-stage model ages $t_{(DM)}$ that would indicate extremely high crustal residence (3.8–2.0 Ga) for part of the felsic rocks. The crustal evolution in the Western Carpathians is better constrained by a two-stage evolution model, as is recommended by Liew & Hofmann (1988). Graphic expression of Nd evolution is given by Fig. 8. The highest apparent age was found in the leucocratic sample ZK-4 (1.6 Ga), which has the highest $\varepsilon_{Nd}(0)$ value as well. The gabbro model age is 620 Ma, that is in accord with the evolution of a hypothetical mantle reservoir in the Carpathian realm during the Pan-African orogeny (700–500 Ma). The impor-

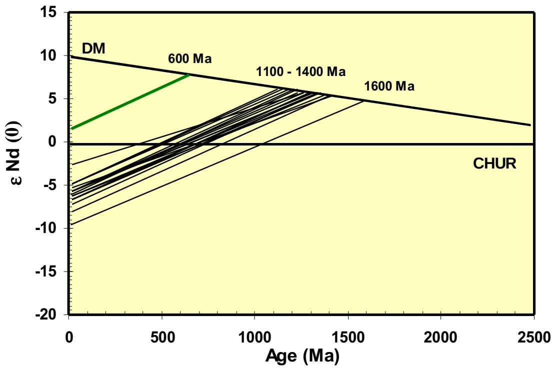

Fig. 8. Diagram Nd isotope evolution against time, showing depleted mantle model ages $t_{(DM2st)}$. DM curve according to Goldstein et al. (1984).

tance of the crustal contribution to the West-Carpathian granitoids is also confirmed by the neodymium crustal index (DePaolo et al. 1992) NCI = 0.4–1, mostly between 0.6–0.8 (Table 2). This is in accordance with the presence of huge amount of anatectic granite rocks elsewhere within the European Hercynides.

Discussion

Source of rocks

The source rocks of the West-Carpathian granitoids were discussed many times (e.g. Cambel & Petrík 1982; Kráľ 1992, 1994; Hovorka et al. 1994; Petrík et al. 1994; Kohút & Nabelek 1996; Petrík & Kohút 1997). According to Kráľ (l.c.), the Tatric and the Veporic granitoids were generated from an isotopically inhomogeneous source (mixing of mantle and crustal material) with a low Rb/Sr ratio. Petrík et al. (1994), considering the S-type rocks, suggested melting of peraluminous muscovite- and biotite-bearing metasedimentary rocks with carbonaceous, graphitized intercalations, via dehydration melting. Biotite- and biotite-hornblende plagiogneisses, according to the authors (l.c.), seem to be a proper source for melting of the I-type group. Kohút & Nabelek (1996), considering part of the Tatric I/S granitoids, suggested the melting of a vertically-zoned lower crust including older products of a volcanic arc (mantle-derived magmas) and crustal metasediments. Petrík & Kohút (1997) preferred for a) the S-type granites — supracrustal, reduced granulite facies rocks with minor addition of a mantle-like component, b) the I-type group — intermediate, non-reduced metaigneous rocks in interaction with underplated basaltic crust, c) the A-type group — H_2O-poor and F-rich granulite and/or tonalite crust, d) the Gemeric granites originated from mature, recycled sedimentary supracrustal rocks, or rocks which experienced sea-floor weathering, and were permeated by volcanic (boron) emanations.

The presented isotopic data (Sr, Nd) preclude a simple mantle or crustal origin for most of the Carpathian granites. Although the lowermost $^{87}Sr/^{86}Sr_{(350)}$ ratio in Fig. 4 is close to the mantle/basalt limit (0.705), in the majority of samples this ratio is slightly higher (0.706–0.708). Such low I_{Sr} are typical for I-type granite rocks e.g. McCulloch & Chappell (1982), Hensel et al. (1985), Liew et al. (1989) and Petford & Atherton (1996). Low I_{Sr} might be interpreted in a variety of ways: (1) melting of sedimentary rocks, containing much young volcanic material; 2) melting of lower crustal rocks with Rb depleted by granulite-facies metamorphism; 3) melting of a mixture of deep sea sediments with sea-floor basalts, 4) subducted oceanic slab melting 5) melting of underplated basaltic crust, and 6) melting of old greenstone. However, the situation 1, 3, 4 and 5, are typical for an active margin (Andean type) or mature island arc geotectonic setting, while the European Hercynides are connected with continental collisions (Burg & Matte 1978; Matte 1986, 1991; Pin & Duthou 1990; von Raumer & Neubauer 1993; Janák 1994 and Petrík & Kohút 1997). The nearly balanced and quasi-homogenized Rb/Sr isotope system (Fig. 4) in contrast with the Sm/Nd system (Fig. 6), demonstrate dominance of the Hercynian processes during the constitution of the West-Carpathian basement. Due to multistage collisional tectonics the pre-Carboniferous crust of the European Hercynides was sufficiently thickened, hot enough and „granite fertile“ (Vielzeuf et al. 1990). The dehydration melting of muscovite, biotite and/or hornblende-bearing rocks has been widely suggested as a melt-forming process during crustal anatexis (Clemens & Vielzeuf 1987; LeBreton & Thompson 1988; Patiño Douce et al. 1990; Skjerlie et al. 1993; Wolf & Wyllie 1994; Singh & Johannes 1996 and Montel & Vielzeuf 1997 amongst others). The highly fertile potential source for this melting could have been greywackes, metapelites, hydrated mafic or intermediate metavolcanics (amphibolites and/or greenstone rocks), primary andesites or tonalites. However, isotopic constraints discard pure depleted mantle source on the basis distinctly negative $\varepsilon_{Nd}^{(350)}$, as well as uncontaminated crustal source due to the low I_{Sr}, for the majority of Carpathian granites, therefore a heterogeneous source can be inferred. The $\varepsilon_{Nd}^{(350)}$ versus $\varepsilon_{Sr}^{(350)}$ data for the West-Carpathian granitoids (Fig. 7) are more or less consistent with derivation from an enriched source in the subcontinental lithosphere or amphibolitic lower crust imbricated during initial stage of intracontinental subduction/collision, with the addition of an upper crustal component. Since, collisional scenarios rule out a substantial input of mantle magma, a sufficient heat source for melting is necessary. Only sedimentary rocks enriched in U, Th and K are characterized by a high radioactive heat production, from potential supra-crustal sources. As was mentioned above, this precursor forms a minor contribution to the magma with observed isotopic signature, therefore some additional heat flux is required for melting of the lower crust. Heat from an underplated and/or intraplated mantle-derived magma could provide the necessary thermal energy for crustal anatexis (Holland & Lambert 1975; Wells 1981; Huppert & Sparks 1988; Dewey 1988 amongst others). However, the genetic relations of the West-Carpathian granitoids with the gabbro from the Veporic Superunit are not clear, recent studies in Branisko Mts. confirmed presence of gabbroic rocks within a greenstone–granite anatectic complex. The tectonic importance of these rocks could be questioned without precise U-Pb dating, inasmuch is not clear, if they promoted the Hercynian tectonic and/or anatectic processes, or represent a Pan-African product of mantle magma (t_{DM} = 613 Ma), forming underplated "juvenile" basaltic crust. Our data, with the exceptions of the Kralička leucogranites and the Gemeric granites, require a minimum of three reservoir components to satisfy the range of values within the complex, as follows: a depleted mantle (DM) component, LREE-enriched mafic lower crust and continental crust (CC). The heterogeneous source is inferred by the variegated association of metamorphic xenoliths (gneisses, amphibolites, eclogites ± granulites) and/or MME, which are observed commonly in the West-Carpathian granites (Hovorka & Petrík 1992; Petrík et al. 1994; Janák 1994; Janák et al. 1996, 1999; Petrík & Kohút 1997). Indeed, the Carpathians basement in its recent form, represents a big puzzle consisting of low- to high-grade metamorphic rocks, amphibolites, migmatites, orthogneisses, granites, greenstone rocks and/or upper Paleozoic sedimentary and volcanic rocks.

Crustal evolution

As for almost all European basement territory, products of the Hercynian orogeny are dominant in the Western Carpathians crystalline areas at the present erosion level. The available isotope data (U-Pb, Rb-Sr and Ar-Ar) mainly date the event between 360 and 340 Ma. The HT/MP metamorphism with concomitant widespread granitoid magmatism was responsible for potential resetting of old Rb-Sr isotopic records within the precursor/source rocks. So far only scarce U-Pb zircon data were published indicating older events, in the Gemeric Superunit — 403 Ma for porphyroid rocks (Scherbak et al. 1988). In the Tatric Superunit, an orthogneiss precursor of age 380–405 Ma (Poller et al. 1997; Poller et al in review) and/or a 500 Ma old metamorphic event from metasedimentary rocks of the lower unit (Todt et al. 1998), have been documented. The presented apparent crustal model ages $t_{(DM2st)}$ = 1.6 ~ 1.1 Ga (Table 2 and Fig. 8) are partly in accord with recent U-Pb zircon upper intercept data (2.5 ~ 1.2 Ga: Poller et al. 1997; Poller et al in review; Kráľ et al. 1997 and Michalko et al. 1998). Available Sm-Nd model ages $t_{(DM)}$ single-stage, upper intercept ages from conventional and single grain U-Pb zircon dating, as well as Pb-Pb isochrons of leached samples were used to derive semi-quantitative estimates on crustal growth rates (Kohút et al. 1998). The Hercynian crust of the Western Carpathians consists predominantly of reworked–recycled Proterozoic crust with a minor addition (ca. 10 %) of amalgamated Archean rocks (Kohút et al. l.c.). The Western Carpathians crustal growth was continuous during the Proterozoic period, which is more consistent with the growth of the supercontinent Laurasia, than of Gondwana (Gebauer et al. 1989; Gebauer & Williams 1990) — showing an episodic character. The Western Carpathians average crustal age is 1590 Ma (Kohút et al. 1998), however, the presented Sm-Nd data (Table 2) indicate only 1250 Ma, which is younger than in other segments of the European Hercynides -1.8 Ga (Gebauer & Williams 1990). During the Hercynian orogeny mainly Middle Proterozoic rock products of crustal origin were influenced by collision. This is in accord with new Pb-Pb whole rock isotope studies from the Tatra Mts., where rocks gave a secondary isochron with the age of 1200 Ma and μ = 8.2 and/or κ = 3.8 — typical for a crustal source of the precursor (Todt et al. 1998). All facts support the concept that Hercynian Europe comprises mainly recycled Proterozoic components with significant new Paleozoic additions as well as minor Archean contributions (Liew & Hofmann 1988).

Conclusions

The Sr-Nd isotopic compositions of the West-Carpathian granitic rocks are comparable with other segments of the European Hercynides such as the Bohemian Massif, Massif Central and/or Eastern Alps. Low I_{Sr}, typical for I-type granite rocks, are consistent with derivation from Rb depleted lower crustal rocks. The $\varepsilon_{Nd}(0)$ values varying from -2.3 to -9.4 are analogous to those common in crustal anatectic granites of Central Europe, although from the position of the samples in the CHUR-UR diagram, (IV quadrant with affinity to quadrant I), indicating Sm enrichment of these rocks, an enriched source in the subcontinental lithosphere or amphibolitic lower crust, can be inferred. The geochemical and isotopic signature of the studied samples reflects, rather open system processes with mixing of (mainly crustal) magmas from heterogeneous sources, and/or crustal contamination, than a simple mantle and/or crustal origin for most of the Carpathian granites. We cannot exclude, from the presented data, a hypothetical mantle (DM) source, at least as heat flux during crustal anatexis processes. The apparent crustal residence ages, indicated by Nd model age — $t_{(DM2st)}$ = 1.6 ~ 1.1 Ga, are in accord with others from the Hercynian belt of Europe. All geochemical features suggest that the West-Carpathian granitoids are analogous to the VAG (CAG) igneous suites, commonly related to subduction processes at an active (Andean) continental margin. However, the surrounding metamorphic rock associations and their P-T conditions indicate rather intracontinental subduction, or a collisional setting, involving high-grade metasedimentary and metaigneous rocks at lower- to mid-crustal conditions. The spatial and temporal distribution of Late Paleozoic sedimentary basins in the Western Carpathians (Vozárová & Vozár 1996) suggest continental interior source areas. In view of all the facts outlined here, we can conclude that the West-Carpathian granite rocks were generated by partial melting of mainly crustal Proterozoic material, during subduction-collisional processes of the Hercynian orogeny.

Acknowledgements: We are grateful to Dr. Igor Broska, Dr. Ľubomír Hraško, Dr. Igor Petrík and Dr. Vojtech Vilinovič, who have kindly donated samples for this study and permitted publication of primary chemical data. Prof. Petr Černý (The University of Manitoba, Winnipeg) and Dr. Pavel Uher (SAS Bratislava) are thanked for major and trace element analyses, performed due to NSERC Grant #311-1727-17. Dr. Claudia Carl (BGR Hannover) is greatly acknowledged for Rb/Sr isotope analyses. This paper greatly benefited from construtive reviews by Vojtěch Janoušek, Igor Petrík and Ján Kráľ. The paper is a contribution to the IGCP Project No. 373.

Appendix

Sample description and location.

		X	Y	Z
VF- 43	— muscovite-biotite granite, natural outcrop Vyšná Krivá,	412114.31	1196930.65	1 035.0
VF-356	— biotite tonalite, quarry Vyšné Matejkovo,	408061.99	1200190.42	812.0
VF-639	— biotite granodiorite, natural outcrop Blatná valley,	414769.84	1198772.91	742.0
VF-700	— muscovite granite, natural outcrop Nižné Matejkovo,	406991.06	1199585.00	825.0
VF-298	— muscovite-biotite granodiorite, nat.o., Vyšné Matejkovo,	406993.63	1200361.06	705.0
VK-139	— biotite granodiorite, natural outcrop Malý Javorník,	569486.33	1268494.94	545.0
BGPI-1	— biotite granodiorite, natural outcrop Hradná valley,	501917.89	1235838.12	290.0
T-87	— biotite granodiorite, natural outcrop Krnča,	484357.55	1246524.83	250.0
MM-29	— muscovite-biotite granite, natural outcrop Poruba valley,	460325.62	1212841.99	665.0
Z-164	— biotite-muscovite granite, quarry Veľká valley,	444358.90	1216640.10	590.0
MF-4a	— muscovite-biotite granodiorite, quarry Bystrička,	416914.89	1179812.65	575.0
NT-401	— biotite granodiorite, natural outcrop Liptovská Lúžna,	401950.15	1204520.10	960.0
ZK-4	— muscovite granite, natural outcrop Vyšná Boca,	372810.20	1210650.23	1 045.0
TL-117	— muscovite-biotite granodiorite, nat.o., Prostredný ridge,	350195.62	1182543.09	1 920.0
VG-46	— biotite granodiorite, quarry Klementka,	383220.96	1238311.30	870.0
VG-47	— muscovite-biotite granodiorite, quarry Chorepa,	366596.55	1247755.24	555.0
V-7312	— biotite-muscovite granite, natural outcrop České Brezovo,	371030.13	1259533.48	340.0
V-9738	— muscovite-biotite granite, natural outcrop Solisko,	343414.11	1236571.87	660.0
VVM-129	— biotite-muscovite granite, drill well Peklisko,	313567.80	1226895.76	596.9
CH-3/72	— muscovite-biotite granodiorite, quarry near Ružín dam,	274405.09	1223137.43	360.0
KV-3/622	— gabbro, borehole Rochovce,	333852.00	1238006.15	408.5

References

Bagdasaryan G.P., Gukasyan R.Kh., Cambel B. & Veselský J., 1983: Results of Rb-Sr age determinations of metamorphic rocks of the Malé Karpaty crystalline complex. *Geol. Zbor. Geol. Carpath.,* 34, 387–397 (in Russian, English summary).

Bagdasaryan G.P., Gukasyan R.Kh., Cambel B. & Veselský J., 1985: Rb-Sr isochron dating of the Ďumbier zone granitoids of the Nízke Tatry Mts. (Western Carpathians). *Geol. Zbor. Geol. Carpath.,* 36, 637–645 (in Russian, English summary).

BenOthman D., Fourcade S. & Allégre C.J., 1984: Recycling processes in granite-granodiorite complex genesis: the Querigut case studied by Nd-Sr isotope systematics. *Earth Planet. Sci. Lett.,* 69, 290–300.

Boynton W.V., 1984: Geochemistry of the rare earth elements: meteorite studies. In: Henderson P. (Ed.): *Rare earth elements geochemistry. Elsevier*, 63–114.

Burchart J., 1968: Rubidium-strontium isochrone ages of the crystalline core of the Tatra Mts., Poland. *Amer. J. Sci.,* 266, 895–907.

Burg J.P. & Matte Ph., 1978: A cross-section trough the French Massif Central and the scope of its Variscan geodynamic evolution. *Z. Dtsch. Geol. Gesell.*, 109, 429–460.

Cambel B. & Petrík I., 1982: The West Carpathian granitoids: I/S classification and genetic implications. *Geol. Zbor. Geol. Carpath.,* 33, 255–267.

Clemens J.D. & Vielzeuf D., 1987: Constraints on melting and magma production in the crust. *Earth Planet. Sci. Lett.,* 86, 287–306.

DePaolo D.J. & Wasserburg, 1976: Nd isotope variations and petrogenetic models. *Geophys. Res. Lett.*, 3, 249–252.

DePaolo D.J., Perry F.V. & Baldridge S.W., 1992: Crustal versus mantle sources of granitic magmas: a two parameter model based on Nd isotopic studies. *Trans. R. Soc. Edinburgh, Earth Sci.,* 83, 439–446.

Dewey J.F., 1988: Extensional collapse of orogens. *Tectonics,* 7, 1123–1139.

Dupej J. & Siegl K., 1984: Geology of the Kralička granite and its environment (Nizke Tatry Mts., Western Carpathians) *Geol. Zbor. Geol. Carpath.,* 35, 395–411.

Faure G., 1986: Principles of Isotope Geology. *Wiley,* New York, 2nd ed., 1–589.

Finger F., Frasl G., Haunschmidt B., von Quadt A., Schermaier A., Schindlmayr A.O. & Steyrer H.P., 1992: Late Paleozoic plutonism in the Eastern Alps. *ALCAPA Field Guide,* IGP/KFU Graz, 37–45.

Finger F., Frasl G., Haunschmidt B., Lettner H., von Quadt A., Schermaier A., Schindlmayr A.O. & Steyrer H.P., 1993: The Zentralgneise of the Tauern window (Eastern Alps): Insight into an intra-Alpine Variscan batholith. In: Von Raumer J.F. & Neubaue F. (Eds.): *Pre-Mesozoic geology of the Alps. Springer,* Berlin–Heidelberg–New York, 375–391.

Gebauer D., Williams I.S., Compston W. & Grünenfelder M., 1989: The development of Central European continental crust since the early Archean based on conventional and ion-microprobe of up to 3.84 by. old detrital zircons. *Tectonophysics,* 157, 81–96.

Gebauer D. & Williams I.S., 1990: Crust and mantle evolution of the European Hercynides. *Abstr. ICOG 7*, Canberra, *Geol. Soc. Austr*., 27, 38.

Goldstein S.J., O'Nions R.K. & Hamilton P.J., 1984: A Sm-Nd isotopic study of atmospheric dusts and particulates from major river systems. *Earth Planet. Sci. Lett.*, 70, 221–236.

Goldstein S.J. & Jacobsen S.B., 1988: Nd and Sr isotopic systematic of rivers water suspended material: implications for crustal evolution. *Earth Planet. Sci. Lett.*, 87, 249–265.

Hensel H.D., McCulloch M.T. & Chappell B.W., 1985: The New England Batholith: constraints on its derivation from Nd and Sr isotopic studies of granitoids and country rocks. *Geochim. Cosmochim. Acta*, 49, 369–384.

Holland J.G. & Lambert R.St.J., 1975: The chemistry and origin of the Lewisian gneisses of Scottish mainland: The Scourie and Inver assemblages and sub-crustal accretion. *Precambrian Res.*, 2, 161–188.

Hovorka D., Méres Š. & Ivan P., 1994: Pre-Alpine Western Carpathian basement complexes: lithology and geodynamic setting. *Mitt. Österr. Geol. Gesell.,* 86, 33–44.

Hovorka D. & Petrík I., 1992: Variscan granitic bodies of the Western Carpathians — the backbone of the mountain chain.

In: Vozár J. (Ed.): *The Paleozoic geodynamic domains of the Western Carpathians, Eastern Alps and Dinarides. Spec. Vol. IGCP Project 276*, Bratislava, 57–66.

Hraško Ľ., 1993: The Alpine granitoids — possibility of existence within contact zone between Veporicum and Gemericum and their role in the Western Carpathians structure. *Open File Report, GÚDŠ,* Bratislava, 1–144 (in Slovak).

Hraško Ľ., Kotov A.B., Salnikova E.B. & Kovach V.P., 1998: Enclaves in the Rochovce granite intrusion as indicators of the temperature and origin of the magma. *Geol. Carpathica,* 49, 2, 125–138.

Huppert H.E. & Sparks R.S., 1988: The generation of granitic magmas by intrusion of basalt into continental crust. *J. Petrology,* 29, 599–624.

Jacobsen S.B. & Wasserburg G.J., 1980: Sm-Nd isotopic evolution of chondrites. *Earth Planet. Sci. Lett.*, 50, 139–155.

Janák M., 1994: Variscan uplift of the crystalline basement, Tatra Mts., Central Western Carpathians: Evidence from $^{40}Ar/^{39}Ar$ laser probe dating of biotite and P-T-t paths. *Geol. Carpathica,* 45, 293–300.

Janák M., O´Brien P.J., Hurai V. & Reutel C., 1996: Metamorphic evolution and fluid composition of garnet-clinopyroxene amphibolites from the Tatra Mountains, Western Carpathians. *Lithos,* 39, 57–79.

Janák M., Hurai V., Ludhová L., O´Brien P.J. & Horn E.E., 1999: Dehydration melting and devolatilization of high-grade metapelites: the Tatra Mountains, Western Carpathians. *J. Metamor. Geol.* (in print).

Janoušek V., Rogers G. & Bowes D.R., 1995: Sr-Nd isotopic constraints on the petrogenesis of the Central Bohemian pluton, Czech republic. *Geol. Rdsch.,* 84, 520–534.

Keay S., Collins W.J. & McCulloch M.T., 1997: A three-component Sr-Nd isotopic mixing model for granitoid genesis, Lachlan fold belt, eastern Australia. *Geology,* 25, 4, 307–310.

Kohút M., Carl C. & Michalko J., 1996: Granitoid rocks of the Veľká Fatra Mts. Rb/Sr isotope geochronology (Western Carpathians, Slovakia). *Geol. Carpathica,* 47, 2, 81–89.

Kohút M., Kotov A.B., Salnikova E.B., Kovach V.P. & Michalko J., 1995: Hercynian granitic rocks of the Western Carpathians: products of crustal reactivation. In: Brown M. & Piccoli Ph.M. (Eds.): *The origin of granites and related rocks, USGS Circular 1129,* Reston, 81–82.

Kohút M. & Nabelek P.I., 1996: Sources of the Veľká Fatra granitoid rocks, Slovakia: Isotopic constraints or contradiction? *Pol. Miner. Soc., Spec. Pap.,* 7, 47–50.

Kohút M., Poller U., Todt W. & Janák M., 1998: Where are the roots of the Western Carpathians (Slovakia)? — Evidence from isotope study. *POCEEL Praha, Acta Univ. Carolinae, Geologica,* 42, 2, 277.

Kovach A., Svingor E. & Grecula P., 1986: Rb-Sr isotopic ages of granitoid rocks from the Spišsko-gemerské rudohorie Mts. *Miner. slovaca,* 18, 1–14.

Kráľ J., 1992: Outline of the strontium isotope evolution in the basement of Tatric and Veporic units. *Miner. slovaca*, 24, 197–208.

Kráľ J., 1994: Strontium isotopes in granitic rocks of the Western Carpathians. *Mitt. Österr. Geol. Gesell.,* 86, 75–81.

Kráľ J., Hess J.C., Kober B. & Lippolt H.J., 1997: $^{207}Pb/^{206}Pb$ and $^{40}Ar/^{39}Ar$ age data from plutonic rocks of the Strážovské vrchy Mts. basement, Western Carpathians. In: Grecula P., Hovorka D. & Putiš M. (Eds.)*: Geological evolution of the Western Carpathians. Miner. slovaca—Monograph,* 253–260.

Krist E., Korikovsky S.P., Putiš M., Janák M. & Faryad S.W., 1992: Geology and petrology of metamorphic rocks of the Western Carpathian metamorphic complexes. *Univ. Comen.,* Bratislava, 7–342.

LeBreton N. & Thompson A.B., 1988: Fluid-absent (dehydration) melting of biotite in metapelites in the early stage of crustal anatexis. *Contr. Mineral. Petrology*, 99, 226–237.

Liew T.C. & Hofmann A.W., 1988: Precambrian crustal components, plutonic associations, plate environment of the Hercynian fold belt of Central Europe: Indications from a Nd and Sr isotopic study. *Contr. Mineral. Petrology,* 98, 129–138.

Liew T.C., Finger F. & Höck V., 1989: The Moldanubian granitoid plutons of Austria: Chemical and isotopic studies bearing on their environmental setting. *Chem. Geol.*, 76, 41–55.

Matte Ph., 1986: Tectonics and Plate Tectonics Model for the Variscan Belt of Europe. *Tectonophysics,* 126, 329–374.

Matte Ph., 1991: Accretionary history and crustal evolution of the Variscan belt in Western Europe. *Tectonophysics,* 196, 309–337.

Michalko J., Bezák V., Kráľ J., Huhma H., Mäntäri I., Vaasjoki M., Broska I., Hraško Ľ. & Határ J., 1998: U/Pb zircon data from the Veporic granitoids (Western Carpathians). *Krystalinikum*, 24, 91–104.

McCulloch M.T. & Chappell B.W., 1982: Nd isotopic characteristic of S- and I-type granites. *Earth Planet. Sci. Lett.,* 58, 51–64.

Montel J.M. & Vielzeuf D., 1997: Partial melting of metagreywackes, Part II. Compositions of minerals and melts. *Contr. Mineral. Petrology*, 128, 2–3, 176–196.

Moreno-Ventas I., Rogers G. & Castro A., 1995: The role of hybridization in the genesis of Hercynian granitoids in the Gredos Massif, Spain: inferences from Sr-Nd isotopes. *Contr. Mineral. Petrology*, 120, 137–149.

Neymark L.A., Kovach V.P., Nemchin A.A., Morozova I.M., Kotov A.B., Vinogradov D.P., Gorochovsky B.M., Ovchinikova G.V., Bogomolova L.M. & Smelov A.P., 1993: Late Archaean intrusive complexes in the Olekma granite-greenstone terrain (Eastern Siberia): geochemical and isotopic study. *Precambrian Res.*, 62, 453–472.

Patiño Douce A.E., Humphreys E.D. & Johnston A.D., 1990: Anatexis and metamorphism in tectonically thickened continental crust exemplified by the Sevier hinterland, western North America. *Earth Planet. Sci. Lett.,* 97, 290–315.

Petford N. & Atherton M., 1996: Na-rich partial melts from Newly Underplated Basaltic Crust: the Cordiliera Blanca Batholith, Peru. *J. Petrology,* 37, 6, 1491–1521.

Petrík I. & Broska I., 1994: Petrology of two granite types from the Tríbeč Mountains, Western Carpathians: an example of allanite (+magnetite) versus monazite dichotomy. *Geol. J.*, 29, 59–78.

Petrík I., Broska I. & Uher P., 1994: Evolution of the Western Carpathian granite magmatism: Age, source rock, geotectonic setting and relation to the Variscan structure. *Geol. Carpathica,* 45, 283–291.

Petrík I. & Kohút M., 1997: The evolution of granitoid magmatism during the Hercynian orogen in the Western Carpathians. In: Grecula P., Hovorka D. & Putiš M. (Eds.): *Geological evolution of the Western Carpathians. Miner. slovaca—Monograph,* 235–252.

Pin Ch. & Duthou J.L., 1990: Sources of Hercynian granitoids from the French Massif Central: inferences from Nd isotopes and consequences for crustal evolution. *Chem. Geol.*, 83, 281–296.

Plašienka D., 1995: Passive and active margin history of the northern Tatricum (Western Carpathians, Slovakia). *Geol. Rdsch.,* 84, 748–760.

Plašienka D., Grecula P., Putiš M., Hovorka D. & Kováč M., 1997. Evolution and structure of the Western Carpathians: an overview. In: Grecula P., Hovorka D. & Putiš M. (Eds.): *Geological Evolution of the Western Carpathians. Miner. slovaca—Monograph,* 1–24.

Poller U., Todt W., Janák M. & Kohút M., 1997: Pre-Variscan orthogneisses of the Western Tatra Mts.: U-Pb single zircon data by cathodoluminiscence controlled dating. *Terra Abstracts,* 9, 1, EUG 9, Strasbourg, 488.

Poller U., Janák M., Kohút M. & Todt W., 1998: Pre-Variscan evolution of the Western Tatra Mts (Slovakia): A Sm-Nd, Rb-Sr and Pb-Pb isotope study. *The IXth ICOG meeting Beijing*, *Chin. Sci. Bull*., 43, 103.

Poller U., Janák M., Kohút M. & Todt W., in review: U-Pb zircon data from the Tatra Mountains, Western Carpathians, Slovakia: Evidence for a multistage Variscan granite magmatism. *Submitted to Geologische Rundschau.*

von Raumer J.F. & Neubauer F., 1993: Late Proterozoic and Paleozoic evolution of the Alpine basement — an overview. In: von Raumer J.F. & Neubauer F. (Eds.): *Pre-Mesozoic Geology of Alps. Springer,* Berlin, Heidelberg, New York, 625–639.

Richards P., Shimizu N. & Allegre C.J., 1976: $^{143}Nd/^{144}Nd$, a natural tracer: An application to oceanic basalts. *Earth Planet. Sci. Lett.,* 31, 269–278.

Shcherbak N.P., Bartnicky E.N., Mickevich N.Y., Stepanyuk L.M., Cambel B. & Grecula P., 1988: U-Pb radiometric zircon age determination from the Modra granodiorite of the Malé Karpaty Mts. and a porfyroid of the lower Paleozoic of the Spišsko -gemerské rudohorie Mts. (Western Carpathians), *Geol. Zbor. Geol. Carpath.,* 39, 427–436 (in Russian, English summary).

Shaw A., Downes H. & Thirlwall M.F., 1993: The quartz diorites of Limousin: elemental and isotopic evidence of Devono-Carboniferous subductionin the Hercynian belt of the French Massif Central. *Chem. Geol.,* 107, 1–18.

Siegl K., 1976: The structure of the Low Tatra pluton (West Carpathians). *Geol. Zbor. Geol. Carpath.,* 27, 149–164.

Singh J. & Johannes W., 1996: Dehydration melting of tonalites. Part II. Composition of melts and solids. *Contr. Mineral. Petrology,* 125, 26–44.

Skjerlie K.P., Patiño Douce A.E. & Johnston A.D., 1993: Fluid-absent melting of a layered crustal protolith: Implications for the generation of anatectic granites. *Contr. Mineral. Petrology*, 114, 356–378.

Todt W., Poller U., Janák M. & Kohút M., 1998: U-Pb Zircon dating of metamorphic rocks of the West-Tatra using single zircon grains under cathodoluminescence control. *The IXth ICOG meeting Beijing, Chin. Sci. Bull.,* 43, 130.

Vielzeuf D., Clemens J.C., Pin Ch. & Moinet E., 1990: Granites granulites and crustal differentiation. In: Vielzeuf D. & Vidal Ph. (Eds.): *Granulites and Crustal Evolution. Kluwer*, Dordrecht, 59–85.

Vozárová A. & Vozár J., 1996: Terranes of Western Carpathians — North Pannonian Domain. *Slovak Geol. Mag.,* 1/96, 65–85.

Wedepohl K.H., 1995: The composition of continental crust. *Geochim. Cosmochim. Acta*, 59, 7, 1217–1232.

Wells P.R.A., 1981: Accretion of continental crust: thermal and geochemical consequences. *Philos. Trans. R. Soc. London*, A301, 347–357.

Wendt I., 1986: Radiometrische Methoden in der Geochronologie. *Ellen Pigler Verlag,* Clausthal Zellerfeld, 80–86.

Wolf M.B. & Wyllie P.J., 1994: Dehydration-melting of amphibolite at 10 kbar: Effects of temperature and time. *Contr. Mineral. Petrology,* 115, 369–383.