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MULTIPLE SOURCES OF THE WEST-CARPATHIAN VARISCAN GRANITOIDS: A REVIEW OF Rb/Sr AND Sm/Nd DATA

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Abstract: Detailed reviewing of several existing Rb/Sr datings from the West-Carpathian granitic massifs shows that the Rb/Sr dates older than U/Pb zircon data are possibly caused by inclusion of high Rb/Sr samples in the sample collections. Such samples, usually occurring as leucocratic veins in metamorphic complexes, usually have higher initial $^{87}Sr/^{86}Sr$ ratios which results in generating pseudo-isochrons. Therefore, there is no need for an initial mixing line as suggested earlier. Some samples outlying both above and below isochrons may be interpreted in terms of system opening at a time different from the initial closure. Depending on reconstructed Rb/Sr ratios late Variscan to Early Alpine ages are obtained for the opening. In contrast to Rb/Sr, previously published Sm/Nd data show that the initial $^{143}Nd/^{144}Nd$ ratios were not homogenized making it possible to suggest end-members responsible for the observed variation. Such end-members are sought in (1) the peraluminous (leuco)granites that originated through dehydration melting of gneisses with fairly high I_{Sr} and (2) gabbro/dioritic rocks occurring within granite massifs or as mafic enclaves. Assimilation of supracrustal rocks by the mafic magma could have produced either sub- to metaluminous I-type granitoids or peraluminous S-type granites depending on proportions of the end-members. The varying proportions may also have been responsible for the mineralogical and petrological differences observed between the two groups. Seven different sources are suggested for all the Variscan granitoids in the Western Carpathians.

Key words: Western Carpathians, open system, source rock, end-member, granitoids, leucogranite, diorite, assimilation, Rb/Sr, Sm/Nd, pseudoisochron.

Introduction

The problem of the source rocks of the West-Carpathian Variscan granitoids (Fig. 1) has been addressed several times mainly on isotopic grounds discussing the possible role of a mantle component. Less frequently, the probable protolith was characterized by petrological considerations. While early researchers preferred a metasedimentary source and palingenetic origin of granitoids (Cambel 1980; Hovorka 1980), later, mainly due to accumulating Rb/Sr data, the role of „mantle component“ has been increasingly emphasized (Cambel & Petrík 1982; Kráľ 1994). The recognition of S-, I- and A-type features borne by these granitoids enabled different source lithologies to be assumed (Cambel & Vilinovič 1987; Petrík et al. 1994; Uher & Broska 1996; Petrík & Kohút 1997).

Recently, the existing body of Rb/Sr data was complemented by new Sm/Nd determinations (Kohút et al. 1999). The authors found in contrast to the Rb/Sr system, that the Sm/Nd system was not homogenized and samples do not generate isochrons. To explain the heterogeneity in $^{143}Nd/^{144}Nd$ ratios they also invoked processes of contamination and/or magma mixing. Based on depleted mantle Nd model ages, the role of a Middle Proterozoic component recycling was stressed (l.c.).

All the isotopic data clearly preclude a single source for the West-Carpathian granitoids. Although this was concluded by all authors, the lithological character of possible precursors was mentioned only in a general way, mainly in the isotopic context. The aim of the present work is to confront the available data with actual, granite-related rocks found in outcrops, and to suggest probable protoliths.

Geological setting

The West-Carpathian Variscan granitoids comprise considerable parts of the Variscan crystalline terranes imbricated in the Alpine structural edifice (Fig. 1). The edifice was formed by contraction of the Variscan continental crust disintegrated by Early Jurassic rifting and Early Cretaceous extension. Three main megaunits were thrust one over another during the Late Cretaceous: the Tatric Superunit, Veporic Superunit and Gemeric Superunit (Plašienka et al. 1997). The bulk of granitoids were emplaced during the Carboniferous (350–300 Ma B.P.) when they intruded the thickened Early Paleozoic basement, and after initial uplift and erosion in the Early Triassic, they were submerged and remained buried until the Tertiary. Then, in the Paleogene, first the Vepor pluton was exhumed along normal faults, followed in the Neogene by Tatric plutons (Kováč et al. 1994) to form the characteristic present day core-and-cover structure. The granitoids in the Tatric Superunit crop out in eleven “core” mountains. In the Veporic Superunit the largest and most complex Vepor pluton has been uncovered. All the Tatric and Veporic granitoid plutons intruded high-grade metamorphic rocks: migmatites, gneisses and amphibolites. By contrast, in the Gemeric Superunit small bodies of Permian Gemeric granites intruded low

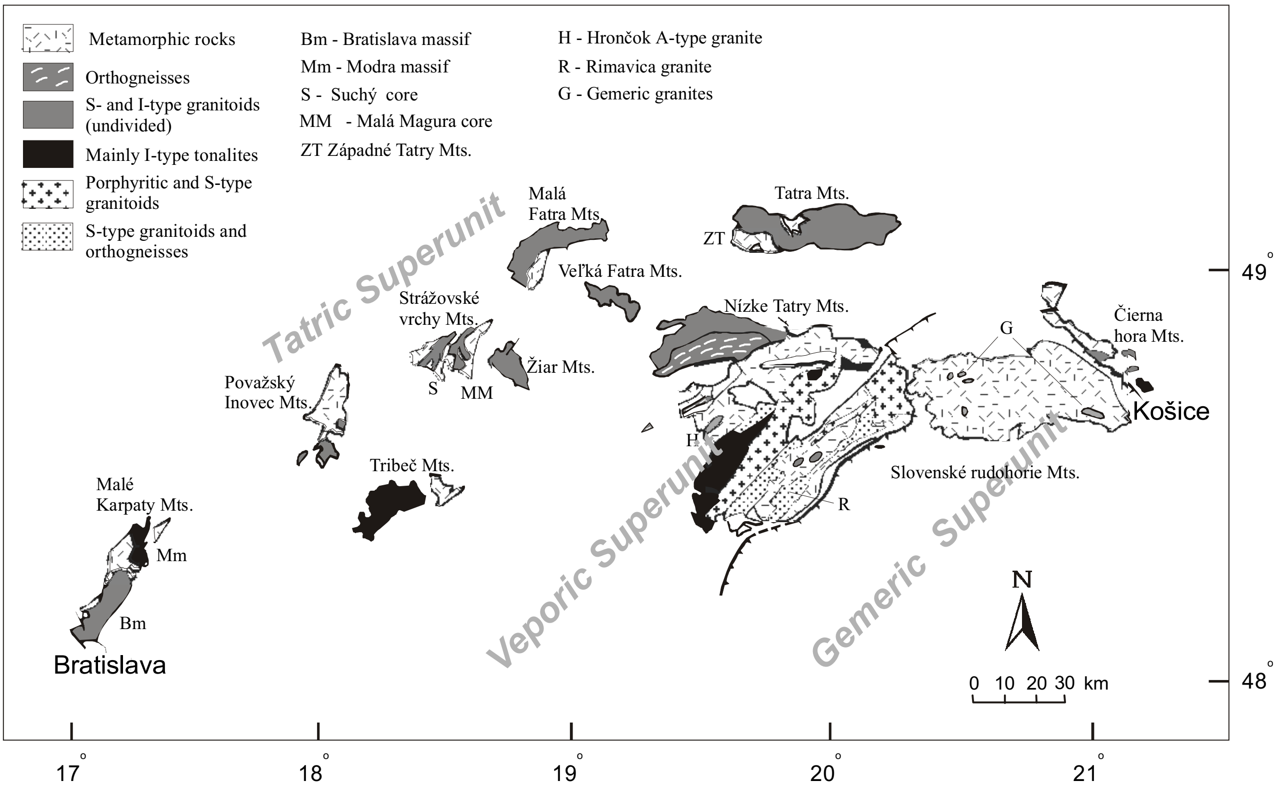

Fig. 1. Crystalline basement outcrops in the Western Carpathians showing main granitoid types and mountain ranges.

grade metapelites and now occur in the form of tectonic slices. While Tatric granitoids bear mostly primary, Variscan features, the Veporic and Gemeric granitoids are often sheared and strongly reworked due to the Alpine burial resetting their K/Ar and $^{40}Ar/^{39}Ar$ ages (Dallmayer et al. 1996; Kováčik et al. 1996).

The isotopic evidence

A major part of the granitoids with a peraluminous, commonly leucocratic, character and a more or less obvious relationship to metasedimentary wall rocks (migmatite belts, paragneiss xenoliths) was included in the S-type group. Some of them have slightly increased initial Sr isotope ratios (Rimavica Granite in the Veporic Superunit or Malé Karpaty granitoids), or very high ratios (Kralička Granite of the Nízke Tatry Mts., Gemeric granites), while others do not (Strážovské vrchy or Vysoké Tatry Mts.), Table 1. A minor part of the biotite-rich granitoids (granodiorites and tonalites), showing sub- to metaluminous natures, and scattered mafic microgranular enclaves (MME) form the I-type group. They mostly have low Sr initial ratios around 0.705 (Tribeč Mts., Sihla tonalite) however, a significant exception is represented by the Prašivá/Ďumbier granodiorite of the Nízke Tatry Mts. with I_{Sr} = 0.7078, Table 1. The A-type group represented by the Hrončok Granite also shows a high I_{Sr} (0.7114). Based on detailed discussion of the Rb/Sr data, Kráľ (1994) distinguished two groups of granitoids with I_{Sr} > 0.707 and = 0.706 (approximating the S- and I-type group) and suggested wall rock assimilation to explain the higher I_{Sr} values.

Rb/Sr systematics

The accumulated Rb/Sr whole rock and U/Pb zircon data showed that a discordancy exists between them, the former giving higher dates. Kráľ (1994) and Petrík et al. (1994) discussed the discordancy, speculated about a possible lack of homogenization and postulated an inherited $^{87}Sr/^{86}Sr$ mixing line of the source rock. If so, the Rb/Sr data should help to identify possible end-members. However, a closer inspection of several published Rb/Sr data sets shows that at least some of the published dates are based on pseudoisochrons constructed using unrelated or altered rocks. [All the following age calculations were performed by Isoplot (Ludwig 1994), using the errors given by authors, and results are at 95% probability level (2σ), see Table 1].

Strážovské vrchy Mts. (Suchý granitic core)

The original Rb/Sr age (Kráľ et al. 1987, recalculated as 392 ± 17 Ma, Table 1), based on four selected samples (SR-3, 4, 5, 6), exceeds the zircon age (356 ± 9 Ma, Kráľ et al. 1997) by 36 Ma. The original slope is rather steep owing to the exclusion of a low Sr sample SR-2, and accepting a high Rb/Sr sample SR-6 (Fig. 2A). The latter sample is a leucocratic sill (one of several) alternating with paragneisses in the Suchý core. The sills occur within a gneiss belt 500 m wide steeply dipping into the main granitic body and showing no transition to it. The sample was included because of its high Rb/Sr ratio, being considered a leucocratic off-spring of the main body. A view that such aplitic leucocratic veins are products of the dehydration melting of the metapelitic

Table 1: Rb/Sr isochron ages of selected West-Carpathian granite cores recalculated at 95% probability level (Isoplot & Ludwig 1994). *Notes:* Errors are those given by authors ($^{87}Rb/^{86}Sr$, $^{87}Sr/^{86}Sr$): 2 %, 0.02 % (1σ) by Bagdasaryan, Cambel and co-workers; 0.25 %, 0.005 % (1σ) by Kráľ and co-workers; 1%, 0.03% (2σ) by Kohút and co-workers. For samples with MSWD>1 also magnified errors 2σ*√MSWD are given. n^{1-16} refer to the following samples: n^1 — SR-3A, 3B, 4, 5, 6; n^2— as for n^1 with SR-2, without SR-6; n^3— T-18, 50, 25, 87, 27; n^4— as for n^3 without T-27; n^5— T-22, 36, 37, 62, 63, 70; n^6: as for n^5 without T-37; n^7— ZK-14, 24, 92, 117, 120, J-3, 5, 16; n^8— ZK-68, Kr-1, 2, 3, 2/83, 3/83; n^9— as for n^8 with ZK-3; n^{10}— VF-356, 135, 639, 612, 695, 40, 43, 45, 385, 229, VFMa-1, 2a, 2b, 3, 4, 6; n^{11} as for n^{10} without VFMa-1, 2a, 2b, 6; n^{12}— ZK-28, 118, 121, 83, 57, 58; n^{13}— as for n^{12} without ZK-58 with ZK-76, 66, 9; n^{14}— ZK-26, 27, 69, 122; n^{15}— ZK-72, 67, 56, 19, KV-1, 2, 3, 4; n^{16}— as for n^{15} without KV-2 and with D-1, 2, 3.

Massif Granite type	Age (Ma) ±2σ	MSWD ±2σ √MSWD	Isr	Age (Ma) ±2σ	MSWD ±2σ √MSWD	Isr
Tatric massifs		**isochron variant**			**isochron variant**	
Suchý Mts.	n^1= 5 392 ± 17	13.5 392 ± 62	0.70596 ± 0.00027	n^2= 5 353 ± 34	19.4 353±150	0.70616 ± 0.00037
Tribeč Mts. Monazite series	n^3= 5 337 ± 33	4.94 337 ± 73	0.70594 ± 0.00079	n^4= 4 349 ± 12	0.55	0.70586 ± 0.00023
Tribeč Mts. Allanite series	n^5= 6 432 ± 69	2.06 432 ± 99	0.70522 ± 0.00046	n^6= 5 305 ± 125	1.39 305±147	0.70579 ± 0.00059
Nízke Tatry Mts. Kralička type	n^8= 6 361 ± 40	0.305	0.71601 ± 0.00144	n^9= 7 361 ± 40	0.307	0.71596 ± 0.00143
Veľká Fatra Mts.	n^{10}= 16 359 ± 47	53.6 359 ± 344	0.70631 ± 0.00069	n^{11}= 12 422 ± 77	34.9 422±455	0.70570 ± 0.00087
Nízke Tatry Mts. Ďumbier & Prašivá	n^7= 8 369 ± 122	0.115	0.70782 ± 0.00135			
Veporic massifs		**isochron variant**			**isochron variant**	
Sihla type	n^{12}= 6 373 ± 163	0.129	0.70537 ± 0.00101	n^{13}= 8 298 ± 79	0.056	0.70563 ± 0.00078
Rimavica type	n^{15}= 8 393 ± 24	0.48	0.70771 ± 0.00071	n^{16}= 10 385 ± 47	0.55	0.70766 ± 0.00087
Hrončok type	n^{14}= 4 247 ± 8	0.952	0.71140 ± 0.00099			

source (paragneisses) rather than late differentiates of the main body is now considered more probable. The SR-2 sample with no signs of postmagmatic alteration or contamination was reconsidered and included into a new set. The new arrray including five samples gives 353 ± 34 Ma, a value concordant with the zircon dating, although with larger error and MSWD = 19.4 (Table 1).

Rb and Sr mobility. For one of the originally excluded samples (SR-1) Kráľ et al. (1987) suggested a possible Rb mobility. The sample with the lowest Rb (40 ppm, compared to the typical range of 70–100 ppm) contains abundant late sillimanite (3.5 vol. %) accompanied by minor muscovite (3.7 %). Various sillimanite-bearing granitoids were found along a belt at least 5 km long containing up to 7 % sillimanite and 6 % muscovite. The assemblage is thought to have formed at a high-temperature subsolidus stage in a low pH environment (acid leaching, Korikovsky et al. 1987; Burnham 1979). The decrease of the Rb/Sr ratio at a time significantly different from that of the initial system closure may result in an outlying position of the altered sample — above the isochron, and vice versa. The distance from the isochron (defined by non-altered samples) will be proportional to the Rb/Sr decrease and the time elapsed since the initial closure (i.e. the greater and younger the Rb escape, the greater the deviation). Provided that we are able to reconstruct the original Rb/Sr ratio, the time elapsed between the initial closure and system opening can be calculated [see Fig. A1 and equations (A1, A2) in Appendix].

Hradetzky & Lippolt (1993) discussed in detail the Rb/Sr system and concluded that in superficial conditions it is the Sr mobility which causes the system opening. The example of Suchý sillimanite granitoids suggests that in high-temperature, acid hydrothermal solutions, Rb may become more mobile than Sr. Marquer & Peuqat (1994) found that in granites deformed in ductile shear zones the Rb/Sr ratio increases in greenschist facies and decreases in amphibolite facies conditions. Moreover, the greenschist facies mylonites fall below and the amphibolite facies mylonites above the intrusive Rb/Sr isochron.

In the given example, the Rb/Sr values prior to alteration were derived assuming various degrees of the Rb escape (Table 2). For the Suchý sillimanite granitoids, t_1 = 51–102 Ma and t_c = 302 – 251 Ma [eq. (A1), (A2), Appendix], assuming the intrusive age of 353 Ma (Table 2).

It is realized that the derived ages depend on the method of Rb and Sr reconstructions (by inspection of outliers in variations diagrams, Fig. 2B,C,D) and are based on one sample. Therefore, special research is needed to confirm the open system interpretation of anomalous areas in granitic massifs. However, if real, the obtained Permian age data would coincide with the Permian to Lower Triassic post-collisional transtension and rifting in the West-Carpathian basement. Increased heat flow could have initiated circulation of high temperature fluids along weakened zones of the northern Tatra basement complex (Tatra — Fatra Belt, Plašienka et al. 1997). A parallel, much more pronounced process, is recorded in the southern Vepor Belt where significant Permian to Lower Triassic magmatism and volcanism occurred (Uher & Broska 1996; Kotov et al. 1996; Putiš et al 2000). Two additional cases are shown below where outliers below the isochron correlate well with apparent Rb/Sr increases (Table 2).

Tribeč Mts.

The Tribeč tonalites dated by the Rb/Sr method (Bagdasaryan et al. 1990) yielded 362 ± 27 Ma (recalculated at

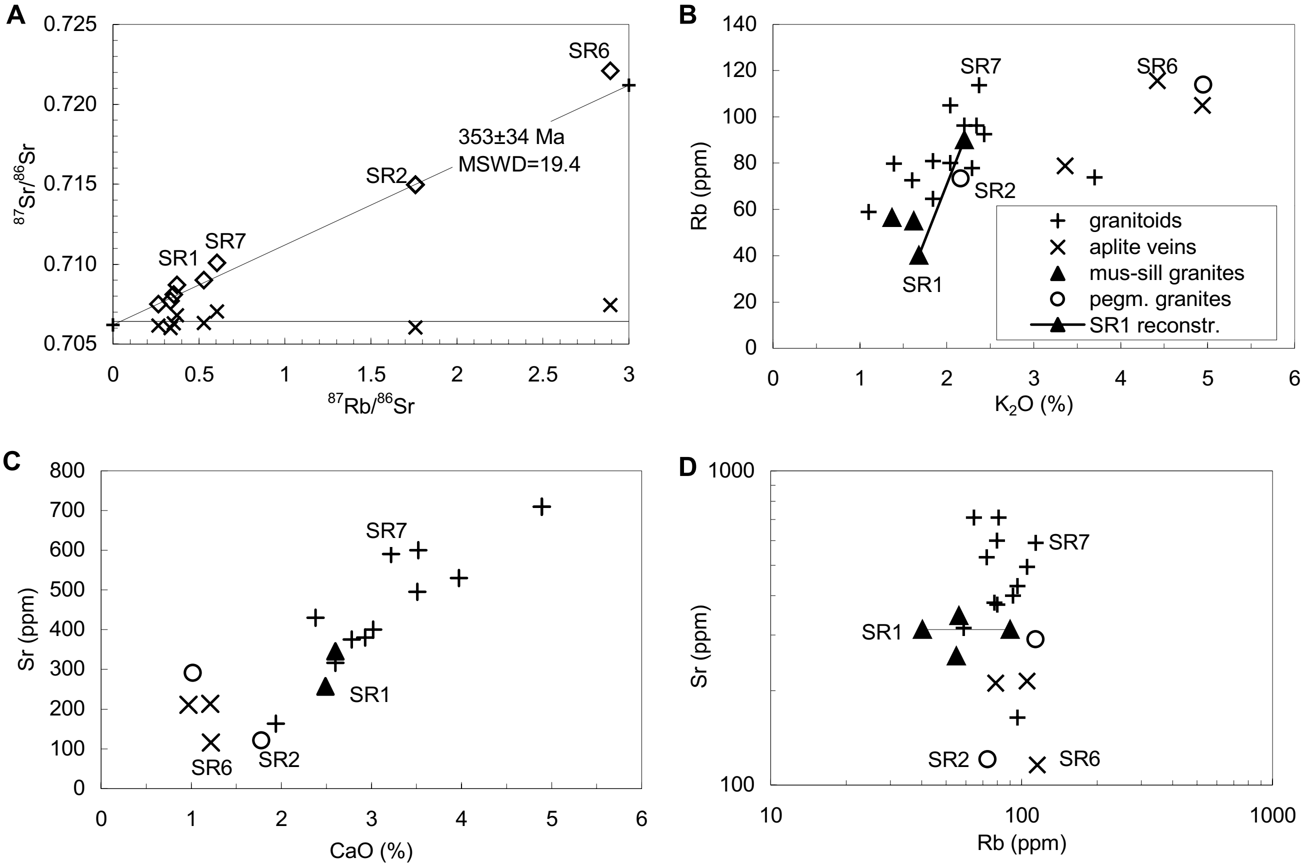

Fig. 2. Rb/Sr system in the Suchý granitoid core: (**A**) Isochron with outlying samples SR-1, 6, 7. $^{87}Sr/^{86}Sr_{(350)}$ ratios of the samples are also shown; (**B, C, D**) Correlations between Rb, Sr, K_2O and CaO. Reconstructed SR-1 position (90 ppm Rb) is shown in B, D.

Table 2: Calculations of the age of system opening using the examples of the Suchý, Veľká Fatra and Tribeč granitoids using equations (A1, A2). See Appendix for details.

Massif Sample	Intrusive age (Ma)	I_{Sr}	Rb ppm Measured	Sr ppm Measured	Rb ppm Reconstructed	Sr ppm Reconstructed	$^{87}Sr/^{86}Sr$ Measured S_m	$^{87}Sr/^{86}Sr$ Recon. S_r	$^{87}Rb/^{86}Sr$ Measured R_m	$^{87}Rb/^{86}Sr$ Recon. R_r	Age (Ma) t_c
Suchý	353	0.70616	40.22	312.2	90	312.2	0.7087	0.70803	0.3728	0.8341	251
SR-1					140					1.2976	302
Veľká Fatra	340	0.70649	99.77	148	99.77	200	0.71512	0.71594	1.9518	1.4443	227
VFMa-2	350							0.71622			198
Tribeč	350	0.70586	153.71	60.45	153.71	100	0.7391	0.74263	7.3795	4.4610	265
T-27						200				2.2304	302

2σ) contrasting with the U/Pb age of 306 ± 10 Ma (Broska et al. 1990). After subdividing the sample set according to criteria based on the allanite and monazite dichotomy (Broska & Gregor 1992; Petrík & Broska 1994) broadly corresponding to I- and S-type subgroups, respectively, two slopes are obtained in the Nicolaysen diagram. The monazite-bearing group yields 337 Ma ± 33 Ma with one outlying sample T-27 (a leucocratic vein) below the isochron (Fig. 3A). This sample has a significantly decreased Sr content (60 ppm, compared to the observed range of 600–70 ppm) allowing us to presume that the original Rb/Sr was lower (Table 1). Using equations (A1, A2) for the age of system opening the values of 265–302 Ma are obtained for estimated Sr 100 and 200 ppm (Table 2). Excluding this sample from the monazite group improves the isochron statistics to 349 ± 12 Ma and MSWD = 0.55 (Table 1).

The allanite-bearing group with very low Rb/Sr ratios yields 432 ± 69 Ma with one sample T-37 (leucocratic vein) steepening the slope. Unfortunately, in the absence of chemical data for this sample there is no possibility to evaluate its chemistry. Again, the main granitoid body supplies only tonalites with low, tightly grouped Rb/Sr ratios which produce isochrons with very high errors. For example, excluding T-37 would give 305 ± 125 Ma (Table 1).

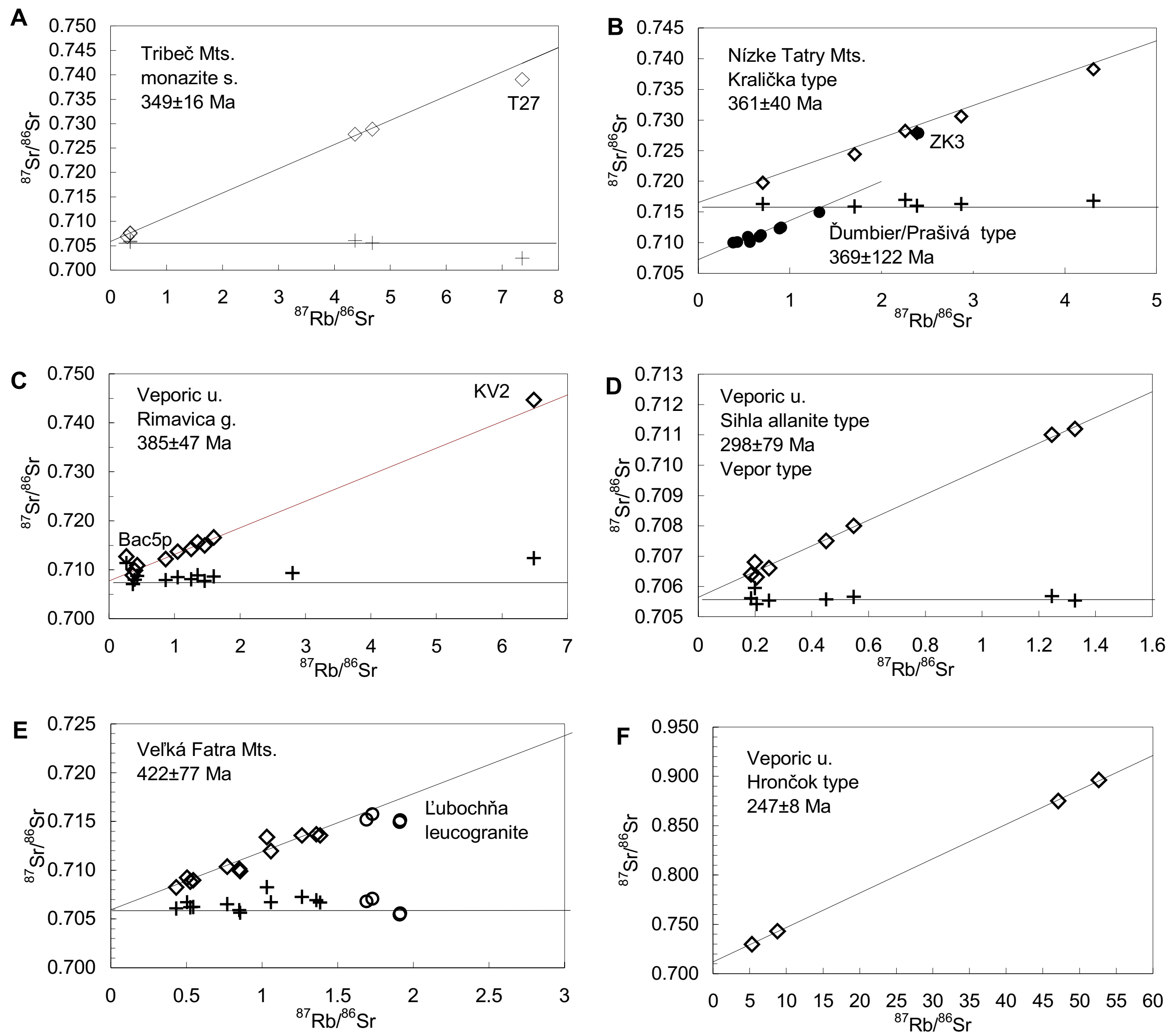

Fig. 3. Rb/Sr isochrons for granitic rocks of the Tribeč Mts (**A**), Nízke Tatry Mts. (**B**), Rimavica Granite (**C**), Sihla type tonalite (**D**), Veľká Fatra Mts. (**E**) and Hrončok type granite (**F**). Crosses: samples age-corrected to 350 Ma.

The Nízke Tatry pluton

The Nízke Tatry granitoid pluton belongs to a petrologically key area with various granitoid types dated by the Rb/Sr method (Bagdasaryan et al. 1985). No high precision zircon data are available at present from the area. While the southern slopes of the Nízke Tatry consist of orthogneisses (mainly ductilely deformed S-type granitoids, Petrík et al. 1998) the ridge and northern slopes are formed by the postkinematic, undeformed Ďumbier tonalite/granodiorite and the Prašivá Granite. The specific, leucocratic Kralička Granite crops out within the orthogneiss belt. It is believed to have been formed by partial melting of the orthogneisses (Zoubek 1951). The Ďumbier/Prašivá granitoids form a tight array corresponding to 369 ± 122 Ma, I_{Sr} = 0.70782 and MSWD = 0.115, whereas the Kralička type yields 361 ± 40 Ma with the high I_{Sr} = 0.71601, MSWD = 0.305 (Fig. 3B, Table 1). There is one obvious outlier in the Ďumbier/Prašivá sample set (ZK-3), a sample discussed already by Kráľ (in Cambel et al. 1990a) who hypothesized its possible high age (with the Ďumbier/Prašivá initial Sr ratio of 0.716 it gives 595 Ma). It is argued here that ZK-3 belongs to a different granite type, possibly akin to the Kralička Granite rather than to the Ďumbier/Prašivá type (as all the rocks on the main ridge between Chopok and Ďereše peaks) thus having the same age. The Kralička granite isochron including ZK-3 gives an age identical to Ďumbier/Prašivá age (361 ± 40 Ma). The Rb and Sr chemistry of the Kralička granites is compared with other Nízke Tatry granitoid types in Fig. 4. Also shown is a newly analysed set of samples (labeled Chopok) from the area between Chopok and Ďereše. The Kralička type granitoids differ by their much lower Sr contents overlapping with the Chopok type and orthogneisses.

The Ďumbier/Prašivá granitoid samples come from localities which are more than 40 km apart implying Sr isotopic inhomogeneity. They include both monazite and allanite-bear-

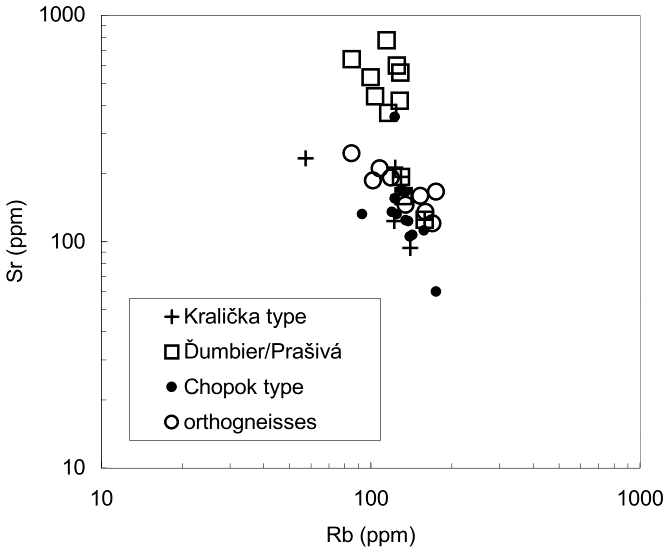

Fig. 4. Rb vs. Sr in the Nízke Tatry Mts.: Kralička, Ďumbier/Prašivá type granitoids and orthogneisses. The Kralička type and "Chopok" type are identical in terms of Rb/Sr ratios.

ing rocks with subaluminous nature showing one of the highest I_{Sr} within I- and S-type granitoids (except the Kralička type). Their close association with orthogneisses and their presumed derivatives (Kralička and Chopok granite?) having extremely high I_{Sr}, is considered significant for explaining this anomaly.

Veľká Fatra Mts.

The granitoids of the Veľká Fatra Mts. are the only ones in the Western Carpathians where Rb/Sr and Sm/Nd systematics are available (in addition to K/Ar and $^{40}Ar/^{39}Ar$ data) through the comprehensive work by Kohút (1992) and Kohút et al. (1996, 1998, 1999). Mainly for geological reasons, Kohút (1992) treated the groups of main pluton granitoids separately from the leucocratic Ľubochňa granites, showing cutting contacts with the zoned pluton. While all the samples give 359 ± 47 Ma (Table 1), the main granitoids yields 422 ± 77 Ma and the Ľubochňa granite samples fail to form an isochron at all (Fig. 3E). Although the author accepts the high age interpreting it as that of a „pre-existing pluton" he also discusses the possibility of pseudoisochron due to the inhomogeneity of source(s). Considering the U/Pb zircon age of 356 ± 25 Ma obtained from the main pluton (Kohút et al. 1997), the latter interpretation seems to be more probable in explaining different initial ratios of the main petrographic types. The Ľubochňa leucogranites form a negative slope, the sample with apparently lower $^{87}Sr/^{86}Sr$ (VFMa-2) also having the lowest concentration of Sr (148 ppm). The possible increase of the Rb/Sr ratio allows us to try an open system interpretation. The ages of 227 Ma for the system opening are obtained assuming original Sr 200 ppm and the intrusive age of 340 Ma, and 198 Ma for the intrusive age of 350 Ma (Table 2). Similarly, anomalous Veľká Fatra orthogneiss samples (5, 44 in Bagdasaryan et al. 1992) may be explained by a Sr loss (not shown).

Vepor pluton (the Sihla and Rimavica granitoids)

In their original work Bagdasaryan et al. (1986) interpreted the Rb/Sr data obtained on Sihla I-type tonalites as an isochron giving (as recalculated in Table 1) 373 ± 163 Ma and data on Vepor/Ipeľ granodiorites as isochron 254 ± 150 Ma. By redefining the granitoids after the allanite/monazite dichotomy criterion, as in the case of the Tribeč tonalites, a new array (8 allanite-bearing samples) is obtained corresponding to 298 ± 79 Ma (MSWD = 0.056) concordant with the U/Pb age 304 ± 3 Ma (Bibikova et al. 1990), Fig. 3D. The monazite-bearing samples are apparently disturbed and their increased $^{87}Sr/^{86}Sr$ ratios indicate different source(s). The samples age-corrected to 300 Ma do not form any mixing line, rather than two „plateaus" of the Sihla and Vepor/Ipeľ groups (not shown in Fig. 3).

Rimming the southeastern boundary of the Vepor pluton, the Rimavica S-type granitoids represent a rather inhomogenous group with strong Alpine overprint. Their Rb/Sr age claimed by the authors (Cambel et al. 1988) is 393 ± 24 (as recalculated in Table 1) based on eight samples taken as much as 22 km apart. A constant Sr isotope ratio can hardly be expected over such an area. Actually, twelve samples were measured from five localities, two of them, Krokava and Chyžné (KV and D in Notes to Table 1) covered by five and four samples, respectively. The Chyžné Group yields 316 ± 111 Ma, the Krokava group yields 394±195 Ma. The Krokava samples also supplied zircons for the U/Pb dating (350 ± 5 Ma, Bibikova et al. 1990). Other samples (leucocratic veins of muscovite granitoids Bac-5p and KV-2, Fig. 3C) have apparently increased Sr initial ratios of 0.71138 and 0.71238 respectively (age-corrected to 350 Ma, further on denoted by subscript $_{350}$). Thus, the S-type granitoids of the SE Veporic Superunit seem to comprise several granite types (intrusions?) with Rb/Sr ages overlapping the zircon age.

Sm/Nd systematics

In contrast to Rb and Sr, typically dispersed elements, Sm and Nd reside mainly in accessory minerals. In the West-Carpathian granitoids where hornblende is rare, the relevant accessories are monazite in the S-type, and allanite and titanite in the I-type rocks. As the Sm/Nd ratio changes only slightly during partial melting, the Nd evolution line of a granite may be extrapolated into the past where, at the intersection with the depleted mantle (DM) evolution line, it provides the crustal residence age (T_{DM}). Due to much slower diffusivity of rare earth elements (REE), the Nd isotopes do not homogenize and may preserve source characteristics (e.g. Pin & Duthou 1990). An attempt to identify these source(s) is made below using both Sm/Nd and Rb/Sr data.

The bulk of the Sm/Nd data comes from Kohút et al. (1999) who provided twenty-one samples covering all main granite occurrences (one sample per massif except the Veľká Fatra Mts. with five samples). The authors found that the granitoids lack homogenization of $^{143}Nd/^{144}Nd$ isotopes, which is also expressed by their model ages (two stage T_{DM}, $^{147}Sm/^{144}Nd$, and $^{143}Nd/^{144}Nd$ values for depleted mantle are after Liew & Hofmann 1988) in the range of 1.6–0.62 Ga. This range was interpreted analogically with other workers on the European Variscides as resulting from source inhomogeneities. The sources are regarded as mixtures of at least two end members (Liew & Hofmann 1988; Pin & Duthou 1990; Janoušek et al. 1995). Kohút et al. (1999) also identified a gabbro from the Veporic Superunit and the Kralička Granite from the Nízke Tatry Mts. as samples with the highest $^{143}Nd/^{144}Nd_{(350)}$ = 0.511834 and lowest $^{143}Nd/^{144}Nd_{(350)}$ = 0.512474 ratios, respectively with corresponding T_{DM2st} = 1.6 and 0.62 Ga [DM2st refers to two-stage mantle melting according to Liew & Hoffman (1988)]. The bulk of granitoids shows a lesser $Nd_{(350)}$ isotopic range between 0.51215 (Tribeč tonalite) and 0.51197 (Považský Inovec leucogranite) with corresponding T_{DM2st} = 1.11–1.4 Ga. This range most probably reflects variable proportions of (at least) two contrasting sources of the granitoid magma.

Summary of the isotope systematics

The detailed inspection of the Rb/Sr systematics of the most important granitoid massifs showed that (1) the main body tonalites and granodiorites if subdivided according to the allanite /monazite criterion yield dates within error concordant with U/Pb zircon ages. However, due to the small ranges of the Rb/Sr ratios they show too large errors (Tribeč, Ďumbier/ Prašivá type, Sihla type). (2) The incorporation of high Rb/Sr samples occurring often only as leucocratic veins or sills results in the increase of the presumably apparent age since the veins arising from a different (metapelitic) protolith (e.g. Suchý, Tribeč Mts., Veporic Superunit) have higher initial $^{87}Sr/^{86}Sr$ ratios. (3) Although an initial slope may form due to higher I_{Sr} of the leucocratic melts, the hypothesis of a „source mixing line“ existing in the initial $^{87}Sr/^{86}Sr$ ratios of the main granitoid groups does not seem to be confirmed. (4) Correlation between the distances of outliers above the isochron and their anomalously low Rb/Sr ratios (and vice versa) may be interpreted in terms of the Rb/Sr system opening at a time different from the initial closure time. Using the equations (A1, A2) and good guesses for the original Rb/Sr ratios, late Variscan to early Alpine ages are obtained for this opening.

Interpretation of the isotope systematics

The need for differing precursors

The Sm/Nd data show that the most radiogenic samples have the lowest Sm/Nd ratios. Such rocks (gabbro, tonalites) have steep light rare earth element patterns, but flat Nd evolution lines which intersect the DM evolution line at the youngest ages (Fig. 5A). In contrast, the samples with the highest Sm/Nd ratios (flat light rare earth element patterns characteristic mainly of leucogranites) are least radiogenic, which means that they must have started their crustal history at a very low Nd isotopic ratio, that is they have high DM model ages. Lithological and model age contrasts exist between the end-members as is confirmed by a negative correlation between $^{143}Nd/^{144}Nd_{(350)}$ and SiO_2 shown in Fig. 5B. Thus, a young mafic, infracrustal end member (IC_m) is required to mix with an old, felsic supracrustal end member (SC_f) to give the observed span in $^{143}Nd/^{144}Nd_{(350)}$ ratios. The requirement of a low Sm/Nd ratio for the IC_m end member precludes a mid ocean ridge type basalt with Sm/Nd 0.33 (e.g. Jenner et al. 1987), and points rather to light rare earth element enriched gabbros and diorites. The SC_f end member best correlates with peraluminous leucocratic melts formed by metapelite/metagreywacke dehydration melting in upper crustal conditions.

The end-members

IC_m end-member. The only known basic rocks with low Sm/Nd ratios found in a close relation to granitoids are dioritic rocks. They are known from many West-Carpathian basement massifs, where they form small-sized bodies within granitoids commonly too small to be shown on geological maps. Diorites, as known from the Malé Karpaty Mts. (Cam-

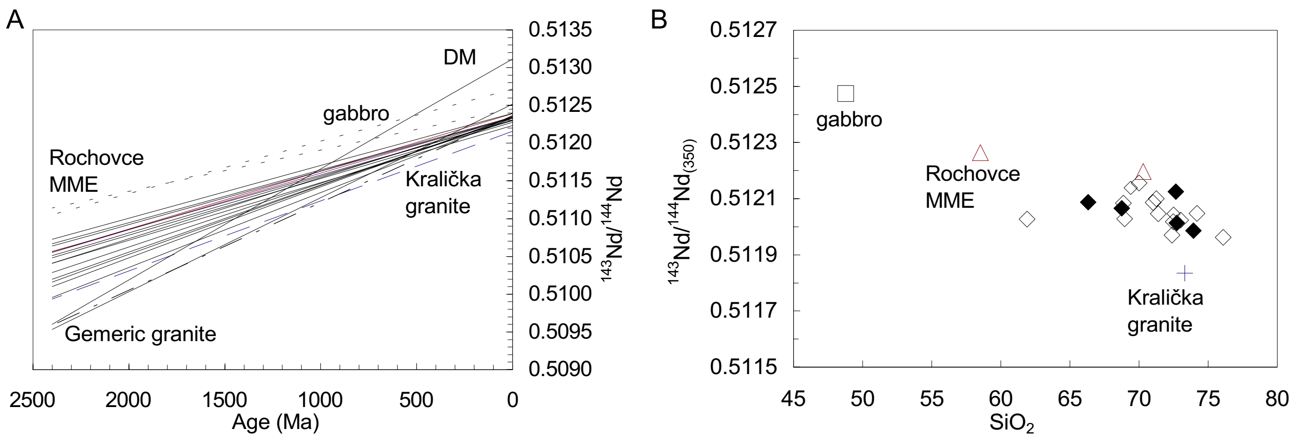

Fig. 5. (A) Nd evolution diagram, dotted: gabbro and diorite mafic enclave, dashed: felsic rocks (Kralička type), thin lines: Tatric and Veporic granitoids; Depleted mantle (DM) evolution after Liew & Hofmann (1988). (B) $^{143}Nd/^{144}Nd_{(350)}$ vs. SiO_2; gabbro: KV-3 from the contact zone of the Veporic and Gemeric superunits (Kohút et al. 1999); enclave: from the Rochovce Granite (Hraško et al. 1999); closed symbols: Veľká Fatra granitoids.

bel & Pitoňák 1980; Cambel & Vilinovič 1987), are fine- to medium-grained plagioclase- and hornblende-dominated rocks with SiO_2 ranging from 54 to 63 % and steep rare earth element patterns (Sm/Nd = 0.12–0.18). The main carrier of light rare earth elements, besides hornblende, is allanite. Cambel & Vilinovič (1987) showed that major and minor elements of these diorites are found along trends defined by granitoids in Harker diagrams (Fig. 6). Since much of the granite variation may be interpreted by a magma differentiation process, such as crystal fractionation (Vilinovič & Petrík 1984), the observed trends may coincide just because the compositions of cumulates and diorites are similar. This would preclude simple mixing relations, as indicated in the diagram Zr vs. SiO_2 (Fig. 6D), but it does not rule out the diorite magma playing a role in granite genesis. Even more indicative, that mafic magmas are involved, is the presence of mafic microgranular enclaves (MME) in I-type tonalites (Petrík & Broska 1989). The Tribeč MME with dioritic to tonalitic compositions lie on linear trends with host tonalites in both major and trace element variations, Figs. 7A,B. The compositional range of the enclaves is best explained by their mixing with granitoid magma before being individualized into enclaves. The fact that the MME occur only in the most mafic varieties of host tonalites implies an interaction (mixing) of both magmas which has shifted the host granitoid magma toward a more mafic composition. Thus, the diorites, occurring either as individual bodies or as MME, appear a suitable IC_m candidate in the granite magma genesis. They themselves appear to be products of the hybridization of a mantle-derived gabbroic (basaltic) precursor by a felsic magma.

SC_f end member. Felsic rocks with high Sm/Nd ratios are typically represented by leucogranites occurring within para- and orthogneiss complexes. They commonly show flat rare earth elements patterns often with increased heavy rare earth elements. Peraluminous leucogranites are considered to be typical products of partial dehydratration melting of metapelite precursors (Montel & Vielzeuf 1997; Stevens et al. 1997; Patino-Douce & Harris 1998). Their light REE depleted nature is known from the geochemical studies of granites of collisional orogenic belts (Dietrich & Gansser 1981; Nabelek & Glascock 1995) which showed that they had Sm/Nd ratios typically between 0.2–0.4. The strongly peraluminous Kralička Granite with the lowest $^{143}Nd/^{144}Nd_{(350)}$ and highest $^{87}Sr/^{86}Sr_{(350)}$ ratios is considered to be a melting product of the Nízke Tatry orthogneisses which also have flat REE patterns (Sm/Nd = 0.2–0.3). The orthogneisses were interpreted as ductilely deformed S-type granitoids (Petrík et al. 1998). Thus both para- and orthogneisses may produce characteristic leucogranites when being melted. They have the properties of the SC_f end-member which escaped Sr isotopic homogenization common in main granite bodies, and reflect the $^{87}Sr/^{86}Sr$ ratio of their source. The high $^{87}Sr/^{86}Sr$ value indicates a recycled crustal material. This is, in the case of orthogneisses, confirmed by the high Nd T_{DM2st} age

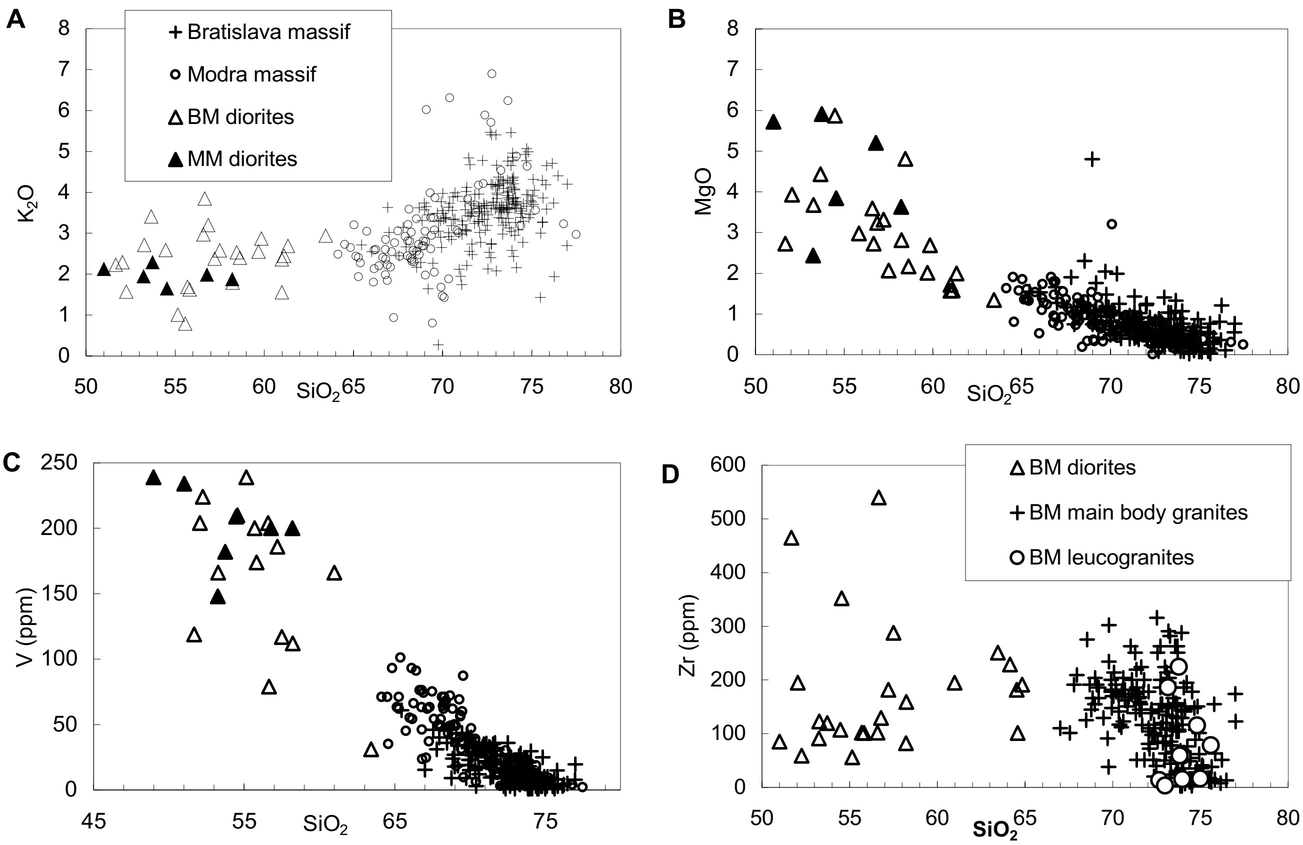

Fig. 6. Harker diagrams for K_2O (**A**), MgO (**B**), V (**C**) and Zr (**D**) in the Malé Karpaty granitoids and diorites. (A–C) data from both Bratislava and Modra massifs, (D) the Bratislava Massif only (source data Cambel & Vilinovič 1987).

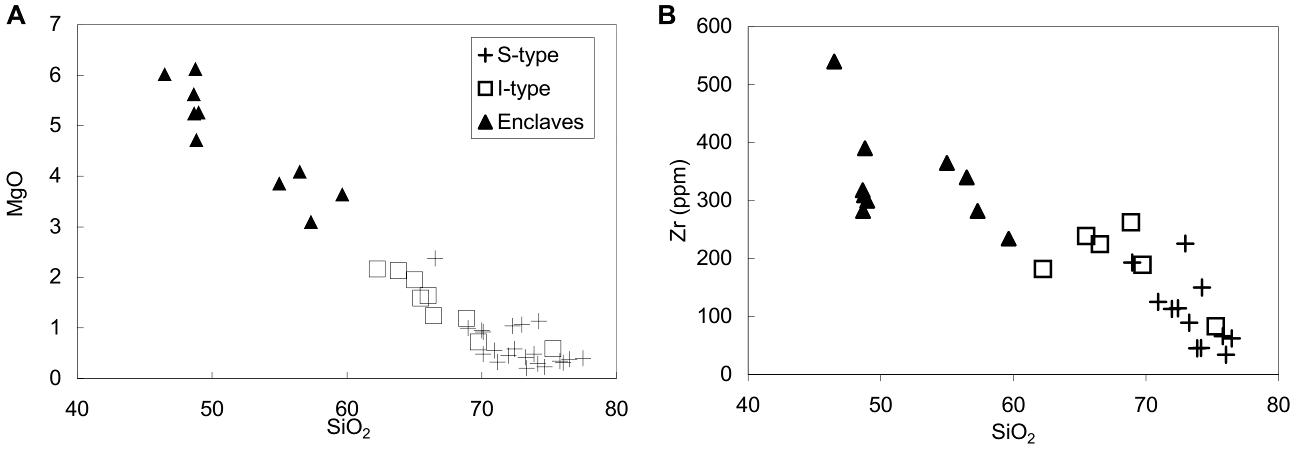

Fig. 7. Harker diagrams of MgO (**A**) and Zr (**B**) in granitoids and mafic microgranular enclaves in the Tribeč Mts. (source data Petrík & Broska 1989). Formed presumably from the same magma as diorites, the enclaves show mixing relations with I-type tonalites.

(1.6 Ga) and the upper intercept zircon age (for the Western Tatra orthogneiss >1.6 Ga, Poller et al. 1999a). The metagreywackes (gneisses) have not yet been dated by high precision methods, however earlier zircon datings for the Tatra paragneiss range between 620–700 Ma (Cambel et al. 1990).

Mixing of the end-members

The relationship between the end-members characterized above and the whole group of granitoids is shown in diagram Sm/Nd vs. $^{143}Nd/^{144}Nd$ (Fig. 8A). Diorites, spatially and genetically related to granitoids, are preferred to the gabbro which is tectonically sandwiched between metapelites and the Alpine Rochovce Granite (Krist et al. 1988) with no apparent relationship to them. The end members are bounded using the following data.The Sm/Nd data for diorites (IC_m end member) come from the Tatry Mts. Poller et al. (1999b) found $\varepsilon_{Nd(330)}$ values of 0–2 which correspond to $^{143}Nd/^{144}Nd_{(330)}$ = 0.512213–0.512315 [initial $\varepsilon_{Nd(330)}$ calculated using magmatic zircon age]. The value of 0.51228 within the range given above was used for the mixing model. The range of Sm/Nd ratios (0.12–0.19) is taken mainly from the Malé Karpaty diorites. The SC_f end member is bounded by the Sm/Nd ratios of leucogranites (Suchý and Považský Inovec garnet aplites, Kralička Granite) ranging from 0.16 to 0.29, and the $^{143}Nd/^{144}Nd$ ratios of the Western Tatra micaschists (Poller et al. 1999b) ranging from 0.51162 to 0.5118. The outlined fields with the joining mixing line (calculated according to Faure 1989) cover the observed scatter of granitoids. The two outliers are the Veporic two-pyroxene gabbro, apparently a pure mantle-derived rock with $\varepsilon_{ND(350)}$ = 5.6 and the Gemeric Granite with extremely high Sm/Nd and $^{87}Sr/^{86}Sr_{(350)}$ ratios (0.29–0.31, 0.720–0.734 respectively) suggesting a different supracrustal source.

Sr vs. Nd isotopes

The mixing relations of IC_m and SC_f end-members are also illustrated in a $(^{87}Sr/^{86}Sr)_{350}$ vs. $(^{143}Nd/^{144}Nd)_{350}$ diagram (Fig. 8B). Two mixing lines are shown between the same IC_m end-

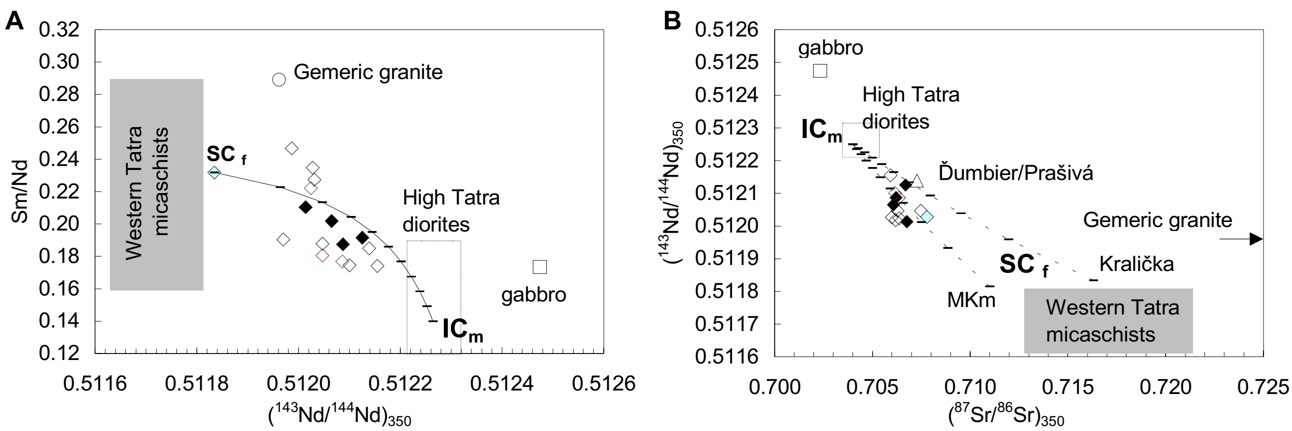

Fig. 8. (A) Mixing in $^{143}Nd/^{144}Nd$ vs. Sm/Nd plot (Nd IC ppm: 60, SC: 15). (B) $^{87}Sr/^{86}Sr$ vs. $^{143}Nd/^{144}Nd$ plot with mixing line [Sr used in mixing (ppm): IC_m 600, SC_f 122/150, Nd SC_f 15/18]. Tick marks at 10 %. MKm — Malé Karpaty gneisses. Source data: Kohút et al. (1999) — individual points (closed symbols — Veľká Fatra granitoids), Poller et al. (1999b) — the fields of micaschists and diorites.

member as in Fig. 8A and two SC_f end-members with different $^{87}Sr/^{86}Sr$ ratios, 0.710 and 0.716. They represent the I_{Sr} values of the Malé Karpaty gneisses (Bagdasaryan et al. 1983) and the Kralička Granite (Kohút et al. 1999), respectively. The $^{143}Nd/^{144}Nd$ ratio of the first SC end-member is assumed to be the same as for orthogneisses, at the upper limit of the Tatra micaschist range (Poller et al. 1999b). The mixing range covers the observed field of granitoids which are spread mainly between diorite and gneiss end-members. However, some of them with relatively high $^{143}Nd/^{144}Nd$ ratios are shifted to higher $^{87}Sr/^{86}Sr$ values (Ďumbier tonalite) thus lying on the other line, diorite — Kralička Granite. An end-member with such a high $^{87}Sr/^{86}Sr$ ratio seems to be necessary to explain the relatively increased I_{Sr} (0.706–0.708) of some more mafic types (Ďumbier/Prašivá): a smaller SC_f end-member proportion (60 % in this model) is sufficient to increase the I_{Sr} while keeping the high Nd isotopic ratio and the more mafic composition of the tonalites. The S-type granitoids with $^{87}Sr/^{86}Sr_{(350)}$ around 0.706–0.707 would require 60–80 % of the gneissic end-member which is in agreement with their more felsic nature.

The mechanism of mixing

The mechanism of mixing can hardly be traced unambiguously. In principle three processes are conceivable: (1) melting of a mixed source rock, (2) mixing of contrasting magmas and (3) assimilation of a felsic rock by a mafic magma. All of them have been invoked in literature. On the basis of Sm/Nd data from lower crustal xenoliths, Pin & Duthou (1990) preferred a composite source mixed on a small-scale. However, the potential source rocks in the Western Carpathians (paragneisses, orthogneisses) do not show a mixed character and actually they were treated as end-members. Therefore, melting and assimilation of a metagreywacke precursor by the hybrid gabbro-diorite magma and subsequent mixing and mingling are considered more likely.

An important result of melting experiments with various metasedimentary rocks is that they can produce only peraluminous and mostly leucocratic melts (Vielzeuf & Montel 1994; Montel & Vielzeuf 1997). Slightly more mafic peraluminous melts originate by melting of a metagreywacke protolith as demonstrated by Montel & Vielzeuf (1997). Such melts resemble the compositions of typical two-mica S-type granitoids which form bulk massifs in the Western Carpathians. Montel and Vielzeuf's results are shown in an A–B plot (after Debon & Le Fort 1983) and compared with Malé Karpaty granitoids and metamorphic rocks (Fig. 9). The greywacke starting compositions are matched by less peraluminous and less mafic varieties of Malé Karpaty gneisses. The more mafic greywacke-derived experimental melts (circles), straddle the boundary of leucogranites and overlap the peraluminous part of the Malé Karpaty monzogranites. However, they do not cover minor subaluminous and metaluminous granodiorites. Therefore, the input of a mafic end-member is necessary to get the more mafic, metaluminous granodiorites and tonalites (Patino-Douce 1995; Castro et al. 1999). This is also supported by the lower I_{Sr} of the Malé Karpaty granitoids (0.707; Cambel et al. 1982) compared to that of gneisses (0.710; Bagdasaryan et al. 1986).

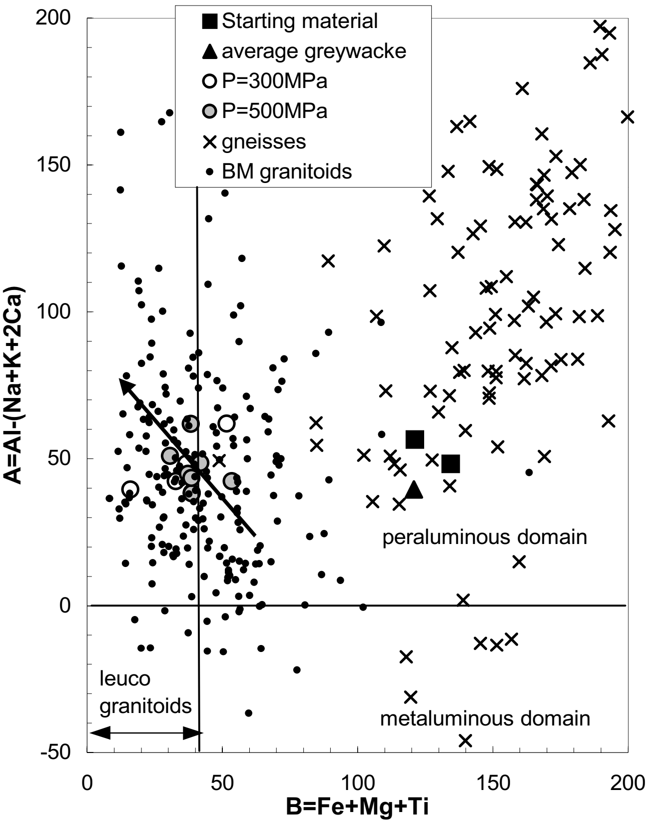

Fig. 9. Malé Karpaty granitoids and metamorphic rocks in the A–B plot (Debon & Le Fort 1983) compared with experimental melts (Montel & Vielzeuf 1997). Evolution trend of granitoids is shown by the arrow. Source data Cambel & Vilinovič (1987) and Cambel et al. (1990).

Generally, the input appears to have been more pronounced in I-type granitoids with I_{Sr} between 0.706 and 0.705. The contrasting mineralogical composition and petrological properties of the S- and I-type granitoids, as inferred by Petrík & Broska (1994), may thus reflect varying proportions of the mafic gabbroic infracrustal end-member, rich in water and rare earth elements. Such magmas originate above a subducting slab (Peacock 1993). The melting of deeply buried metapelites in the course of Variscan thrusting is documented by extensive migmatization. Janák et al. (1999) estimated the melting conditions of the Tatra migmatites at 700–750 °C, 1100–1200 MPa (kyanite zone) and 680–825 °C, 530–800 MPa (sillimanite zone). The peak temperatures seem to require a mantle-derived heat source. The hybrid diorite zone present in the area (Kohút & Janák 1994) supports the role of infracrustal magmas both as suppliers of heat and material.

Other granitoid types

Besides the common S- and I-type granitoids discussed above, the A-type granites of the Veporic Superunit, and specialized granites of the Gemeric Superunit are treated separately.

The Rb/Sr age of the Hrončok A-type granite is 247 ± 8 Ma as recalculated according to the data of Cambel et al. (1989) and redefinition by Petrík et al. (1995), Fig. 3F, Table 1. It is concordant with the zircon dating which yielded the lower and upper intercept ages of 238.6 ± 1.4 Ma and 1096 Ma ± 44, respectively (Putiš et al. 2000). The I_{Sr} (= 0.7114), the second highest after the Kralička Granite, and mildly alkalic chemistry with high Rb/Sr ratios (2–18) point to a mature source, possibly older biotite granites. The intersection of the Hrončok protolith Sr evolution (I_{Sr} = 0.7114 at 240 Ma) with the mantle value at 1 Ga gives the Rb/Sr ratio about 0.32, a value typical of granites. This, and the high I_{Sr}, precludes the Sihla tonalite as a potential precursor as suggested by Petrík & Kohút (1997).

The Gemeric granites with I_{Sr} 0.720–0.734 (after Cambel et al. 1990) also show the most extreme Rb/Sr and Sm/Nd ratios (>10 and 0.29 respectively). They also have the highest single stage Nd age = 2.4 Ga, Fig. 5A (two stage Nd age is 1.3 Ga at t = 280 Ma). In the absence of high precision zircon data no protolith age constraints can be made. The Permian age appears most probable for an event when a muscovite and quartz rich source (recycled metapelite) underwent melting to produce the observed highly specialized Rb, Li, F, B, Sn, Mo enriched melts.

Conclusions

Existing Rb/Sr data from several Western Carpathians granite massifs were re-interpreted after a detailed inspection of outlying samples. It appears that a mixing line in source $^{87}Sr/^{86}Sr$ ratios is not neccessary to explain higher Rb/Sr ages from these massifs. The high Rb/Sr samples (vein leucogranites) are often unrelated to other granitoids and, with their increased I_{Sr}, generally reflect heterogeneous sources of S-type granitoids. Some individual samples lying above and below the isochron may be interpreted in terms of the Rb/Sr system opening at a time different from the initial closure. The samples from the Tatra belt granitoids indicate Permian to Triassic ages for this event, coeval with extensional magmatism in the Vepor Belt.

While being homogenous in terms of I_{Sr}, the main body granitoids still preserve a range of initial $^{143}Nd/^{144}Nd$ ratios reflecting various proportions of at least two contrasting source components. The components were identified with old supracrustal metasediments producing peraluminous leucogranitoids and young basaltic (gabbroic) producing diorites. The assimilation of the supracrustal component by the diorite magma may have produced observed isotopic, trace and major element variations of both S- and I-type granitoids.

The following source rocks, arranged with decreasing proportions of the supracrustal component, are recognized among the West-Carpathian granitoids: (1) Gemeric granites derived from a several times recycled crustal material with extreme Sr initials (I_{Sr} > 0.720), possibly muscovite metapelite. (2) The Kralička type granite (I_{Sr} = 0.715) and its equivalents derived from a recycled crustal complex dominated by older S-type granitoids (orthogneisses). (3) The Hrončok A-type granite (I_{Sr} = 0.7114) derived from a mature high Rb/Sr, probably granitic source. (4) Peraluminous leucocratic aplitic veins, migmatite related in metamorphic complexes, the products of gneiss dehydration melting (Strážovské vrchy, Považský Inovec, Malé Karpaty Mts.). (5) Undeformed, peraluminous, mainly S-type granitoids with I_{Sr} = 0.708–0.706 showing transitional characteristics, derived from a metagreywacke (gneissic) protolith with minor infracrustal contribution (Bratislava type granitoids). (6) Sub- to metaluminous I-type granodiorites and tonalites (I_{Sr} = 0.705) with moderate infracrustal contribution. (7) Dioritic rocks and MME probably themselves products of crustal contamination of mantle-derived gabbroic melts.

The variable proportions of H_2O and REE-rich IC_m end-member (7) and H_2O and LREE-poor SC_f end-member (4) may explain the contrasting mineralogical and petrological properties observed and inferred for the major (5, 6) groups of S- and I-type granitoids (Petrík & Broska 1994) which follow mainly from contrasting water contents.

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Appendix

System opening

The time elapsed since the system opening (t_1) is given by:

$$t_1 = 1/\lambda \ln[(S_m - S_r)/(R_r - R_m) + 1] \qquad (A1)$$

where S_m, R_m and S_r, R_r are measured and reconstructed $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ ratios, respectively and λ is the ^{87}Rb decay constant. The age of the Rb/Sr change (t_c) is then:

$$t_c = t_2 - t_1 \qquad (A2)$$

where t_2 is intrusive age of the sequence. The reconstructions of SR-1 and T-27 samples are shown in Fig. A1. A series of samples with the same t_c and various degrees of Rb/Sr change would form an isochron corresponding to the t_c. It is noted that the equation (A1) neglects the decrease of $^{87}Rb/^{86}Sr$ ratios with time, but the error so introduced is much smaller than the uncertainty due to the Rb/Sr ratio reconstruction. There is also an implicit assumption that the Rb escape (sample SR-1) was not accompanied by a change in the $^{87}Sr/^{86}Sr$ ratio. This seems unrealistic when we realize that the ^{87}Sr resides precisely at the sites of its formation, i.e. in the Rb^+ positions of K-rich minerals. However, the change of $^{87}Sr/^{86}Sr$ ratio requires decoupling of radiogenic and common Sr. This may occur when the rock is thermally overprinted and the biotite-produced ^{87}Sr escapes to plagioclase until a new whole rock $^{87}Sr/^{86}Sr$ ratio is established. In the case of biotite to sillimanite breakdown, interlayer cations including Rb, and Sr (common and

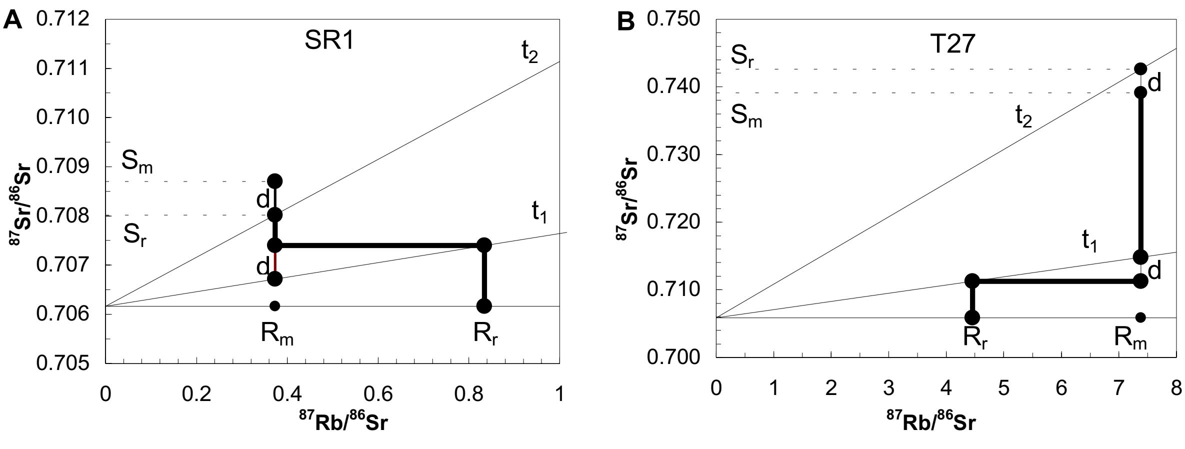

Fig. A1. $^{87}Sr/^{86}Sr$ ratio evolution with episodical change of the Rb/Sr ratio as illustrated by the Suchý SR-1 granodiorite (A) and Tribeč T-27 granite (B). The Rb/Sr ratio either decreases (A) or increases (B) at time t_1 ($R_r \rightarrow R_m$) that corresponds to the slope $(S_m - S_r)/(R_r - R_m)$ (eq. A1). The age of the change is $t_2 - t_1$ (eq. A2). $d = S_m - S_r$ corresponds to the excess (A) or deficit (B) of radiogenic Sr of the sample, inherited from the time prior to the Rb/Sr change. S_m and S_r are measured and reconstructed $^{87}Sr/^{86}Sr$ ratios; R_m and R_r are measured and reconstructed $^{87}Rb/^{86}Sr$ ratios, respectively.

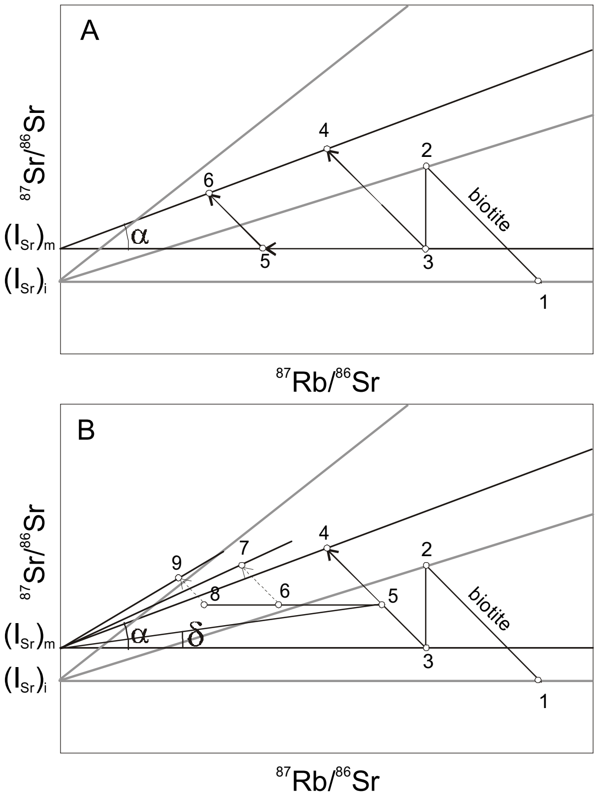

Fig. A2. $^{87}Sr/^{86}Sr$ mineral evolution: (A) A metamorphic event occurring at the time corresponding to the angle α (path 1–3), is immediately followed by various decreases of Rb/Sr ratio (paths 3–4, 3–5–6). (B) The metamorphic event is followed by various degrees of the Rb escape after a time delay (angle δ, paths 3–5–7 and 3–5–9). In this case the $^{87}Sr/^{86}Sr$ evolution produces mineral pseudoisochrons with higher "age" than that of the metamorphic event. $(I_{Sr})_i$ and $(I_{Sr})_m$ are intrusive and metamorphic Sr initial ratios, respectively.

radiogenic) are likely to escape together without the change of $^{87}Sr/^{86}Sr$ ratio. The ^{87}Sr excess in the SR-1 sample seems to be preserved from an earlier history confirming that the $^{87}Sr/^{86}Sr$ ratio does not change in the course of the reaction. However, as pointed by Hradetzky & Lippolt (1993) if Sr is emitted mainly from plagioclase, the $^{87}Sr/^{86}Sr$ increases, because it is common Sr that escapes. If so, the data obtained for low Sr outliers (VMFa-2, T-27 in Table 2) represent upper limits for the age of system opening possibly indicating rather an Alpine than a late Variscan event.

Mineral isochron

While Sr mobility is typical of weathering products, Rb escaped during high temperature acid leaching (above 600 °C, Korikovsky et al. 1987) implying a thermal overprint, redistribution and homogenization of ^{87}Sr between minerals (Fig. A2a, path 1–2–3). The new whole rock $^{87}Sr/^{86}Sr$ ratio $(I_{Sr})_m$ is not influenced by the subsequent Rb or Sr escape because biotite undergoing the breakdown releases both radiogenic and common Sr. Therefore, the high-temperature system opening has no effect on the mineral isochron age provided that the Rb escape occurred simultaneously with mineral ^{87}Sr homogenization (path 1–2–3–5–6). Actually, Kráľ (2000, personal comm.) obtained a mineral isochron for SR-1 biotite corresponding to approximately 300 Ma. Such an age (t_c) for the system opening would require a reconstructed Rb value of 140 ppm (Table 2). This seems too high a value compared to the observed range (40.2–115.6 ppm). A delay between the metamorphism and Rb/Sr change would, however, raise the biotite $^{87}Sr/^{86}Sr$ ratio above mineral isochron (Fig. A2b, path 1–2–3–5–6–7 or –8–9) and generate an apparent biotite mineral age. The neccessary delay (angle δ) is strongly dependent on the biotite Rb/Sr change (path 5–6–8), for example at t_c = 251 Ma the apparent biotite age of 300 Ma is produced at 75 % Rb/Sr ratio drop and the delay of 12 Ma, or at 50 % drop and the delay of 24 Ma. The geological relevance of the delay between metamorphism and system opening is not discussed here mainly because of the lack of the neccessary high-precision mineral trace element data.