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Original paper

Geochemical and isotopic (Sr, Nd and O) constraints on sources of Variscan granites in the Western Carpathians – implications for crustal structure and tectonics

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A Sr, Nd, and O isotopic study of Variscan granitoid rocks from the Western Carpathians reveals the dominance of heterogeneous crustal sources for the most of the granitic rocks. Their neodymium crustal index (NCI) is 0.4 to 1.0 (mainly 0.6–0.8). Initial $(^{87}Sr/^{86}Sr)_{350}$ of 0.7053 to 0.7078 and $\varepsilon_{Nd}^{(350)}$ of -0.6 to -6.9 preclude a simple mantle and/or crustal origin for most of granitoids and suggest more complex sources, such as vertically zoned lower crust consisting of old metaigneous, amphibolitic and metasedimentary rocks. Apparent crustal residence ages, indicated by two-stage depleted-mantle Nd model ages ranging from 1.6 to 1.1 Ga, are comparable with other segments of the European Variscan belt. The whole rock $\delta^{18}O_{(SMOW)}$ values of the granites are heterogeneous and range from 8.4 ‰ in tonalites to 11.3 ‰ in leucogranites, reflecting source compositions ranging from mafic to silicic. Petrographically, these granites are representative of common crustal anatectic rocks with magmatic muscovite; however, their isotopic signature reflects petrogenesis related to subduction processes at active continental margins. Recent metamorphic, sedimentary and/or structural studies of the Variscan basement of the Western Carpathians suggest a continental collisional rather than a volcanic arc setting. The Western Carpathian granitic rocks were most likely generated by partial melting of mainly recycled Proterozoic crustal material during subduction-collisional processes of the Variscan orogeny, with possible input of mafic magmas from the mantle. These mafic magmas may have served as a heat source for melting of the lower crust.

Keywords: granite origin, isotope geochemistry, source of rocks, crustal evolution, Western Carpathians
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1. Introduction

The present-day structure of the Alps and Carpathians, forming part of Stille's (1924) Alpine "Neo-Europa", is mainly the result of convergent processes between the African Plate fragments (Adria–Apulia) and the North European Plate (Eurasia) spanning from the Late Jurassic to the present (Plašienka et al. 1997). Tethian sedimentary rocks dominate this orogenic mobile belt. However, the pre-Mesozoic basement is an important component of the structure of the Carpathians (Petrík and Kohút 1997). Its polyorogenic history is characterised by juxtaposition of various terranes and/or blocks that in most cases originated at the Gondwana margin due to multistage tectonic evolution with large-scale nappe and strike-slip tectonics as part of the European Variscan orogeny (Stampfli and Borel 2002; von Raumer et al. 2002). Although the basement rocks form only discrete fragments in the Alpine Carpathians structure, the granitic rocks dominate at the present erosion level. One of the salient features of the Western Carpathians is a great variety of granitic rocks within small areas (Petrík and Kohút 1997). There exist many similarities between the Variscan granitic rocks of the Alpine "Neo-Europa" and those of the European Variscan belt in the Iberian Massif, the Massif Central, and the Bohemian Massif that represent "Meso-Europa" in sense of Stille (1924). The varieties of granitoid suites include: (a) high-K–Mg, (b) peraluminous, (c) calc-alkaline; (d) ferro-potassic, (e) subalkaline, and (f) anorogenic – alkaline (Bonin et al. 1993; Finger et al. 1997; Schaltegger 1997; Bussy et al. 2000; Kohút 2002, among others). These suites were generated during main and late-Variscan orogenic stages. However, distribution of these series within particular basement blocks is not uniform and is still a matter of debate. The aim of this paper is to present Sr-Nd-O isotopic data from Western Carpathian granitic rocks that place constraints on their sources, petrogenesis, as well as the Variscan crustal evolution and tectonics.

2. Geological setting

Similarly to the Pyrenees and Alps, the Carpathian Mountain chain is a typical Alpine collisional fold belt. However, its pre-Mesozoic basement rocks were part of the Variscan orogenic belt. During the Alpine orogeny, the Carpathian part of the Variscan belt was disrupted and sliced into nappe and terrane blocks that were variously uplifted (Andrusov 1968; Plašienka et al. 1997). This polyorogenic history makes reconstruction of the Variscan structures rather difficult but provides excellent exposure of various levels of the Variscan 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) which consist of three principal crustal-scale superunits (from north to south): the Tatricum, the Veporicum and the Gemericum. In addition there are several cover-nappe systems, including the Fatricum, the Hronicum and the Silicicum, also generally emplaced in sequence from north to south (Plašienka et al. 1997). The Variscan granitoid rocks occur in all three superunits of the CWC (Fig. 1; a more detailed geological map of the Western Carpathians can be found at *http://www.geology.sk*).

In the **Tatricum** the granitoids along with pre-Mesozoic metamorphic rocks build backbones of the so-called "core mountains". Both rock types are overlain by Mesozoic cover sediments and/or nappes. The basement rocks were only weakly affected by Alpine metamorphism (Krist et al. 1992). A large composite granodiorite–tonalite body, strongly affected by the Alpine shear tectonics, dominates the **Veporicum**. Other basement rocks include high- to low-grade metamorphic rocks. These are overlain by Upper Paleozoic and Mesozoic cover. Due to complex Variscan and Alpine tectonics, this unit has a very complicated imbricate structure. The degree of penetrative brittle–ductile deformation increases from the northwest to the southeast. The **Gemericum** is dominated by a large hidden granitoid body, which penetrates the overlying Lower Paleozoic rocks in the form of apophyses (Kohút and Stein 2005 and references therein). The Paleozoic rocks are composed of Silurian to Late Carboniferous, mostly low-grade flysch-like metasedimentary rocks and metavolcanics with remnants of an ophiolite complex. Granitoid magmatism dominated in the Variscan orogeny of the Western Carpathians from 360 to 250 Ma (Petrík and Kohút 1997; Finger et al. 2003). In response to variable geotectonic events, different types of granitic magmas have formed during: a) Early Carboniferous crustal thickening, b) Late Carboniferous thermal event, and c) Permian transtension, as recorded by the respective presence of S-, I- and A-type granitic suites (Petrík and Kohút 1997; Broska and Uher 2001; Finger et al. 2003). Available age data (U-Pb, Rb-Sr and Ar-Ar) indicate the main phase of granite magmatism to have been between 360 and 340 Ma (Petrík and Kohút 1997; Kohút 2007); therefore we adopted the age 350 Ma for calculations of initial isotopic compositions.

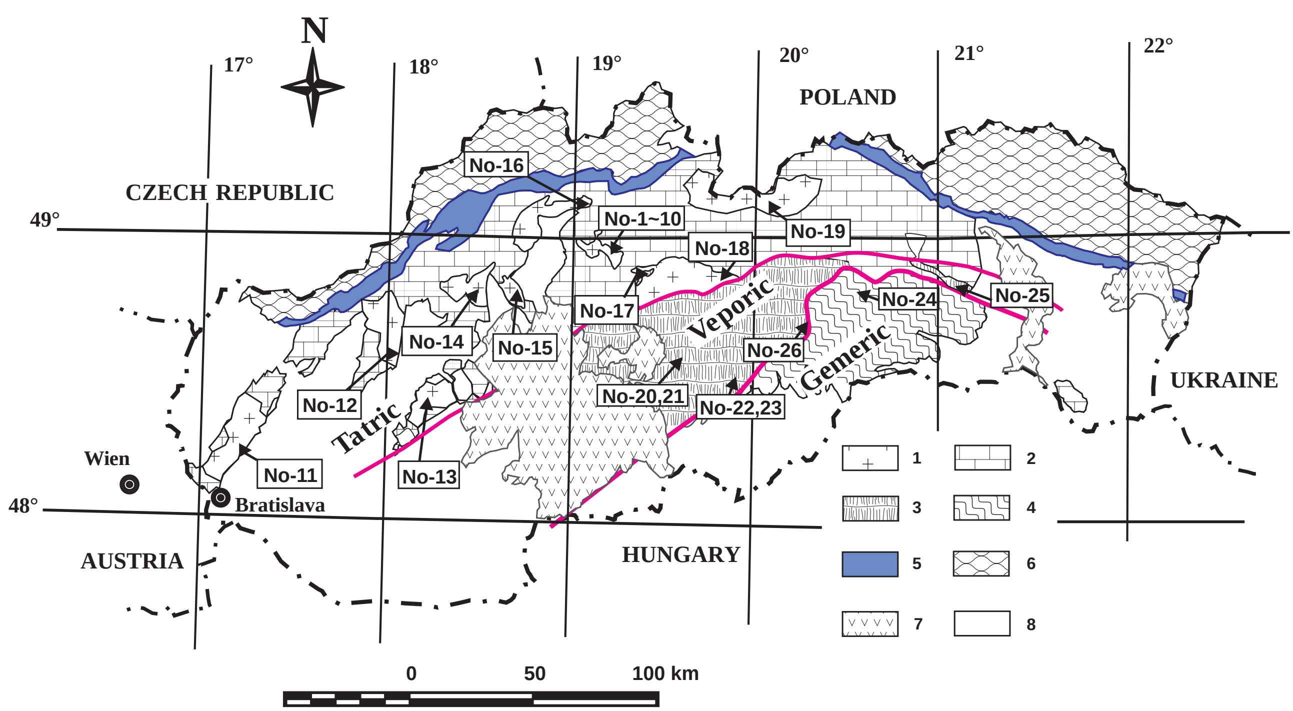

Fig. 1 Simplified tectonic-geological sketch of the Western Carpathians (Slovak part) with location of investigated samples. **1** – Pre-Alpine crystalline basement of Tatric Unit, **2** – Mesozoic sedimentary cover and nappe structures, **3** – Veporic Unit, **4** – Gemeric Unit, **5** – Klippen belt,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

3. Analytical methods

Geochemical analyses were performed at the University of Ottawa by X-ray fluorescence and at the Dionýz Štúr Institute of Geology, Bratislava using classical wet chemical techniques. The REE concentrations were analyzed at the Memorial University of Newfoundland, St. John's by ICP-MS (Jenner et al. 1990) and by INAA at MEGA Brno Inc. The measurements were verified against international GM and BM standards. The Sm-Nd isotope analyses were performed at the Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences, St. Petersburg, and Rb-Sr data were acquired in the laboratories of BGR Hannover on a Finnigan MAT 261 mass spectrometer. The powdered whole-rock samples (WR) for Sm-Nd studies were analysed following the method of Richards et al. (1976) and the Rb-Sr analyses were carried out using the method of Wendt (1986). Pulverized samples were spiked with a mixed ^{149}Sm-^{146}Nd or a ^{85}Rb-^{84}Sr solution, respectively, and then dissolved in a mixture of HF + HNO_3 + $HClO_4$. Separation of the relevant elements was done using conventional cation-exchange chromatography, followed, for Nd, by 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, 0.03–0.07 ng for Rb and 0.5–0.8 ng for Sr. Accuracy of the measurements of Sm and Nd concentrations at the 2σ level was ±0.5 %, for ^{147}Sm/^{144}Nd ±0.5 %, for ^{143}Nd/^{144}Nd ±0.005 %, for ^{87}Rb/^{86}Sr ±0.5 %, and for ^{87}Sr/^{86}Sr ±0.005 %. The weighted average of 31 measurements 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 determinations, internal standards NBS 987 and NBS 607 were used, respectively; all measurements were fractionation corrected to ^{86}Sr/^{88}Sr = 0.1194. Further details on the analytical techniques were described by Neymark et al. (1993) and Kohút et al. (1996, 1999).

Oxygen isotope analyses were conducted on a Finnigan MAT Delta-E mass spectrometer at the University of Missouri. The samples were reacted with BrF_5 in Ni vessels and the liberated oxygen was converted to CO_2 by reaction with a hot carbon rod (Clayton and Mayeda 1963). All values are reported in permil deviation relative to V-SMOW. Repeated analyses of NBS 28 (quartz) gave a δ^{18}O value of 9.68 ± 0.21‰.

The εNd(0) values were calculated using ^{147}Sm/^{144}Nd = 0.1967 and ^{143}Nd/^{144}Nd = 0.512638 for the Chondritic Uniform Reservoir (CHUR) following Jacobsen and Wasserburg (1980). A linear model with parameters ^{147}Sm/^{144}Nd = 0.2136 and ^{143}Nd/^{144}Nd = 0.513151 was used for the Depleted Mantle reservoir (DM) according to Goldstein and Jacobsen (1988). Two-stage apparent crustal residence ages were calculated with a correction for crustal component ^{147}Sm/^{144}Nd$_{(CC)}$ = 0.12 and the Depleted Mantle parameters ^{143}Nd/^{144}Nd$_{(DM)}$ = 0.513151 and ^{147}Sm/^{144}Nd$_{(DM)}$ = 0.219 following the model of Liew and Hofmann (1988). The εSr(0) values were calculated using ^{87}Sr/^{86}Sr = 0.7045 and ^{87}Rb/^{86}Sr = 0.0816 for the present-day Bulk Earth (or Uniform Reservoir, UR) composition (DePaolo and Wasserburg 1976; Faure 1986). The values of the neodymium crustal index (NCI) were computed according to the model of De Paolo et al. (1992).

4. Results

The major- and trace-element chemical compositions of the studied samples are given in Tab. 1. The sample set includes ten specimens from one core in the Veľká Fatra Mts. and several representative samples from each of the Western Carpathian granite massifs. The broad sample set, covering all principal granitic types, including tonalites, granodiorites, granites and/or leucogranites (Fig. 2) and hybrid samples from the Veporic Unit, is complemented by one sample of gabbro that is used to constrain the petrogenetic model. The majority of the Carpathian granitoid plutons are composed of several rock types, including tonalites, trondhjemites, granodiorites and leucogranites (granites and granodiorites predominate). Generally, the granitoids have SiO_2 concentrations ranging from *c.* 60 to 77 wt. %, have increasing alkalinity from the more basic to the most acid varieties, but overall they are calc-alkaline. They are metaluminous to peraluminous (A/CNK = 0.7–1.5). Noteworthy is the markedly peraluminous character of hybrid tonalites (A/CNK = 1.4–1.5), in contrast to the subaluminous character of the Veľká Fatra Mts. leucogranites (A/CNK = 0.96–1.04). The prevalence of Na_2O over K_2O is a common feature (K_2O/Na_2O by weight = 0.25–1.15), including the porphyritic "Prašivá" type granite whose alkali ratio is close to 1. The medium- to high-K calc-alkaline character is a common attribute of the European Variscan granitoids (Bonin et al. 1993). Biotite is the dominant ferromagnesian mafic mineral, whereas hornblende occurs only rarely in dioritic enclaves. Accessory mineral assemblages, magnetite + allanite versus monazite + ilmenite, define in some plutons two granite groups (Petrík and Broska 1994) – the occurrence of mafic microgranular enclaves (MME) in magnetite-bearing granites and the presence of metamorphic country-rock xenoliths in magnetite-free granites support division of the Western Carpathian granites into I- and S-type suites. The Sm-Nd, Rb-Sr and oxygen isotopic data are listed in Tab. 2. The Rb-Sr isotopic systematics of the granitoids are shown in Fig. 3. With the exception of two leucogranite samples (ZK-4 and VVM-129), the granitoids fall on a linear array that is in a good agreement with the 350 Ma reference isochron. It is obvious as HT/MP metamor-

Tab. 1 Chemical composition (wt. % and ppm) of the Western Carpathian granites. Symbols: bT – biotite tonalite, mbGD – muscovite-biotite granodiorite, mG – muscovite granite

Number	1	2	3	4	5	6	7	8	9	10	11	12	13
Sample	**VF-43**	**VF-153**	**VF-157**	**VF-283**	**VF-298**	**VF-356**	**VF-417**	**VF-636**	**VF-639**	**VF-700**	**VK-139**	**BGPI-1**	**T-87**
Type	mbG	bT	mG	mbGD	mbG	bT	mbGD	bGD	bGD	mG	mbGD	mbG	bGD
SiO_2	72.66	66.14	74.08	72.27	72.74	68.76	70.69	66.88	66.33	73.94	72.51	72.38	70.01
TiO_2	0.21	0.64	0.11	0.30	0.16	0.51	0.55	0.72	0.58	0.16	0.41	0.17	0.37
Al_2O_3	14.64	16.23	13.09	15.21	15.12	15.59	14.69	15.90	15.70	13.27	14.31	14.86	15.61
Fe_2O_3	0.47	1.79	0.26	0.35	0.33	0.81	0.74	1.33	1.62	0.94	1.00	0.59	1.31
FeO	1.43	2.55	0.89	1.12	0.72	2.33	1.52	1.96	1.93	1.25	1.53	1.60	1.41
MnO	0.03	0.06	0.03	0.05	0.02	0.04	0.05	0.05	0.05	0.02	0.04	0.05	0.04
MgO	0.61	1.35	0.13	0.41	0.37	1.22	0.61	1.32	1.21	0.15	0.81	0.67	0.95
CaO	1.42	2.47	0.49	1.92	1.44	2.83	2.12	2.20	2.89	0.69	1.96	2.88	2.29
Na_2O	3.74	3.93	4.37	4.18	4.24	4.04	4.20	4.51	5.01	4.39	3.23	4.51	3.22
K_2O	3.52	2.79	5.07	2.90	3.83	2.24	3.31	2.83	2.94	3.98	3.19	1.11	2.88
P_2O_5	0.13	0.27	0.48	0.21	0.22	0.21	0.12	0.66	0.24	0.21	0.09	0.17	0.31
H_2O^+	0.75	1.38	0.87	1.02	0.83	0.94	1.07	1.16	1.24	0.76	0.64	0.82	1.60
H_2O^-	0.18	0.26	0.06	0.05	0.06	0.14	0.14	0.12	0.13	0.08	0.22	0.26	0.22
Total	99.79	99.86	99.93	99.99	100.08	99.66	99.81	99.64	99.87	99.84	99.94	100.07	100.22
Sr	259	521	161	179	146	563	302	369	365	103	285	284	482
Rb	110	82	65	117	108	91	105	93	91	177	99	61	92
Ba	864	1110	183	610	534	826	1120	747	641	405	1550	145	575
Zr	112	223	36	78	52	185	139	184	203	40	316	86	156
Y	12.36	8.90	10.89	12.32	11.10	6.98	13.21	13.43	11.50	6.36	16.00	4.69	11.62
Nb	8.79	5.74	10.17	6.53	4.85	8.56	5.87	7.76	8.34	6.00	7.98	9.06	7.41
Ta	0.79	0.28	1.14	0.55	0.46	0.62	0.46	0.51	0.44	0.33	0.63	0.83	0.84
Hf	2.96	4.61	1.36	2.84	1.88	4.30	3.95	4.08	4.62	1.21	3.38	2.27	3.92
Th	6.40	11.75	2.69	5.31	6.52	6.26	10.20	8.56	8.90	2.95	15.40	8.16	8.73
U	2.50	3.25	4.89	2.96	3.70	2.10	4.30	3.05	2.20	3.80	1.70	2.42	2.51
La	20.79	36.07	8.81	16.89	11.82	24.56	28.66	27.41	31.20	5.36	24.20	22.85	25.52
Ce	42.99	76.75	18.12	34.84	26.26	51.11	58.56	54.89	66.34	11.04	54.50	47.47	49.94
Nd	19.73	34.39	8.03	15.38	12.31	23.07	24.18	24.53	29.52	4.84	21.00	20.18	21.15
Sm	4.20	6.03	1.95	3.36	2.80	4.17	4.74	4.82	5.41	1.27	4.00	3.78	3.80
Eu	0.76	1.25	0.67	0.64	0.56	1.19	0.91	0.93	1.09	0.42	0.82	0.84	1.10
Gd	3.32	4.05	1.78	2.43	2.87	2.98	3.06	3.09	3.85	1.22	2.62	2.63	2.84
Tb	0.47	0.45	0.29	0.35	0.38	0.35	0.38	0.40	0.49	0.21	0.37	0.30	0.40
Tm	0.16	0.10	0.11	0.10	0.13	0.08	0.11	0.11	0.15	0.08	0.12	0.06	0.15
Yb	0.94	0.62	0.66	0.74	0.68	0.51	0.79	0.68	0.95	0.51	0.67	0.31	0.95
Lu	0.13	0.09	0.09	0.10	0.09	0.08	0.12	0.10	0.13	0.07	0.11	0.05	0.14

Number	14	15	16	17	18	19	20	21	22	23	24	25	26
Sample	**MM-29**	**Z-164**	**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	mbG	bmG	mbGD	bGD	mG	mbGD	bT	mbGD	bmG	mbG	bmG	bT	Gabbro
SiO_2	72.47	74.19	71.40	69.40	73.31	71.24	68.87	68.95	73.01	71.02	76.09	61.90	48.78
TiO_2	0.18	0.19	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	14.55	14.24	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	0.37	0.70	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	1.04	1.50	1.50	1.35	1.56	2.21	2.13	0.65	1.82	0.98	5.39	6.12
MnO	0.07	0.02	0.03	0.05	0.06	0.04	0.09	0.04	0.02	0.03	0.03	0.07	0.16
MgO	0.60	0.39	0.59	1.61	0.55	0.77	1.58	1.10	0.44	1.01	0.13	1.94	15.21
CaO	2.09	1.66	1.90	1.96	1.10	2.26	2.37	1.79	1.29	1.97	0.49	2.36	7.44
Na_2O	4.14	4.10	4.15	3.48	4.00	4.48	2.35	3.66	3.60	3.24	2.99	2.16	1.74
K_2O	2.57	2.47	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	0.12	0.08	0.08	0.23	0.16	0.21	0.18	0.22	0.14	0.17	0.18	0.23	0.34
H_2O^+	0.68	0.51	1.10	1.14	1.32	1.10	1.56	1.31	1.02	0.75	0.78	1.96	0.19
H_2O^-	0.29	0.19	0.14	0.10	0.04	0.18	0.22	0.20	0.16	0.13	0.11	0.16	0.25
Total	99.63	99.78	99.85	99.79	100.47	99.76	99.61	99.89	99.80	99.70	99.81	99.53	100.15
Sr	327	305	473	600	122	449	344	210	120	320	21	464	638
Rb	56	80	65	125	158	88	89	131	240	72	448	102	139
Ba	957	1200	1030	730	316	880	871	851	713	956	60	1040	635
Zr	128	134	124	129	31	159	179	215	96	150	66	268	123
Y	15.23	19.00	10.29	8.75	14.99	7.00	157.59	44.20	24.00	12.00	17.73	40.50	18.00
Nb	5.30	9.00	5.19	12.50	9.19	10.00	17.06	14.35	5.00	7.00	19.65	12.25	4.80
Ta	0.29	0.26	0.37	0.98	1.24	0.29	0.66	0.80	1.10	0.50	5.46	0.59	0.50
Hf	3.53	3.30	3.12	4.46	0.91	4.10	4.44	5.32	3.80	6.80	2.08	4.83	5.10
Th	12.80	10.30	7.20	11.40	5.50	6.30	52.00	14.00	16.90	22.50	9.55	12.05	8.80
U	10.30	3.20	2.80	3.80	3.40	2.60	8.00	3.20	4.80	1.70	6.40	4.30	4.00
La	34.56	31.08	26.87	30.47	6.45	26.67	78.84	31.46	28.52	30.48	7.67	57.20	55.58
Ce	70.83	64.22	55.63	60.26	13.40	54.56	175.60	71.73	58.90	58.14	17.99	120.00	109.70
Nd	29.32	29.10	24.59	27.37	5.81	25.67	84.29	33.97	24.00	29.12	9.51	48.61	45.84
Sm	5.51	5.04	4.72	4.51	1.82	3.91	26.57	8.10	5.23	5.13	2.68	10.20	9.90
Eu	1.24	0.83	0.96	1.01	0.45	0.95	1.37	1.06	0.89	1.13	0.13	1.20	2.05
Gd	4.13	4.12	3.41	3.36	2.05	2.89	32.46	8.22	3.60	3.26	2.20	7.42	4.69
Tb	0.55	0.54	0.44	0.40	0.43	0.36	5.26	1.40	0.71	0.43	0.48	1.27	0.68
Tm	0.26	0.18	0.14	0.16	0.24	0.13	1.81	0.61	0.27	0.17	0.24	0.52	0.27
Yb	1.76	1.04	0.87	1.04	1.65	0.71	9.94	3.74	1.60	0.99	1.34	3.25	1.40
Lu	0.27	0.16	0.13	0.15	0.24	0.12	1.46	0.51	0.25	0.14	0.18	0.41	0.19

Tab. 2 Isotopic composition and related parameters for the studied Western Carpathian granitic rocks

Sample	Rb	Sr	1/Sr	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr(2\sigma)$	$\varepsilon_{Sr(0)}$	$(^{87}Sr/^{86}Sr)_{350}$	$\varepsilon_{Sr(350)}$	Sm
VF-43	110	259	0.0039	0.42	1.3838	0.71359 ± 21	129.03	0.706695	36.95	3.05
VF-153	82	521	0.0019	0.16	0.4759	0.70856 ± 16	57.56	0.706184	29.69	5.89
VF-157	65	161	0.0062	0.40	1.1644	0.71214 ± 18	108.43	0.706338	31.87	2.26
VF-283	117	179	0.0056	0.65	2.9164	0.71985 ± 22	217.87	0.705318	17.40	3.41
VF-298	108	146	0.0068	0.74	3.0970	0.72220 ± 20	251.24	0.706770	38.01	3.25
VF-356	91	563	0.0018	0.16	0.4330	0.70824 ± 21	53.09	0.706083	28.25	4.73
VF-417	105	302	0.0033	0.35	1.1067	0.71164 ± 20	101.31	0.706123	28.82	4.27
VF-636	93	369	0.0027	0.25	0.5673	0.70962 ± 16	72.65	0.706792	38.32	4.55
VF-639	91	365	0.0027	0.25	0.5255	0.70882 ± 20	61.32	0.706202	29.94	4.72
VF-700	103	177	0.0056	0.58	1.6920	0.71521 ± 16	152.02	0.706780	38.15	2.07
VK-139	99	285	0.0035	0.35	0.9891	0.71240 ± 34	112.14	0.707472	47.98	5.66
BGPI-1	61	284	0.0035	0.21	1.6198	0.71492 ± 22	147.91	0.706850	39.15	3.52
T-87	92	482	0.0021	0.19	0.3500	0.70768 ± 28	45.14	0.705936	26.17	4.82
MM-29	56	327	0.0031	0.17	1.7590	0.71496 ± 24	148.47	0.706196	29.86	5.72
Z-164	80	305	0.0033	0.26	1.5696	0.71403 ± 16	135.27	0.706210	30.05	5.77
MF-4a	65	473	0.0021	0.14	0.4390	0.70848 ± 18	56.49	0.706293	31.24	4.19
NT-401	125	600	0.0017	0.21	0.5644	0.71010 ± 30	79.49	0.707288	45.37	4.19
ZK-4	158	122	0.0082	1.30	3.4260	0.73700 ± 28	461.32	0.719930	224.93	3.57
TL-117	88	449	0.0022	0.20	0.6092	0.70920 ± 20	66.71	0.706165	29.42	3.75
VG-46	89	344	0.0029	0.26	0.5480	0.70800 ± 40	49.68	0.705270	16.71	25.50
VG-47	131	210	0.0048	0.62	1.4660	0.71510 ± 30	150.46	0.707796	52.58	7.96
V-7312	240	120	0.0083	2.00	0.9727	0.71123 ± 28	95.53	0.706384	32.53	5.00
V-9738	72	320	0.0031	0.23	0.7440	0.71005 ± 24	78.78	0.706343	31.95	5.04
VVM-129	448	21	0.0476	21.33	17.4520	0.87094 ± 36	2362.5	0.783988	1134.70	2.58
CH-3/72	102	464	0.0022	0.22	1.0252	0.71110 ± 22	93.68	0.705992	26.97	11.83
KV-3/622	139	638	0.0016	0.22	0.1965	0.70330 ± 20	-17.03	0.702321	-25.17	11.39

$t_{(DM2st)}$ – two-stage apparent crustal residence ages (Liew and Hofmann 1988); NCI – neodymium crustal index (DePaolo et al. 1992)

phism with widespread granitic magmatism is typical of European Variscides, and could have lead partial isotopic homogenization throughout wide areas during Early Carboniferous period or sources could have been isotopically similar *a priori* (F. Finger, personal com-

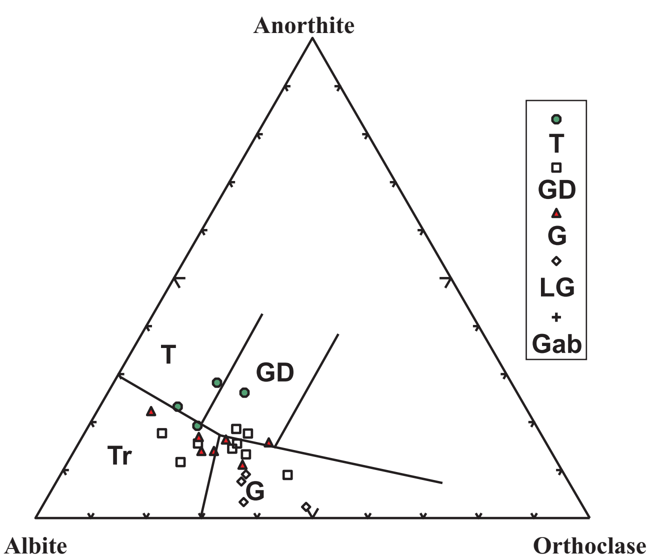

Fig. 2 An-Ab-Or CIPW normative diagram (Barker 1979) showing varied character of the Variscan Western Carpathian igneous rocks. Symbols: circles – tonalites, squares – granodiorites, triangles – granites, diamonds – leucogranites, cross – gabbro.

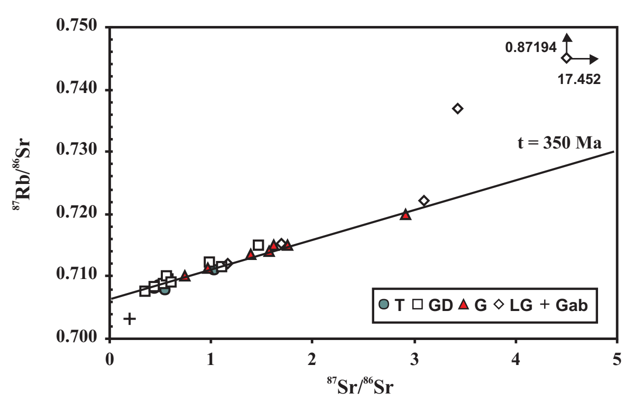

Fig. 3 Whole-rock Rb/Sr isochron (Nicolaysen-type) plot indicating evolution of the Western Carpathian granitic rocks with dominance of studied samples clustering around the reference 350 Ma isochron. Symbols as in Fig. 2.

Nd	Sm/Nd	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ (2σ)	$\varepsilon_{Nd(0)}$	$(^{143}Nd/^{144}Nd)_{350}$	$\varepsilon_{Nd(350)}$	$t_{(DM2st)}$	NCI	$\delta^{18}O$
15.93	0.19	0.11602	0.512391 ± 5	-4.82	0.512125	-1.21	1155	0.58	9.8
32.25	0.18	0.11636	0.512323 ± 6	-6.14	0.512056	-2.56	1261	0.70	9.3
8.54	0.26	0.13045	0.512284 ± 8	-6.91	0.511985	-3.95	1370	0.77	10.5
15.85	0.22	0.12985	0.512273 ± 10	-7.12	0.511975	-4.14	1385	0.79	11.3
15.45	0.21	0.12768	0.512306 ± 11	-6.48	0.512013	-3.39	1327	0.73	11.0
23.44	0.20	0.12241	0.512346 ± 6	-5.70	0.512065	-2.38	1247	0.66	9.7
23.89	0.18	0.11918	0.512265 ± 9	-7.28	0.511992	-3.81	1359	0.81	10.4
24.47	0.19	0.11444	0.512338 ± 8	-5.85	0.512076	-2.18	1231	0.67	9.6
25.19	0.19	0.11364	0.512347 ± 7	-5.68	0.512087	-1.97	1214	0.66	9.5
8.39	0.25	0.14990	0.512330 ± 13	-6.01	0.511986	-3.92	1368	0.69	9.0
30.80	0.18	0.11135	0.512302 ± 6	-6.55	0.512047	-2.74	1275	0.74	10.2
18.50	0.19	0.11551	0.512235 ± 9	-7.86	0.511970	-4.24	1393	0.86	11.1
27.70	0.17	0.10548	0.512397 ± 7	-4.70	0.512155	-0.62	1109	0.57	10.7
30.60	0.19	0.11346	0.512278 ± 11	-7.02	0.512018	-3.30	1319	0.78	11.2
31.99	0.18	0.10947	0.512298 ± 10	-6.63	0.512047	-2.74	1275	0.75	10.0
22.30	0.19	0.11362	0.512307 ± 11	-6.46	0.512047	-2.75	1276	0.73	9.8
22.66	0.18	0.11216	0.512396 ± 9	-4.72	0.512139	-0.94	1134	0.57	8.6
15.40	0.23	0.14044	0.512156 ± 8	-9.40	0.511834	-6.89	1601	1.00	9.6
21.50	0.17	0.10597	0.512343 ± 4	-5.75	0.512100	-1.70	1194	0.67	9.5
82.10	0.31	0.18865	0.512516 ± 5	-2.38	0.512084	-2.02	1219	0.36	8.4
33.91	0.23	0.14237	0.512354 ± 11	-5.54	0.512028	-3.11	1305	0.65	10.5
22.50	0.22	0.13498	0.512333 ± 14	-5.95	0.512024	-3.19	1311	0.68	8.6
28.50	0.18	0.10717	0.512332 ± 12	-5.97	0.512086	-1.97	1215	0.69	9.3
8.93	0.29	0.17537	0.512364 ± 9	-5.34	0.511962	-4.40	1405	0.63	9.9
52.04	0.23	0.13787	0.512343 ± 9	-5.68	0.512031	-3.05	1299	0.66	9.1
65.68	0.17	0.10515	0.512715 ± 6	1.50	0.512474	5.60	620	0.00	6.6

munication). The $(^{87}Sr/^{86}Sr)_{350}$ ratios in granitoid rocks of the Tatric and Veporic units are low (0.705–0.708), suggesting a mixed lower crustal and mantle source, mixing of more and less radiogenic sources and/or a Rb-poor crustal source (Fig. 4). Granitoids from the Gemeric Unit

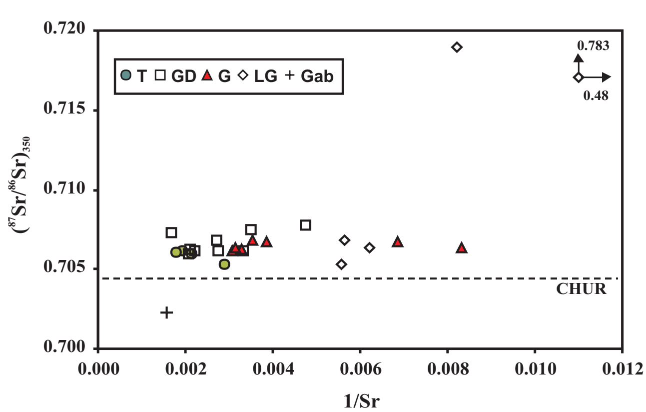

Fig. 4 Initial Sr isotopic ratios at 350 Ma vs. 1/Sr plot documenting nearly balanced and quasi-homogenized isotopic composition during genesis of the Variscan granites in the Western Carpathians. Symbols as in Fig. 2.

(VVM-129) have extremely high $(^{87}Sr/^{86}Sr)_{350} \geq 0.725$ (Kovach et al. 1986), which suggests an older supracrustal metasedimentary source.

The $\varepsilon_{Nd}(0)$ values for the West Carpathian granitoids, ranging from -2.3 to -9.4, are comparable with other data for the Variscan fold belt of Central Europe (Liew and Hofmann 1988), the Massif Central (Pin and Duthou 1990), the Bohemian Massif (Liew et al. 1989; Janoušek et al. 1995; Gerdes 2001) and the Tauern Window (Finger et al. 1993). In contrast to the Rb-Sr isotopic system, no isochron relationship is apparent in the Sm-Nd system at 350 Ma (Fig. 5), and the $(^{143}Nd/^{144}Nd)_{350}$ ratios are more heterogeneous (Fig. 6). Even though, there is an overlap in the Nd isotopic ratios of tonalites, granodiorites, and granites, the leucogranites have systematically less radiogenic Nd. Nevertheless, in comparison to the general broad range of Nd isotope ratios of crustal rocks wordlwide, the range in the CWC granitoids is small. Only the gabbro sample is distinct with the most radiogenic ratio, which reflects its mantle source.The $\delta^{18}O$ values of the granitoids range from 8.4 to 11.3 ‰ (Figs 7 and 8). On average, the tonalites have the lowest $\delta^{18}O$ values of 9.1 ± 0.6 ‰, the granodiorites have 9.9 ± 1.3 ‰, the granites show 10.2 ±

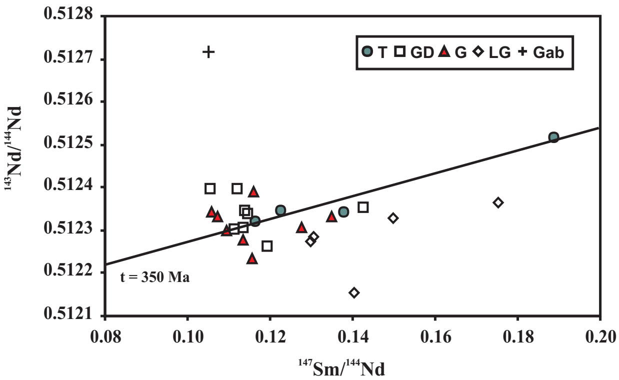

Fig. 5 $^{143}Nd/^{144}Nd$ versus $^{147}Sm/^{144}Nd$ isochron diagram for the Western Carpathian granitic rocks. A reference 350 Ma isochron is drawn for comparison As can be seen, there is no linear relationship reflecting the lack of the regional-scale homogenization. Symbols as in Fig. 2.

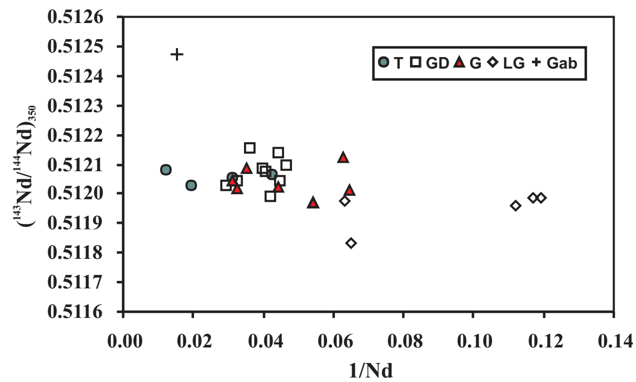

Fig. 6 Initial Nd isotopic ratios at 350 Ma versus 1/Nd ratio diagram. The lack of a linear array rules out simple two-component source mixing and reflects rather heterogeneous sources and/or open-system interactions during genesis of the Carpathian granites.

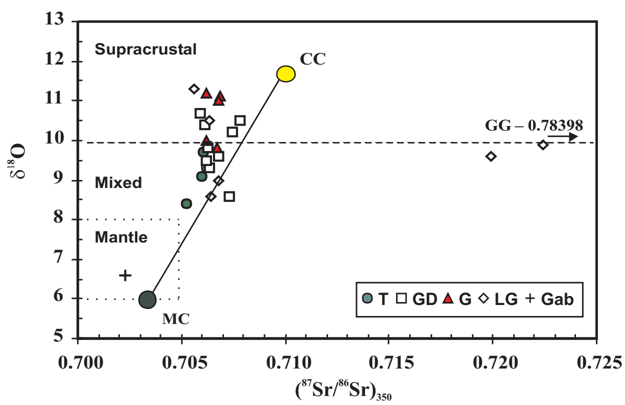

Fig. 7 Diagram $\delta^{18}O$ vs. $(^{87}Sr/^{86}Sr)_{350}$ of the Western Carpathian granites; crustal and mantle components (CC + MC) are taken from James (1981). According this model the CWC granites represent 10–50% assimilation of crustal rocks.

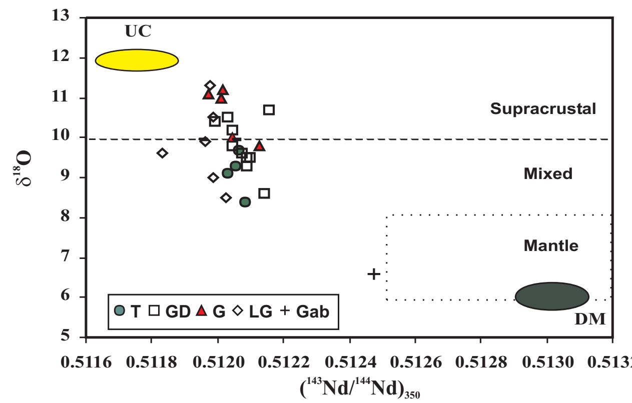

Fig. 8 Plot of $\delta^{18}O$ vs. $(^{143}Nd/^{144}Nd)_{350}$ for granitic rocks of the Western Carpathians. Potential crustal source (upper crust – UC) and depleted mantle component (DM) are shown for comparison.

1.6 ‰, and the leucogranites have 10.0 ± 1.0 ‰. Thus, there is a considerable overlap in the oxygen isotope composition between individual granitoid types. However, with the exception of the leucogranites and one granodiorite sample, there is a fairly good negative correlation of the $\delta^{18}O$ values with $(^{143}Nd/^{144}Nd)_{350}$ (Fig. 8) whereby higher $\delta^{18}O$ values tend to indicate a sedimentary crustal protolith and lower values a mafic protolith (O'Neil and Chappell 1977; Taylor 1988). The gabbro sample has $\delta^{18}O$ value of 6.6 ‰, which is typical of mantle-derived rocks.

5. Discussion

5.1. Sources of granitoids

In spite of the broad range of granitoid types in the Tatric and Veporic superunits, the granitoids have rather narrow ranges of $(^{87}Sr/^{86}Sr)_{350}$ and $(^{143}Nd/^{144}Nd)_{350}$ ratios, particularly in comparison to granitoids of other orogenic belts such as the Lachlan fold belt of Australia (McCulloch and Chappell 1982). The possible source rocks of the Western Carpathian granitoids have previously been discussed (e.g. Cambel and Petrík 1982; Kráľ 1994; Petrík et al. 1994; Kohút and Nabelek 1996; Petrík and Kohút 1997; Petrík 2000; Finger et al. 2003). According to Kráľ (1994), the Tatric and the Veporic granitoids were generated from an isotopically inhomogeneous source by mixing of mantle and crustal material with a low Rb/Sr ratio. Petrík et al. (1994) suggested that S-type granitoids were generated by dehydration melting of peraluminous muscovite- and biotite-bearing metasedimentary rocks with graphitic intercalations because of fairly reduced accessory oxide assemblage. They viewed biotite- and biotite-hornblende plagioclase gneisses as plausible sources for generation of the I-type group. Kohút and Nabelek (1996) suggested for part of the Tatric transitional (I/S) granitoids melting of a vertically zoned lower crust, including a volcanic arc and crustal metasediments. Petrík and Kohút (1997) preferred a) supracrustal, reduced granulite-facies rocks with minor addition of a mantle-like component as sources for the S-type granites, b) intermediate, oxidized metaigneous rocks in combination with underplated mafic crust as protolith for the I-type group, c) H_2O-poor and F-rich granulite and/or tonalite crust as parental to the A-type group, and d) mature, recycled sedimentary supracrustal rocks, or rocks which experienced sea-floor weathering and were permeated by volcanic (boron) emanations as source lithologies for the Gemeric granites. Petrík (2000), on the basis of previously published data, considered various proportions of at least two contrasting source components – old recycled supracrustal metasediments and a young mafic source with possible addition of assimilants. Presented isotopic data (Sr, Nd and O) preclude a simple mantle (like plagiogranites in ophiolitic complexes) or crustal origin (like Himalayan granites) for most of the Tatric and Veporic granites. Although the lowermost $(^{87}Sr/^{86}Sr)_{350}$ ratio in the Fig. 4 is close to the CHUR composition and thus the mantle limit, most samples have this ratio slightly higher (0.706–0.708). Most of the Western Carpathian granitoids define a well-defined field in a $(^{87}Sr/^{86}Sr)_{350}$ *vs*. $(^{143}Nd/^{144}Nd)_{350}$ plot (Fig. 9) that is characteristic of I-type granitoids (McCulloch and Chappell 1982; Hensel et al. 1985; Liew et al. 1989; Petford and Atherton 1996). Only the Kralička and the Gemer granites have isotopic characteristics that indicate involvement of upper-crustal sources. All granitoid samples lie in quadrant IV, but close to the mantle domain in quadrant II. Magma sources with positive values of both enrichment parameters f_{Sm} and f_{Rb} (quadrant I) are not typical of ordinary felsic igneous rocks (Faure 1986) but old amphibolite/greenstone lower crust shows such enrichment behavior (Keay et al. 1997; Poller et al. 1998). Apparent two-stage Nd crustal residence ages (t_{DM2st}) range from 1.6 to 1.1 Ga, but are mostly between 1.4 and 1.1 Ga (Fig. 10). The 1.6 Ga age is for a leucocratic sample ZK-4 which has the lowest $\varepsilon_{Nd(0)}$ value. Overall, the model ages are comparable with those of the Variscan belt elsewhere in Europe. For example, Nd crustal residence ages in the Central Iberian zone vary between 1.7 to 1.4 Ga (Moreno-Ventas et al. 1995; Villaseca et al. 1998; Castro et al. 1999), in the Bohemian Massif between 1.7 and 1.1 Ga (Liew and Hofmann 1988; Janoušek et al. 1995), in Schwarzwald between 1.6 to 1.4 Ga (Liew and Hofmann 1988) and in Massif Central between 1.8 to 1.1 Ga (Pin and Duthou 1990; Turpin et al. 1990; Williamson et al. 1996; Downes et al. 1997). Analogues of dioritic rocks in the Tatra Mountains are scarce – similar rocks are found in Massif Central (Shaw et al. 1993), Corsica (Cocherie et al. 1994) or Bohemian Massif (Janoušek et al. 1995; Sokol et al. 2000).

The gabbro from the Veporic superunit falls on the mantle array in quadrant II, which demonstrates its mantle origin. The gabbro's model age is 620 Ma, which is in accord with evolution of a hypothetical depleted mantle reservoir in the Carpathian realm during the Pan-African orogeny (700–500 Ma). However, recent U-Pb zircon SHRIMP dating of gabbro from the Branisko Mountains anatectic complex suggests a Late Devonian (370 Ma) age (Kohút et al. in print).

The low $(^{87}Sr/^{86}Sr)_{350}$ ratios might be interpreted in several ways: 1) melting of a relatively young crust, 2) melting of lower crustal rocks with Rb depleted during the ancient granulite-facies metamorphism, 3) melting of a mixture of deep sea sediments with seafloor basalts,

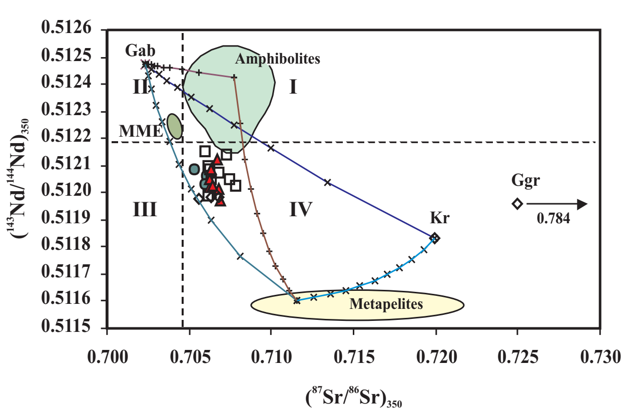

Fig. 9 Initial Nd and Sr isotopic compositions (in relation to CHUR and UR) for granites of the Western Carpathians. Due to extremely high contents of radiogenic Sr in the Gemeric granites (Ggr) the projection point falls beyond the diagram. Quadrants I–IV are indicated according to Faure (1986). Explanations: Kr – Kralička granite, Gab – gabbro, MME – dioritic mafic microgranular enclaves after Poller et al (2001). Symbols as in Fig. 2.

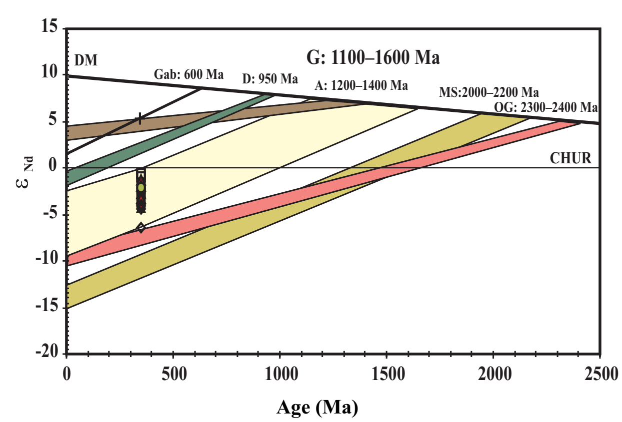

Fig. 10 Diagram of $^{143}Nd/^{144}Nd$ *vs*. time, showing two-stage depleted-mantle (DM) Nd model ages. The evolution curve for DM is after Goldstein et al. (1984). Abbreviations: G – granites and Gab – gabbro of this work in comparison with the fields of D – diorites, A – amphibolites, MS – metasediments and OG – orthogneisses (data taken from Poller et al. 2000, 2001; Kohút et al. 2008).

4) melting of subducted oceanic slab, 5) melting of an underplated basaltic crust, and 6) melting of an old greenstone belt. Given that the European Hercynides are essentially related to subduction and collisional processes (Burg and Matte 1978; Matte 1986, 1991; Pin and Duthou 1990; von Raumer and Neubauer 1993; and/or Petrík and Kohút 1997), one possibility is that the principal source of the Tatric and Veporic granitoids was an underplated volcanic arc below the collisionally thickened continental crust. On the other hand, more mature supracrustal metamorphic rocks and infracrustal igneous rocks were sources for the Gemeric granitoids that have more elevated Sr isotope ratios. From the geochemical point of view, the CWC granitoids seem to be analogues of volcanic-arc granitoids but such a character may have been inherited from products of Early Variscan active margin subduction processes. Similar scenario was described in the Bohemian Massif by Finger and Clemens (1995). The rather broad range of oxygen isotope ratios would then suggest that the arc crust was variably hydrothermally altered prior to underplating.

However, the source region was probably composite and certain portions were perhaps as old as Proterozoic as suggested by the T_{DM} ages of the granitoids. Where exposed by thrusting, the Carpathian basement includes low- to high-grade metamorphic rocks, amphibolites, migmatites, orthogneisses, granites, greenstone rocks and/or Upper Paleozoic sedimentary and volcanic rocks. A heterogeneous source region for the granitoids is inferred by variability of enclave populations, represented by country-rock xenoliths (gneisses, amphibolites, eclogites and granulites), and/or mafic microgranular enclaves (Hovorka and Petrík 1992; Petrík et al. 1994; Janák 1994; Janák et al. 1996, 1999; Petrík and Kohút 1997). An excellent perspective on how the source region may have appeared can be obtained in a new, 4 km long highway tunnel in the Branisko Mountains that exposes a small portion of the Variscan lower crust. The exposed rocks include a greenstone-like granite anatectic complex, composed of various amphibolites alternating with tonalitic gneisses on one side but rather typical greywacke gneisses on the other side of the tunnel. Widespread anatectic phenomena are observed in both lithologies. Stromatic migmatite, metatexite, diatexite and/or dictyonic structure indicate melting and segregation of the melt (Sawyer 1991, 1996; Brown 1994). Salient is the presence of gabbroic enclaves within this anatectic complex and this may indicate input of a juvenile basic magma into the lower crust. It is possible that such a source region yielded the observed spectrum of Variscan granitoids. It is apparent, however, that Sr and Nd isotopes were already fairly homogeneous during the anatectic event as suggested by their narrow ranges in the granitoids.

For better understanding of the nature of the components in the complex source region during the Variscan magmatism, we added fields of amphibolites and metasedimentary rocks from the Tatra Mountains (Poller et al. 1998, Kohút et al. 2008), which represent plausible lower crustal and upper crustal sources, respectively, to the $(^{87}Sr/^{86}Sr)_{350}$ *vs*. $(^{143}Nd/^{144}Nd)_{350}$ diagram (Fig. 9). A prospective mantle source is represented by the gabbro and another upper-crustal component by the Kralička granite (Tab. 3). Although it is possible to construct a simple binary mixing array between a mantle source and the isotopically variable metasedimentary rocks, the occurrence of tonalites indicates that amphibolites were also involved in the melting process. Mixing calculations involving gabbro (mantle source), amphibolites, and metapelites as potential sources yield the following proportions: 25–75 % metasediments, 0–75 % amphibolites and 5–25 % gabbroid rocks, with ranges depending on the assumed isotopic compositions of the metapelites and amphibolites. Mixing calculations involving orthogneisses (represented by the Kralička granite instead of amphibolites) yield 25–75 % metasedimentary rocks, 0–45 % orthogneisses, and 20–35 % mantle-derived melts. In either case, the presence of crustal sources during the generation of the Carpathian granites is evident.

The importance of crustal contribution to the Western Carpathian granitoids is confirmed also by the neodymium crustal index (DePaolo et al. 1992) NCI = 0.4–1.0, mostly between 0.6 and 0.8 (Tab. 2). Furthermore, the $\delta^{18}O$ values of the granitoids are generally elevated relative to mantle values including the gabbro (Figs 7–8), which suggests a significant crustal component in the protolith. This is in accord with the large amount of anatectic granite rocks observed elsewhere within the European Variscides. We note that the two-stage Nd model age for amphibolitic rocks is identical to that of the granitoids and it is in contrast to the Early Proterozoic model ages of metasedimentary rocks and orthogneisses from the Tatra Mountains (Fig. 10). This implies addition of mantle material to the source region that may have initially consisted of more silicic crustal materials. Such an addition is also suggested by the compositions of dioritic MME in the Tatra Mts. granitoids (Poller et al. 2001). The mantle origin of the Tatra Mts. diorites has never been advocated, in accordance with the observation of Pin et al. (1991). However, MME are commonly thought to be products of magma

Tab. 3 Input parameters for individual sources in the mixing models.

	Sr	$(^{87}Sr/^{86}Sr)_{350}$	Nd	$(^{143}Nd/^{144}Nd)_{350}$
Gabbro	638	0.702321	65.7	0.512474
Amphibolite	106	0.707730	13.7	0.512426
Metapelite	95	0.711537	31.9	0.511602
Orthogneiss	122	0.719930	15.4	0.511834

mixing/mingling processes (e.g., Didier 1973; Didier and Barbarin 1991).

5.2. Thermal aspects of melt generation

As is the case for much of the exposed European basement, crystalline products of the Variscan orogeny dominate the present erosion level of the Western Carpathians. Available dates (U-Pb, Rb-Sr and Ar-Ar) support granite-forming events mainly between 360 and 260 Ma. The results of the present study indicate that the source region of the granitoid magmas could have included amphibolites, metasedimentary rocks and orthogneisses, and some mantle-derived material, perhaps in the form of magmas that invaded the source region during anatexis, was probably involved in the petrogenesis. The spectrum of granitoid compositions in the Western Carpathians and their isotopic compositions are consistent with a heterogeneous source region as seen on the exposures in the Branisko Mountains. The source region probably included potentially fertile lithologies, represented by metagreywackes, metapelites and hydrated mafic or intermediate metavolcanics (amphibolites or greenstone-like rocks). The dehydration melting of muscovite, biotite and/or hornblende-bearing rocks has widely been suggested as an anatectic crustal process (Clemens and Vielzeuf 1987; Le Breton and Thompson 1988; Patiño Douce et al. 1990; Skjerlie et al. 1993; Wolf and Wyllie 1994; Singh and Johannes 1996; Montel and Vielzeuf 1997 among others). The continental crust must have been considerably thick (>40 km) and hot enough for melting of a basic metaigneous source to occur. Indeed, the voluminous granitoid production during the Variscan period demonstrates that the pre-Carboniferous crust of the European Variscides was sufficiently thickened by multistage collisional tectonics to become fertile for granite production (Vielzeuf et al. 1990). Although leucogranites can potentially be produced by decompression melting or shear heating of mid-crustal metasedimentary rocks (e.g. Daniel et al. 1987; Nabelek and Barlett 1998; Patiño-Douce and Harris 1998; Nabelek and Liu 1999), these processes are unlikely to result in sufficiently high melt production to explain the volume of the Western Carpathian granitoids. Therefore an enhanced heat flux from mantle or unusually high radioactive heat production is required (e.g. Royden 1993). Supracrustal sedimentary rocks enriched in U, Th and K could potentially sufficiently heat the source region to induce anatexis but a large abundance of such a lithology is not evident in the isotopic composition of the granitoids. The most likely source of heat for anatexis of the Variscan lower crust is an underplated and/or intraplated mantle-derived magma as has been proposed for production of other orogenic granites (e.g. Holland and Lambert 1975; Wells 1981; Huppert and Sparks 1988; Dewey 1988). The gabbro from the Veporicum may represent a product of crystallization from such a magma, although its genetic relationship to the Western Carpathian granitoids is not yet clear. Gabbroic rocks also occur within the Branisko greenstone–granite anatectic complex. Field and petrologic evidence indicates collisionally thickened and inverted structure of the CWC Variscan basement (Janák 1994; Kohút and Janák 1994) with intrusion of lens-like granite bodies within the upper unit. Similar structure occurs in the classical Himalayan convergent orogen (Le Fort 1981; France-Lanord and Le Fort 1988; Harrison et al. 1998). It is suggested that melting of heterogeneous crustal sources in the Western Carpathians occurred during subduction of the lithosphere and continental collision in the early Variscan times. Heating through underplating and/or intraplating of mantle-derived magma facilitated partial melting. After the main collisional stage, the thick and thermally weakened crust most probably collapsed due to gravitational instability (Dewey 1988; Hollister 1993), leading to decompression and rapid exhumation at 2–3 mm/year accompanied by rapid cooling of 35–87 °C/Ma (Janák and Kohút 1996; Kohút et al. 1997). Rapid cooling of the hanging wall containing the melt by thrusting onto the colder footwall in the Carboniferous times was followed by gradual cooling attributed mainly to the extensional denudation and concomitant erosion forced by propagation of normal faults in the Permian. Therefore, majority of the crystalline basement terranes of the Western Carpathians have been eroded before the Alpine–Lower Triassic sedimentation.

6. Conclusions

The Western Carpathians belong to the Alpine Neo-Europe. Even though they may have been variably affected by the Alpine orogeny, the granitic rocks in the Variscan basement show many similarities to other European occurrences of granitic rocks within the Variscan orogenic belt. The Sr-Nd-O isotopic compositions of the Variscan granitic rocks in the Western Carpathians indicate a mixed source consisting of Proterozoic and younger crustal and mantle-derived lithologies. It is inferred that the source was vertically-zoned lower crust consisting of felsic and mafic metaigneous and metasedimentary rocks. A contribution of mantle-derived magma is evident in Sr and Nd isotope compositions. Intrusion of such magma may have contributed to homogenization of the isotope ratios of these elements and provided the heat necessary for melting of the lower crust. Although the geochemical features of the Western Carpathian granitoids are typical of volcanic arc igneous suites, the surrounding metamorphic rocks association and their P-T conditions indicate their generation during an intracontinental subduction or continental collision that involved high-grade metasedimentary and metaigneous rocks in the lower- to mid-crust.

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References

Andrusov D (1968) Grundriss der Tektonik der Nördlichen Karpaten, Veda Publishing House of SAV, Bratislava, pp. 1–188.

Barker F (1979) Trondhjemite: definition, environment and hypotheses of origin. In: Barker F (ed) Trondhjemites, Dacites and Related Rocks. Elsevier, Amsterdam, pp 1–12

Bonin B, Brändlein P, Bussy F, Desmond J, Eggenberger U, Finger F, Graf K, Marro C, Mercolli I, Oberhänsli R, Ploquin A, von Quadt A, von Raumer J, Schaltegger U, Steyrer HP (1993) Late Variscan Magmatic Evolution of the Alpine Basement. In: Von Raumer JF, Neubauer F (eds) Pre-Mesozoic Geology of Alps. Springer Verlag, Berlin, pp 171–201

Broska I, Uher P (2001) Whole-rock chemistry and genetic typology of the West-Carpathian, Variscan granites. Geol Carpath 52: 79–90

Brown M (1994) The generation, segregation, ascent and emplacement of granite magma: the migmatite-to-crustally-derived granite connection in thickened orogens. Earth Sci Rev 36: 83–130

Burg JP, 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

Bussy F, Hernandez J, von Raumer J (2000) Bimodal magmatism as a consequence of the post-collisional readjustment of the thickened Variscan continental lithosphere (Aiguilles Rouges – Mount Blanc Massif, Western Alps). Trans Roy Soc Edinb, Earth Sci 91: 221–233.

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

Castro A, Patiño Douce AE, Corretgé LG, de la Rosa JD, El-Biad M, El-Hmidi H (1999) Origin of peraluminous granites and granodiorites, Iberian Massif, Spain: an experimental test of granite petrogenesis. Contrib Mineral Petrol 135: 255–276

Clayton RN, Mayeda TK (1963) The use of bromine pentafluoride in the extraction of oxygen from oxides and silicates for isotopic analysis. Geochim Cosmochim Acta 23: 43–52

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

Cocherie A, Rossi Ph, Fouillac AM, Vidal Ph (1994) Crust and mantle contributions to granite genesis – an example from the Variscan batholith of Corsica, France, studied by trace element and Nd-Sr-O isotope systematics. Chem Geol 115: 173–211

Daniel C, Vidal P, Fernandez A, Le Fort P, Peucat JJ (1987) Isotopic study of the Manaslu granite (Himalaya, Nepal): inferences on the age and source of Himalayan leucogranites. Contrib Mineral Petrol 96: 78–92

DePaolo DJ, Wasserburg GJ (1976) Nd isotope variations and petrogenetic models. Geophys Res Lett 3: 249–252

DePaolo DJ, Perry FV, Baldridge SW (1992) Crustal versus mantle sources of granitic magmas: a two parameter model based on Nd isotopic studies. Trans Roy Soc Edinb, Earth Sci 83: 439–446

Dewey JF (1988) Extensional collapse of orogens. Tectonics 7: 1123–1139

Didier J (1973) Granites and Their Enclaves. Elsevier, Amsterdam, pp 1–393

Didier J, Barbarin B (eds) (1991) Enclaves and Granite Petrology. Elsevier, Amsterdam, pp 1–625

Downes H, Shaw A, Williamson BJ, Thirlwall MF (1997) Sr, Nd and Pb isotopic evidence for the lower crustal origin of Hercynian granodiorites and monzogranites, Massif Central, France. Chem Geol 136: 99–122

Faure G (1986) Principles of Isotope Geology. Wiley, New York, 2nd ed, pp 1–589

Finger F, Clemens JD (1995) Migmatization and "secondary" granitic magmas: effects of emplacement and crystallization of "primary" granitoids in Southern Bohemia, Austria. Contrib Mineral Petrol 120: 311–326

Finger F, Frasl G, Haunschmidt B, Lettner H, von Quadt A, Schermaier A, Schindlmayr AO, Steyrer HP (1993) The Zentralgneise of the Tauern Window (Eastern Alps): insight into an intra-Alpine Variscan batholith. In: Von Raumer JF, Neubauer F (eds) Pre-Mesozoic Geology of the Alps, Springer Verlag, Berlin, pp 375–391

Finger F, Roberts MP, Haunschmid B, Schermaier A, Steyrer HP (1997) Variscan granitoids of Central Europe: their typology, potential sources and tectonothermal relations. Mineral Petrol 61: 67–96

Finger F, Broska I, Haunschmid B, Hraško L, Kohút M, Krenn E, Petrík I, Riegler G, Uher P (2003) Electromicroprobe dating of monazites from Western Carpathian basement granitoids: plutonic evidence for an important Permian rifting event subsequent to Variscan crustal anatexis. Int J Earth Sci 92: 86–98

France-Lanord C, Le Fort P (1988) Crustal melting and granite genesis during the Himalayan collision orogenesis. Tran Roy Soc Edinb, Earth Sci 79: 183–195

Gerdes A (2001) Magma homogenization during anatexis, ascent and/or emplacement? Constraints from the Variscan Weinsberg granites. Terra Nova 13: 305–312

Goldstein SJ, Jacobsen SB (1988) Nd and Sr isotopic systematic of rivers water suspended material: implications for crustal evolution. Earth Planet Sci Lett 87: 249–265

Goldstein SJ, O'Nions RK, Hamilton PJ (1984) A Sm-Nd isotopic study of atmospheric dusts and particulates from major river systems. Earth Planet Sci Lett 70: 221–236

Harrison TM, Grove M, Lovera OM, Catlos EJ (1998) A model for the origin of Himalayan anatexis and inverted metamorphism. J Geophys Res 103: 27 017– 27 032

Hensel HD, McCulloch MT, Chappell BW (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

Hollister LS (1993) The role of melt in the uplift and exhumation of orogenetic belts. Chem Geol 108: 31–48

Holland JG, Lambert RSJ (1975) The chemistry and origin of the Lewisian gneisses of Scottish mainland: the Scourie and Inver assemblages and sub-crustal accretion. Precambr Res 2: 161–188

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, pp 57–66

Huppert HE, Sparks RS (1988) The generation of granitic magmas by intrusion of basalt into continental crust. J Petrol 29: 599–624

Jacobsen SB, Wasserburg GJ (1980) Sm-Nd isotopic evolution of chondrites. Earth Planet Sci Lett 50: 139–155

James DE (1981) The combined use of oxygen and radiogenic isotopes as indicators of crustal contamination. Ann Rev Earth Planet Sci 9: 311–344

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 Carpath 45: 293–300

Janák M, Kohút M (1996) Cordierite-bearing migmatites from the Veľká Fatra Mts., Western Carpathians: geothermobarometry and implications for Variscan decompression. Geol Carpath 47: 359–365

Janák M, O'Brien PJ, 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 PJ, Horn EE (1999) Dehydration melting and devolatilization of high-grade metapelites: the Tatra Mountains, Western Carpathians. J Metamorph Geol 17: 379–395

Janoušek V, Rogers G, Bowes DR (1995) Sr-Nd isotopic constraints on the petrogenesis of the Central Bohemian Pluton, Czech Republic. Geol Rundsch 84: 520–534

Jenner GA, Longerich HP, Jackson SE, Fryer BJ (1990) ICP-MS – a powerful new tool for high precision trace element analysis in the earth sciences: evidence from analysis of selected USGS standards. Chem Geol 83: 133–148

Keay S, Collins WJ, McCulloch MT (1997) A three-component Sr-Nd isotopic mixing model for granitoid genesis, Lachlan Fold Belt, eastern Australia. Geology 25: 307–310

Kohút M (2002) The Hercynian granitic rocks of the Western Carpathians in the frame of European Hercynides. Geol Carpath 53 (Spec Issue): 219–221

Kohút M (2007) Orogenic granitic magmatism in the Western Carpathians – 500 Ma history: a review. Mineral Pol 31: 30–39

Kohút M, Janák M (1994) Granitoids of the Tatra Mts., Western Carpathians: field relations and petrogenetic implications. Geol Carpath 45: 301–311

Kohút M, Nabelek PI (1996) Sources of the Veľká Fatra granitoid rocks, Slovakia: isotopic constraints or contradiction? Polish Miner Soc Spec Pap 7: 47–50

Kohút M, Stein HJ (2005) Re-Os molybdenite dating of granite-related mineralisation from Hnilec, Gemeric Unit, Slovakia. Mineral Petrol 85: 117–129

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

Kohút M, Todt W, Janák M, Poller U (1997) Thermochronometry of the Variscan basement exhumation in the Veľká Fatra Mts. (Western Carpathians – Slovakia). TERRA Abstracts, 9/1, EUG 9, Strasbourg, pp 494

Kohút M, Kovach VP, Kotov AB, Salnikova EB, Savatenkov VM (1999) Sr and Nd isotope geochemistry of Hercynian granitic rocks from the Western Carpathians – implications for granite genesis and crustal evolution. Geol Carpath 50: 477–487

Kohút M, Poller U, Gurk Ch, Todt W (2008) Geochemistry and U-Pb detrital zircon ages of metasedimentary rocks of the Lower Unit, Western Tatra Mountains (Slovakia). Acta Geol Pol 58: 371–384

Kohút M, Uher P, Putiš M, Sergeev S, Antonov A (in print) Dating of the Western Carpathians Lower Carboniferous granitic rocks by SHRIMP – new zircon U-Pb data. Miner Slov (in Slovak)

KOVACH A, SVINGOR E, GRECULA P (1986) Rb-Sr isotopic ages of granitoid rocks from the Spišsko-gemerské Rudohorie Mts. Miner Slov 18: 1–14

KRÁĽ J (1994) Strontium isotopes in granitic rocks of the Western Carpathians. Mitt Österr Geol Ges 86: 75–81

KRIST E, KORIKOVSKY SP, PUTIŠ M, JANÁK M, FARYAD SW (1992) Geology and petrology of metamorphic rocks of the Western Carpathian metamorphic complexes. Comenius University Press, Bratislava, pp 7–342

LE BRETON N, THOMPSON AB (1988) Fluid-absent (dehydration) melting of biotite in metapelites in the early stage of crustal anatexis. Contrib Mineral Petrol 99: 226–237

LE FORT P (1981) Manaslu leucogranite: a collision signature of the Himalaya. A model for its genesis and emplacement. J Geophys. Res 86: 10 545–10 568

LIEW TC, HOFMANN AW (1988) Precambrian crustal components, plutonic associations, plate environment of the Hercynian fold belt of Central Europe: indications from a Nd and Sr isotopic study. Contrib Miner Petrol 98: 129–138

LIEW TC, 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

MCCULLOCH MT, CHAPPELL BW (1982) Nd isotopic characteristic of S- and I-type granites. Earth Planet Sci Lett 58: 51–64

MONTEL JM, VIELZEUF D (1997) Partial melting of metagreywackes, Part II. Compositions of minerals and melts. Contrib Mineral Petrol 128: 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. Contrib Mineral Petrol 120: 137–149

NABELEK PI, BARTLETT CD (1998) Petrologic and geochemical links between the post-collisional Proterozoic Harney Peak leucogranite, South Dakota, USA and its source rocks. Lithos 45: 71–85

NABELEK PI, LIU M (1999) Leucogranites in the Black Hills of South Dakota: the consequence of shear heating during continental collision. Geology 27: 523–526

NEYMARK LA, KOVACH VP, NEMCHIN AA, MOROZOVA IM, KOTOV AB, VINOGRADOV DP, GOROCHOVSKY BM, OVCHINIKOVA GV, BOGOMOLOVA LM, SMELOV AP (1993) Late Archaean intrusive complexes in the Olekma granite–greenstone terrain (Eastern Siberia): geochemical and isotopic study. Precambr Res 62: 453–472

O'NEIL JR, CHAPPELL BW (1977) Oxygen and hydrogen isotope relations in the Berridale Batholith. J Geol Soc, London 133: 559–571

PATIÑO DOUCE AE, HARRIS N (1998) Experimental constraints on Himalayan anatexis. J Petrol 39: 689–710

PATIÑO DOUCE AE, HUMPHREYS ED, JOHNSTON AD (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 Cordillera Blanca Batholith, Peru. J Petrol 37: 1491–1521

PETRÍK I (2000) Multiple sources of the Western Carpathian Variscan granitoids: a review of Rb/Sr and Sm/Nd data. Geol Carpath 51: 145–158

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, 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 Slov Monograph, Bratislava, pp 235–252

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 Carpath 45: 283–291

PIN C, DUTHOU JL (1990) Sources of Hercynian granitoids from the French Massif Central: inferences from Nd isotopes and consequences for crustal evolution. Chem Geol 83: 281–296

PIN C, BINON M, BELIN JM, BARBARIN B, CLEMENS JD (1991) Origin of microgranular enclaves in granitoids: equivocal Sr-Nd evidence from Hercynian rocks in the Massif Central (France). J Geophys Res 95 B11: 17 821–17 828

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 Slov Monograph, Bratislava, pp 1–24

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, Chinese Science Bull 43: 103

POLLER U, JANÁK M, KOHÚT M, TODT W (2000) Early Variscan magmatism in the Western Carpathians: U-Pb zircon data from granitoids and orthogneisses of the Tatra Mountains (Slovakia). Int J Earth Sci 89: 336–349

POLLER U, TODT W, KOHÚT M, JANÁK M (2001) Nd, Sr, Pb isotope study of the Western Carpathians: implications for Palaeozoic evolution. Schweitz Mineral Pertrogr Mitt 81: 159–174

RICHARDS P, SHIMIZU N, ALLÈGRE CJ (1976) $^{143}Nd/^{144}Nd$, a natural tracer: an application to oceanic basalts. Earth Planet Sci Lett 31: 269–278

Royden LH (1993) The steady state thermal structure of eroding orogenic belts and accretionary prisms. J Geophys Res 98: 4487–4507

Sawyer EW (1991) Disequilibrium melting and the rate of melt-residuum separation during migmatitization of mafic rocks from the Grenville Front Quebec. J Petrol 32: 701–738

Sawyer EW (1996) Melt segregation and magma flow in migmatites: implications for the generations of granite magmas. Trans Roy Soc Edinb, Earth Sci 87: 85–94

Schaltegger U (1997) Magma pulses in the Central Variscan Belt: episodic melt generation and emplacement during lithospheric thinning. Terra Nova 9: 242–245

Shaw A, Downes H, Thirlwall MF (1993) The quartz diorites of Limousin: elemental and isotopic evidence of Devono–Carboniferous subduction in the Hercynian belt of the French Massif Central. Chem Geol 107: 1–18

Singh J, Johannes W (1996) Dehydration melting of tonalites. Part II. Composition of melts and solids. Contrib Mineral Petrol 125: 26–44

Skjerlie KP, Patiño Douce AE, Johnston AD (1993) Fluid-absent melting of a layered crustal protolith: implications for the generation of anatectic granites. Contrib Mineral Petrol 114: 356–378

Sokol A, Domečka K, Breiter K, Janoušek V (2000) The underground storage near Příbram - a source of new information about granitoids of the Central Bohemian Pluton. Věst Čes geol úst 75: 89–104

Stampfli GM, Borel GD (2002) A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. Earth Planet Sci. Lett 196: 17–33

Stille H (1924) Grundfragen der vergleichenden Tektonik. Borntraeger, Berlin, pp 1–443

Taylor HP Jr (1988) Oxygen, hydrogen, and strontium isotope constraints on the origin of granites. Trans Roy Soc Edinb, Earth Sci 79: 317–338

Turpin L, Cuney M, Friedrich M, Bouchez JL, Aubertin M (1990) Meta-igneous origin of Hercynian peraluminous granites in N.W. French Massif Central: implications for crustal history reconstructions. Contrib Mineral Petrol 104: 163–172

Vielzeuf D, Clemens JC, Pin Ch, Moinet E (1990) Granites, granulites and crustal differentiation. In: Vielzeuf D, Vidal Ph (eds) Granulites and Crustal Evolution. Kluwer, Dordrecht, pp 59–85

Villaseca C, Barbero L, Rogers G (1998) Crustal origin of Hercynian peraluminous granitic batholiths of Central Spain: petrological, geochemical and isotopic (Sr, Nd) constraints. Lithos 43: 55–79

von Raumer JF, Neubauer F (1993) Late Proterozoic and Paleozoic evolution of the Alpine basement – an overview. In: von Raumer JF, Neubauer F (eds) Pre-Mesozoic Geology of Alps. Springer Verlag, Berlin, pp 625–639

von Raumer JF, Stampfli GM, Borel GD, Bussy F (2002) Organization of pre-Variscan basement areas at the north-Gondwanan margin. Int J Earth Sci 91: 35–52

Wells PRA (1981) Accretion of continental crust: thermal and geochemical consequences. Philos Trans Roy Soc London A301: 347–357

Wendt I (1986) Radiometrische Methoden in der Geochronologie. Ellen Pigler Verlag, Clausthal Zellerfeld, pp 80–86

Williamson BJ, Shaw A, Downes H, Thirlwall MF (1996) Geochemical constraints on the genesis of Hercynian two-mica leucogranites from the Massif Central, France. Chem Geol 127: 25–42

Wolf MB, Wyllie PJ (1994) Dehydration-melting of amphibolite at 10 kbar: effects of temperature and time. Contrib Mineral Petrol 115: 369–383

Appendix: Sample description and location

Sample number		Rock type, location	Longitude (°E)	Latitude (°N)	Altitude (m)
1	VF- 43	muscovite-biotite granite, natural outcrop Vyšná Krivá	49°01´23˝01	19°11´33˝20	1 035.0
2	VF-153	biotite tonalite, natural outcrop Vyšné Matejkovo	48°59´48˝10	19°13´35˝46	1 130.0
3	VF-157	muscovite granite, natural outcrop Stupecké Valley	49°46´45˝24	19°10´49˝47	820.0
4	VF-283	muscovite-biotite granodiorite, natural outcrop, Matejkov Ridge	48°59´53˝05	19°16´02˝20	831.5
5	VF-298	muscovite-biotite granodiorite, natural outcrop, Vyšné Matejkovo	48°59´44˝21	19°15´57˝02	705.0
6	VF-356	biotite tonalite, quarry Vyšné Matejkovo	48°59´47˝22	19°15´03˝59	812.0
7	VF-417	muscovite-biotite granodiorite, natural outcrop Javorisko	49°02´34˝56	19°10´27˝18	905.0
8	VF-636	biotite granodiorite, natural outcrop Blatná Valley	49°00´29˝39	19°09´05˝16	685.0
9	VF-639	biotite granodiorite, natural outcrop Blatná Valley	49°00´17˝11	19°09´29˝40	742.0
10	VF-700	muscovite granite, natural outcrop Nižné Matejkovo	49°00´09˝26	19°15´54˝23	825.0
11	VK-139	biotite granodiorite, natural outcrop Malý Javorník	48°15´31˝20	17°08´57˝10	545.0
12	BGPI-1	biotite granodiorite, natural outcrop Hradná Valley	48°36´31˝04	18°00´59˝50	290.0
13	T-87	biotite granodiorite, natural outcrop Krnča	48°31´36˝00	18°15´58˝50	250.0
14	MM-29	muscovite-biotite granite, natural outcrop Poruba Valley	48°50´48˝02	18°33´11˝54	665.0
15	Z-164	biotite-muscovite granite, quarry Veľká Valley	48°49´27˝03	18°46´27˝30	590.0
16	MF-4a	muscovite-biotite granodiorite, quarry Bystrička	49°10´24˝12	19°06´34˝44	575.0
17	NT-401	biotite granodiorite, natural outcrop Liptovská Lúžna	48°57´41˝50	19°20´19˝13	960.0
18	ZK-4	muscovite granite, natural outcrop Vyšná Boca	48°55´28˝56	19°44´28˝57	1 045.0
19	TL-117	muscovite-biotite granodiorite, natural outcrop, Prostredný Ridge	49°11´24˝19	20°01´31˝23	1 920.0
20	VG-46	biotite granodiorite, quarry Klementka	48°40´12˝41	19°37´30˝52	870.0
21	VG-47	muscovite-biotite granodiorite, quarry Chorepa	48°35´43˝17	19°51´31˝50	555.0
22	V-7312	biotite-muscovite granite, natural outcrop České Brezovo	48°29´13˝21	19°48´33˝32	340.0
23	V-9738	muscovite-biotite granite, natural outcrop Solisko	48°42´31˝53	20°09´48˝11	660.0
24	VVM-129	biotite-muscovite granite, drill well Peklisko	48°48´40˝58	20°33´39˝49	596.9
25	CH-3/72	muscovite-biotite granodiorite, quarry near Ružín dam	48°51´48˝42	21°05´28˝30	360.0
26	KV-3/622	gabbro, Rochovce borehole	48°42´04˝06	20°17´39˝21	408.5