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Objekttyp: **Article**

Zeitschrift: **Schweizerische mineralogische und petrographische Mitteilungen = Bulletin suisse de minéralogie et pétrographie**

Band (Jahr): **72 (1992)**

Heft 3

PDF erstellt am: **21.07.2024**

Persistenter Link: https://doi.org/10.5169/seals-54915

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SCHWEIZ. MINERAL. PETROGR. MITT. 72, 315–324, 1992

Rb–Sr and Sm–Nd data from diabase dykes of the Swiss Silvretta basement

by *Barbara E. Hellermann Furrer*[1]

Abstract

The isotope analysis of the Rb–Sr system of seven selected diabase dykes of the Swiss part of the Austroalpine Silvretta nappe supports the evidences for post-magmatic interactions with surrounding country rocks. The isotope ratios vary widely and primary magmatic signatures, as crustal contamination are veiled by secondary effects. The Sm–Nd isotope analyses of five dykes show considerable variations in ε Nd. Three dykes plot below the CHUR line, thus indicating that mixing with a crustal contaminant lowered their $^{143}Nd/^{144}Nd$ ratios. Mixing calculations suggest a small degree of contamination by a sedimentary component which was introduced into the mantle reservoir. Both methods showed inadequate for dating the intrusions.

Keywords: Isotope ratio, Rb–Sr, Sm–Nd, magma mixing, diabase dyke, Silvretta basement, Switzerland.

Introduction

Diabase dykes intrude the polymetamorphic rocks of the upper Austroalpine Silvretta nappe in the Graubünden area (Fig. 1). The dykes are exposed over an area of ≈ 60 km^2 and have been described and mapped early this century by ESCHER (1921), EUGSTER (1923), BLUMENTHAL (1926) and BEARTH (1932). In recent years MICHAEL (1985), VON DER CRONE (1989), FLISCH (1981) and HELLERMANN (1990, 1992) conducted chemical analyses and presented classification schemes and tectonic models. The results of the geochemical analysis indicate that the majority of the dykes is highly evolved and therefore of predominantly andesitic composition. However, a group with low silica and higher Mg contents classifies as basalts. These basaltic dykes reveal an overall tholeiitic chemical character (HELLERMANN, 1990). According to the degree of contamination and partial melting two main magma types developed: a high-Ti group and a low-Ti group. The low-Ti samples generally have higher LILE and lower LREE abundances relative to MORB whereas high-Ti dykes show less enriched patterns and flat REE signatures (HELLERMANN, 1992). The age of the dykes has not been well established by isotopic analysis (FLISCH, 1981), but can be constrained by field relations to be between Permo-Triassic and eo-Alpine (≈ 270–70 Ma). It is the aim of this paper to present additional isotopic data from seven selected dykes (Fig. 1) and to provide valuable information on the evolution model of the Silvretta diabase dykes.

Description of dykes

The dykes range in thickness from approx. 50 cm to several meters in width; they intruded irregularily into the basement complex. The maximum observed length for a single dyke is approx. 50 m which reflects the limited exposure of the dykes. They are most abundant in the south and west of the studied area although they do not continue into the Triassic sedimentary layers in the Ducan and Landwasser basins.

The dykes show sharp contacts with the wall rocks and many exhibit quenched chilled margins

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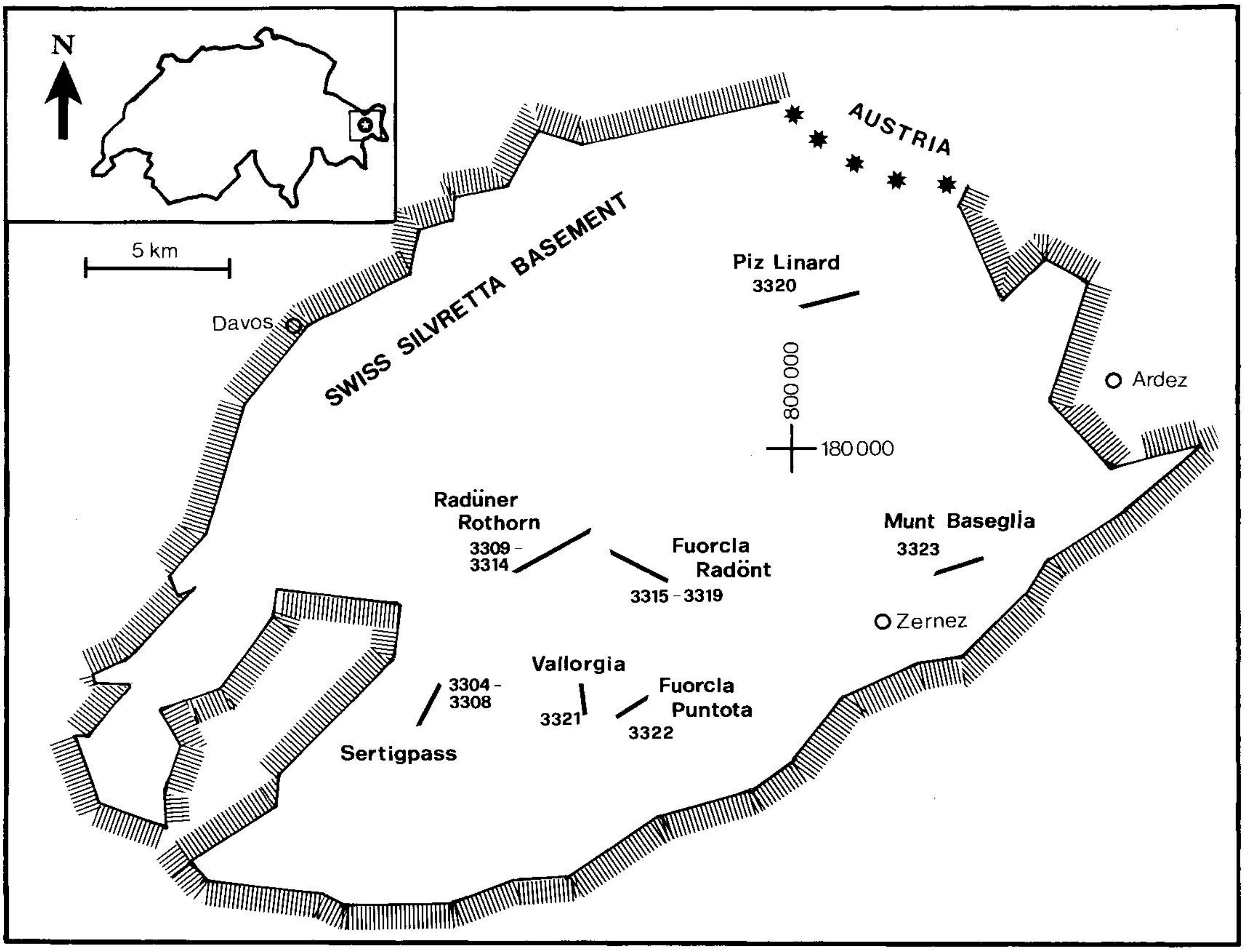

Fig. 1 Sketch map of the Swiss Silvretta basement (modified from BEARTH, 1932), indicating sample localities. Dykes in black, not to scale.

relative to their inner parts. Evidence for shallow intrusion are amygdaloidal textures which were first recognized by BEARTH (1932). Two larger dykes contain few xenoliths of adjacent gneiss country rock. The area comprises up to 200 single dykes which are not observed to cut each other. They are not affected by the Variscan regional metamorphism, but near the young Alpine fault systems and the nappe boundary, foliation and fracturing can be observed. Three main varieties of diabase rocks are recognized: porphyritic varieties with abundant plagioclase phenocrysts, fine-grained diabase with plagioclase and clinopyroxene as primary minerals and hornblende-diabases containing hornblende and plagioclase as predominant minerals. Other magmatic minerals include quartz, magnetite-ilmenite, k-feldspar and apatite. Most dykes are affected by an autohydrothermal episode and by the Alpine metamorphic event, resulting in a secondary mineral assemblage consisting mainly of albite, calcite, clinozoisite-epidote, chlorite, actinolite and white mica.

Analytical methods

Major and trace element abundances were determined by X-ray-fluorescence spectrometry using the Philips PW1400 in Fribourg. FeO contents were determined with the dipyridilic-method and analysed spectroscopically.

The isotopic analyses were carried out at the Institute for Isotope Geology in Berne. Because the dykes show evidence for mobility of the alkali elements as a result of metamorphism and in-situ contamination, only the least altered samples were chosen for the isotope analysis. The specimens selected weighted between 25 and 40 kg to ensure representative sampling. Aliquots of 0.4 grams of whole rock samples were dissolved in hydrofluoric and perchloric acid. They were diluted in 2.5 n hydrochloric acid and a spike of ^{84}Sr,

^{87}Rb, ^{150}Sm and ^{145}Nd respectively, was added to a portion of these aliquots. Using cation exchange columns, Sr, Sm and Nd were separated. A second cation exchange column operated with alpha-hydroxiisobutric acid (alpha-HIBA) further separated Sm and Nd. Sr, Sm and Nd were measured on a VG-Sector thermal ionization mass spectrometer. Rb was measured directly with an Ion Instruments AVCO solid source mass spectrometer. The ^{143}Nd/^{144}Nd ratios were corrected for fractionation to ^{146}Nd/^{144}Nd = 0.72190 before they were renormalized to ^{142}Nd/^{144}Nd = 1.141827. The ^{87}Sr/^{86}Sr ratios are normalized to ^{88}Sr/^{86}Sr = 0.1194.

The La Jolla Nd international isotope standard was measured several times with a mean ^{143}Nd/^{144}Nd ratio (normalized to ^{146}Nd/^{144}Nd = 0.72190) of 0.511829 ± 0.000008. The total error of the obtained results is assumed to be ± 0.01% (analytical precision). In the tabular listing, percent standard error (reproducibility) of the individual measurements on the isotopic ratios are listed. The errors calculated from the evolution diagrams (ages and initials) refer to one sigma errors of the calculated reference lines.

Isotope geochemistry

Sr ISOTOPIC COMPOSITION

The Sr isotopic results of the present study are presented in table 1 and show a range in present-day ^{87}Sr/^{86}Sr ratios of 0.7076–0.7248. The dykes do not form an isochron in the ^{87}Sr/^{86}Sr versus ^{87}Rb/^{86}Sr diagram (Fig. 2). A least squares regression through all data points would yield an age of = 368 Ma and an initial ratio of 0.7075. If the dykes are comagmatic members of a single magma chamber, they should exhibit the same initial ^{87}Sr/^{86}Sr ratios. Because the intrusion age of the dykes is uncertain (270–70 Ma), initial ratios were calculated to a possible age of 250 Ma. Because the samples were taken from different dykes the non-correlation of the Rb–Sr data could be due to an inhomogeneous isotopic distribution during the genesis of the magmas. Therefore the analyses of the single dykes will be discussed.

A longitudinal section of five samples had been taken from the dyke at the Fuorcla Radönt (KAW 3315–3319). In the ^{87}Sr/^{86}Sr versus ^{87}Rb/^{86}Sr diagram (Fig. 3A) four samples (KAW 3315, 3316, 3317 and 3319) lie on a straight line, whereas sample KAW 3318 plots above the others. The analytical error on the measurement of the Sr isotopic composition of this sample is well above the average (Tab. 1). Considering the analytical error and a correction of the measured point, it would nevertheless displace the sample symbol only the size of itself. The sample would then still fall well above the other four points. If a reference line is calculated through the four aligning points it yields an age of 146 Ma with an intercept at ^{87}Sr/^{86}Sr of 0.7111. A plot of the 1/Sr ratios of the samples versus ^{87}Sr/^{86}Sr (see inset of Fig. 3A) shows no coherence of the data points. Merely three out of five samples (KAW 3315, 3317, 3319) may be correlated, thus indicating that Sr mixing processes might not have been important.

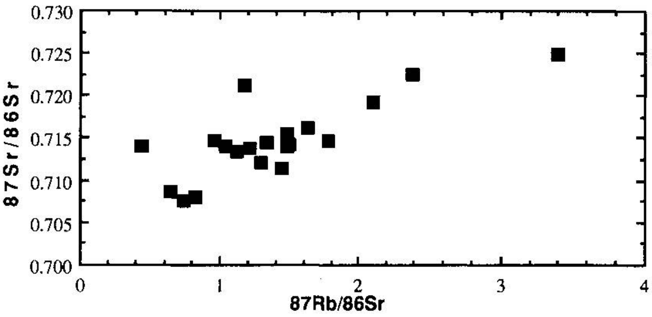

Fig. 2 ^{87}Sr/^{86}Sr versus ^{87}Rb/^{86}Sr evolution diagram for twenty Silvretta dykes. The data points scatter considerably around a reference line which would yield an age of about 368 Ma.

Six samples have been collected from the dyke at the Radüner Rothorn, four from the southern part in the Sertig valley and two from the northern end in the Radönt. The graphical presentation of the six analysed samples in the ^{87}Sr/^{86}Sr versus ^{87}Rb/^{86}Sr diagram (Fig. 3B) shows a certain scatter of the data points. The two samples KAW 3313 and KAW 3314 which have higher ^{87}Rb/^{86}Sr ratios and highest ^{87}Sr/^{86}Sr ratios of 0.72235 and 0.724755 respectively, are the two samples taken from the northern side. A reference line would yield an age of approx. 370 Ma with an intercept at ^{87}Sr/^{86}Sr of 0.7077. This is well below the initial for the dyke of the Radönt and approaches the common range of basic rocks. The ^{87}Sr/^{86}Sr versus 1/Sr diagram (see inset of Fig. 3B) reveals no linear correlation of the data and therefore an mixture of foreign material can probably be ruled out.

Five samples were taken along the largest dyke of the Sertigpass; the data points display in the ^{87}Sr/^{86}Sr versus ^{87}Rb/^{86}Sr diagram (Fig. 3C) a broad range of isotopic ratios and cannot be correlated. Again the ^{87}Sr/^{86}Sr versus 1/Sr diagram (see inset of Fig. 3C) shows no linearity of the samples and again it is assumed that mixing processes are not responsible for the scattering of the data.

From the four dykes at the Piz Linard, Vallorgia, Fuorcla Puntota and Munt Baseglia only one sample of every dyke had been taken to get

Tab. 1 Sr isotopic compositions and selected chemical analyses for diabase dykes.

Sample type	Sample KAW No.	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ ± % error	$^{87}Sr/^{86}Sr$ initial at 250 Ma	SiO_2	TiO_2	Fe_2O_3	FeO	MgO	mg'	K_2O	Y
porphyritic-low-Ti	3304	57	105	1.6231	0.71620 ± 0.0014	0.71036	55.70	1.11	1.71	5.40	4.84	38.57	1.60	35
	3305	92	100	2.1054	0.71918 ± 0.0012	0.71160	53.62	0.98	1.50	5.53	6.21	44.84	2.98	27
	3306	72	146	1.4376	0.71335 ± 0.0020	0.70817	55.79	0.99	1.35	4.64	5.99	47.92	1.72	25
	3307	77	226	0.9571	0.71474 ± 0.0018	0.71129	56.80	1.10	1.64	5.21	6.00	44.68	1.82	32
	3308	66	206	1.3285	0.71456 ± 0.0013	0.70977	58.11	1.11	1.41	5.29	5.30	42.10	1.27	30
low-Ti	3309	79	201	1.0330	0.71411 ± 0.0016	0.71039	55.38	1.53	2.50	6.10	3.60	27.95	2.31	33
	3310	73	141	1.4775	0.71493 ± 0.0110	0.70961	55.73	1.53	1.81	6.04	6.39	42.86	2.29	33
	3311	78	148	1.4761	0.71409 ± 0.0015	0.70878	55.82	1.53	2.01	6.07	6.10	41.05	2.11	36
	3312	82	187	1.2162	0.71373 ± 0.0016	0.70936	55.97	1.49	2.37	5.57	3.84	30.97	2.84	36
	3313	98	114	2.3848	0.72235 ± 0.0016	0.71377	55.82	1.55	1.75	6.28	6.42	42.38	2.66	32
	3314	116	90	3.3982	0.72476 ± 0.0016	0.71252	55.49	1.50	1.80	6.37	6.06	40.56	2.67	35
low-Ti	3315	86	161	1.4899	0.71428 ± 0.0015	0.70892	55.90	1.52	1.84	6.06	3.68	30.02	2.17	32
	3316	103	220	0.5100	0.71214 ± 0.0012	0.71031	55.79	1.50	2.32	5.59	4.12	32.54	2.42	33
	3317	90	144	1.7822	0.71473 ± 0.0022	0.70832	55.82	1.51	1.94	6.10	4.38	33.44	2.26	34
	3318	91	209	1.1748	0.72099 ± 0.0105	0.71676	55.88	1.51	2.09	5.91	3.56	29.13	2.05	35
	3319	89	214	1.1160	0.71344 ± 0.0019	0.70942	56.18	1.49	1.98	6.03	3.47	28.56	2.10	34
high-Ti	3320	69	254	0.7355	0.70760 ± 0.0015	0.70495	55.09	1.85	2.14	7.11	3.18	24.05	1.92	38
low-Ti	3321	92	359	0.6420	0.70872 ± 0.0014	0.70641	47.83	1.69	2.58	6.54	6.26	38.86	1.01	29
high-Ti	3322	43	280	0.4385	0.71409 ± 0.0190	0.71251	49.34	1.83	2.04	7.47	6.10	37.10	0.72	32
low-Ti	3323	79	264	0.8163	0.70807 ± 0.0014	0.70514	53.01	1.40	2.31	5.77	5.98	40.68	1.33	28

Analytical uncertainties are given as percent standard errors as measured, concentrations in ppm.
All samples are whole rock analyses, low-Ti and high-Ti: chemical classification according to HELLERMANN (1992).
mg' = magnesium number [(Mg/(Fe+Mg)*100].

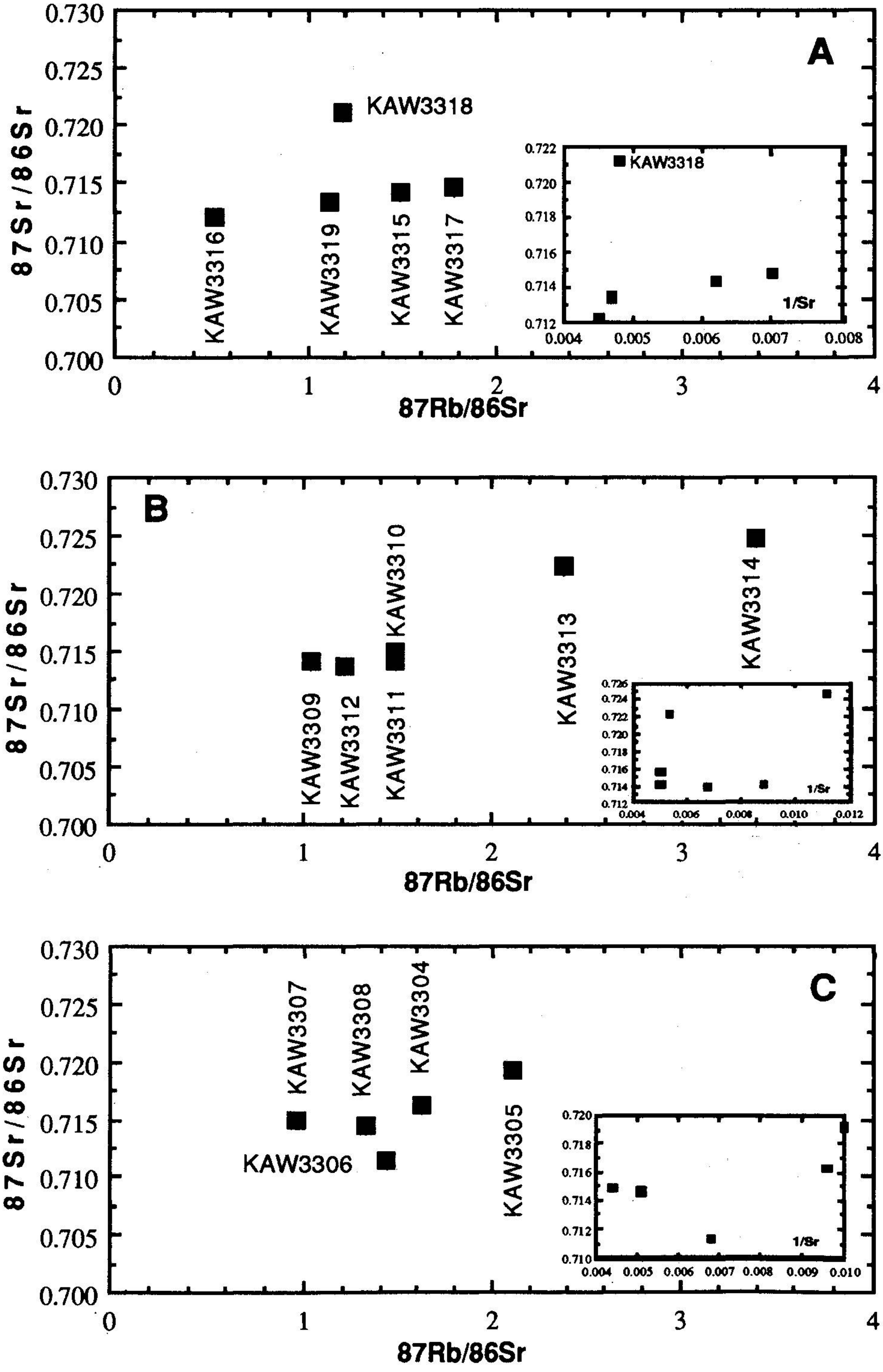

Fig. 3 $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ evolution diagrams for three dykes. A: Fuorcla Radönt, B: Rothorn, C: Sertigpass.

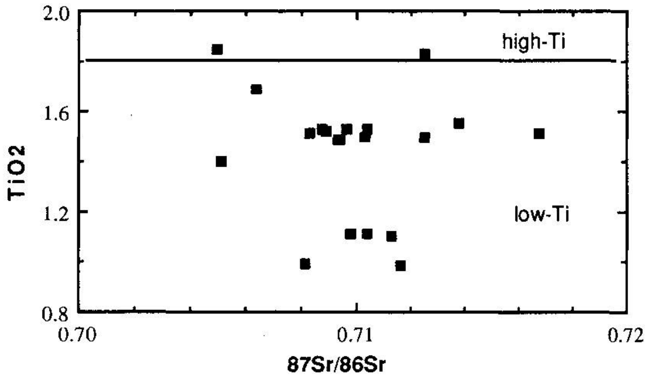

Fig. 4 TiO_2 versus $^{87}Sr/^{86}Sr$ initial ratios. Recalculated to 250 Ma.

comparative information about the different diabase varieties. The dykes at the Piz Linard (KAW 3320) and Munt Baseglia (KAW 3323) are representatives of the hornblende-bearing varieties and their low measured $^{87}Sr/^{86}Sr$ ratios (0.707598 and 0.708074 respectively) differ from the rest of the analysed specimens.

GEOCHEMISTRY

There is no significant correlation between the initial $^{87}Sr/^{86}Sr$ ratios and components showing variation in concentration due to fractionation processes (e.g. TiO_2, Fig. 4). Higher $^{87}Sr/^{86}Sr$ ratios are therefore not considered to be the result of fractionation of the magmas.

If the high $^{87}Sr/^{86}Sr$ ratios are due to contamination with a crustal source it is difficult to find evidence for this process, because the elements which are commonly enriched during contamination are also those which are easily affected by post-emplacement alteration. Thus, a recognition of magmatic contamination is veiled by changes which occurred during later events. Geochemical trends from other Silvretta diabase dykes (HELLERMANN, 1990, 1992) indicate that dykes with high Ti/Y ratios are the most primitive dykes of the suite. They belong to a chemically distinct high-Ti series which can be correlated to other high-Ti series in continental flood basalts. The distinct character of the low-Ti and high-Ti magmas leads to a model of magma genesis in which contamination of the mantle source with continental material and various degrees of partial melting explain the different signatures (HELLERMANN, 1992). Although the discrimination of the high-Ti and low-Ti dykes should also be valid for the Sr data, this correlation cannot be followed in the diagram of initial Sr ratios versus Ti/Y ratios (Fig. 5). Although in general, lower Sr initial ratios correlate with higher Ti/Y ratios, it is obvious that the Sr values do not represent primary magmatic signatures and they cannot support the statements made by other trace elements.

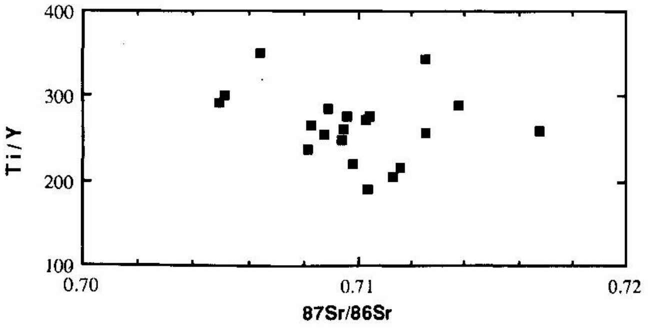

Fig. 5 Ti/Y versus initial $^{87}Sr/^{86}Sr$ ratios. Recalculated to 250 Ma.

Nd ISOTOPIC COMPOSITION

The results of the Sm–Nd analyses are given in table 2. The $^{143}Nd/^{144}Nd$ present day ratios vary between 0.51245 and 0.51282. A graphical presentation of the Sm–Nd results is given in the $^{143}Nd/^{144}Nd$ versus $^{147}Sm/^{144}Nd$ diagram (Fig. 6). Four of five samples form a linear array and a calculated reference line for these four points would yield an age of 2883 Ma with an initial ratio of 0.5099. The $^{143}Nd/^{144}Nd$ versus 1/Nd diagram (see inset of Fig. 6) displays a linear array for all five samples which could signify that the measured $^{143}Nd/^{144}Nd$ ratios are the result of two-component mixing lines.

MIXING CALCULATIONS

To evaluate the effects of partial melting, fractional crystallization and crustal contamination on the trace element and isotope signature of the magmas, several model calculations have been performed (HELLERMANN, 1992). The results will not be discussed in detail, but the most important conclusions that can be drawn for the isotope systems are summarized for a better understanding of the complicated elemental behaviour:

Partial melting of a depleted source and subsequent fractional crystallization of a gabbroic assemblage cannot result in a signature with such enriched $^{87}Sr/^{86}Sr$ and depleted $^{143}Nd/^{144}Nd$ ratios compared with primitive mantle, MORB or chondrite (HELLERMANN, 1992).

For an introduction of a crustal component to the magma two processes were considered: a) the

Tab. 2 Nd isotopic compositions of diabase dykes.

Sample type	Sample KAW No.	Nd ppm	Sm ppm	^{147}Sm/^{144}Nd	^{143}Nd/^{144} Nd ± % error	ε Nd 250 Ma
low-Ti	3312	30.6	6.8	0.1348	0.512465 ± 0.0005	– 1.512
low-Ti	3317	29.8	6.8	0.1373	0.512449 ± 0.0008	– 1.332
high-Ti	3320	27.1	6.2	0.1376	0.512513 ± 0.0009	– 0.55
low-Ti	3321	17.4	4.5	0.1558	0.512820 ± 0.0008	4.749
high-Ti	3322	19.0	4.8	0.1532	0.512800 ± 0.0010	4.440

Analytical uncertainties are given as percent standard errors as measured. CHUR parameters from De Paolo (1988).

magma became contaminated during ascent through the crust and b) the mantle source was contaminated with crustal material prior to magma generation. Simple mixing calculations have been performed, combining a MORB end-member (Saunders and Tracy, 1979) with that of PATS (Post-Archaen Terrestrial Shales, Taylor and McLennan, 1985). These compositions have been found adequate for the calculations (Hellermann, 1992). The calculations take into account that no crystallization occurred during contamination (which is highly unrealistic) or that contamination was accompanied by fractional crystallization (AFC, De Paolo, 1981). The results of the calculations with no crystal fractionation are presented in table 3. Apparently the special signature of trace elements and isotopic ratios of the Silvretta dykes can only be attained with a crustal component which is yet not known.

The results of the AFC calculations on Sr-isotopes (Fig. 8) show that in general the pattern can be simulated provided the initial Sr content of the original magma is sufficiently high (≈ 190 ppm). This amount appears unusually high for N-MORB and proposes either a Sr enrichment prior to the AFC event or, which is more convincing, that the ratios are the result of an enrichment during post-magmatic process. Thus, even if contamination occurred, the signature was later veiled and changed by alteration.

The AFC-modelling on Nd-isotopes (Fig. 9) demonstrates that the signature in the dykes can be fairly well calculated if the degree of contamination is small (1–8%) to a N-MORB magma. The Nd isotopic composition of the country-rock lithologies in the Silvretta complex is very poorly known and from the surrounding paragneisses no data is available. The degree of contamination is a rather low ratio and might indicate that the crustal material was directly introduced into the mantle source.

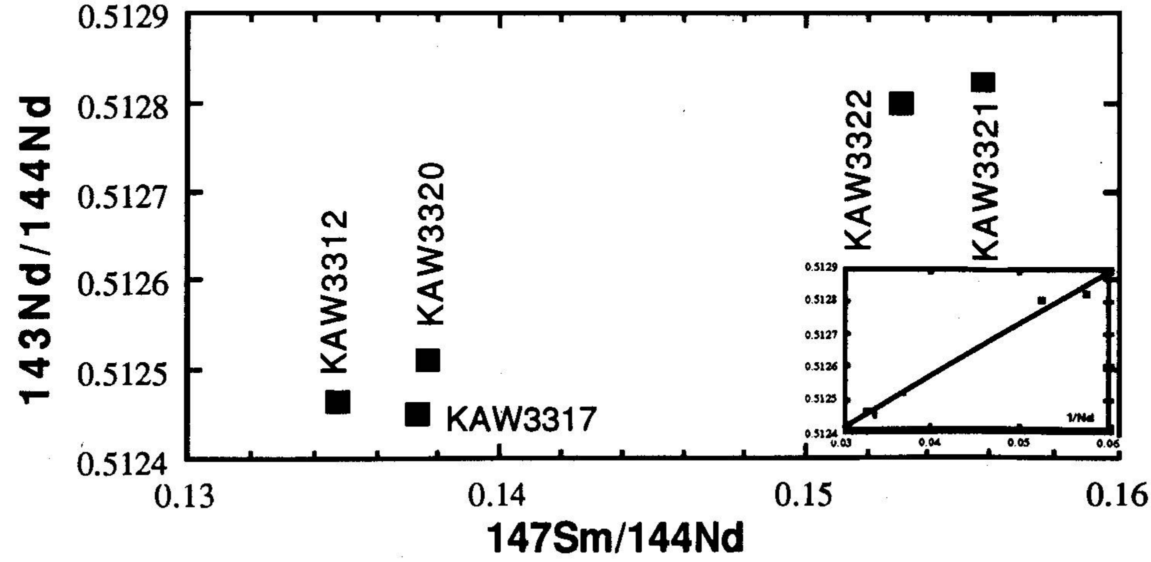

Fig. 6 ^{143}Nd/^{144}Nd versus ^{147}Sm/^{144}Nd for five Silvretta dykes.

Tab. 3 Results of mixing calculations.

ppm	N- MORB	required composition	bi-gneiss	BH383
La	5.71	70.01	38.00	25.00
Ce	16.10	171.77	80.00	62.80
Nd	11.10	75.90	32.00	30.54
Sm	5.79	12.22	5.60	7.72
Zr	170.00	610.00	550.00	302.00
Ti	1.29	0.66	1.00	1.10
Nb	3.00	6.33	15.00	4.00
Y	29.00	72.33	35.00	42.00
Yb	1.89	6.09	2.80	3.15
$^{87}Sr/^{86}Sr$	0.7025	0.7408	0.7200	0.7140
$^{143}Nd/^{144}Nd$	0.5131	0.5108	0.5128	0.5124

Estimates of the compositions required by a crustal contaminant to fit diabase values. Model assumes 30% bulk assimilation into a tholeiitic melt. N-MORB from Saunders and Tarney (1979), biotite-gneiss from Bollin (1991).

Discussion

To compare the diabases with basaltic suites and the evolutionary trend of an original CHUR (CHondrite Uniform Reservoir) composition, their epsilon values were calculated. If the data is plotted in a ε Nd versus initial $^{87}Sr/^{86}Sr$ diagram (Fig. 7), it is obvious that there are significant differences between the dykes. The comparison with Palaeozoic metasediments from Taiwan (Chen et al., 1990) and continental flood basaltic provinces (CFB) shows notable inhomogeneities in Nd and Sr for the dykes. The two dykes with positive ε Nd derived from a depleted mantle source from which magmas had been withdrawn at an earlier time. The three samples plotting below the CHUR line have Sm/Nd ratios which are depleted vis-à-vis to CHUR. The Nd depletion was calculated to originate from processes involving crustal material with lower $^{143}Nd/^{144}Nd$ ratios. The shift of Sr to higher $^{87}Sr/^{86}Sr$ ratios is interpreted as the result of post-magmatic alteration.

To conclude, Nd isotopic ratios support a model of contamination by a crustal component, whereas Sr isotopic ratios cannot provide evidence for primary magmatic features due to post-magmatic exchanges. Mixing calculations show that the degree of contamination for Nd is small (1–8%) which could mean that the effects on other trace elements are almost undetectable.

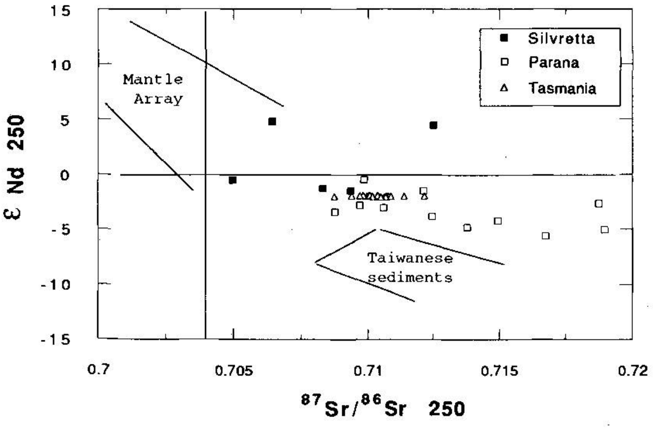

Fig. 7 ε Nd and Sr isotopic variations for Silvetta diabases, age corrected for 250 Ma. Data for the Tasmanian dolerites from Hergt et al. (1989), Paraná low-Ti tholeiites from Bellieni et al. (1984) and Tawainese metasediments from Chen et al. (1990).

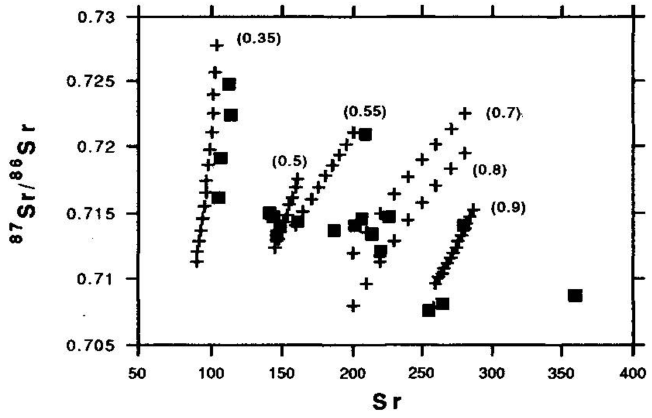

Fig. 8 Results of the AFC model calculations for Sr isotopes. Original magma: 0.703, 190 ppm, contaminant: 0.725, 400 ppm, Kd_{tot}= 0.46, crystallizing assemblage: 60% plg, 30% cpx, 10% ol. Calculated paths show different composition of contaminated magma with increasing ratio assimilation/fractional cystallization (r) at various degrees of crystallization (F, in brackets). Diabase samples as filled squares.

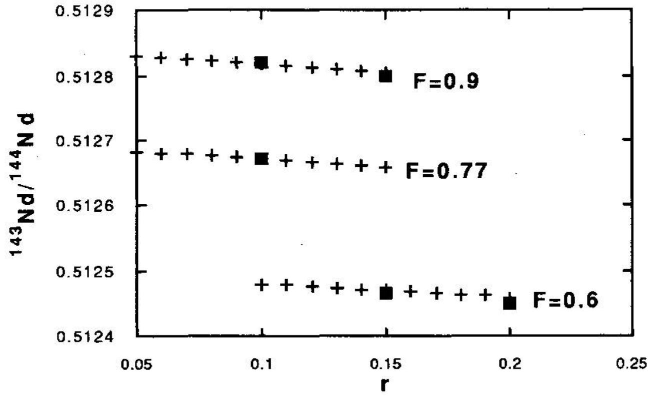

Fig. 9 Results of the AFC model calculations for Nd isotopes with calculated composition of contaminated magma with increasing degree of contamination (r) at various degrees of crystallization (F). Original magma: 0.5129, 11 ppm, contaminant: 0.5118, 23 ppm, Kd_{tot} = 0.219 (Henderson, 1984), crystallizing assemblage: 60% plg, 30% cpx, 10% ol. Diabase dykes as filled squares.

This raises the question which process might be responsible for the depletion of the magmas.

McLennan and Taylor (1981) show that the amount of a crustal component which is introduced directly into the mantle source, can be about an order of magnitude lower to produce the crustal signature, than if it is introduced into the magma. This means that the degree of contamination necessary to produce the crustal signature will be much smaller. The main upper mantle contamination and enrichment process is the subduction of a continental slab (Kyle, 1980; Thompson et al., 1983; Norry and Fitton, 1983) which leads to the enrichment of certain trace elements (e.g. La, Ce, Y, ^{87}Sr, Zr, Pb) and to the depletion of Ti, Nb and ^{143}Nd/^{144}Nd.

The plate-tectonic environment of the Silvretta crystalline during the possible time of intrusion of the dykes (post-Variscan to pre-Alpine) is not documented in detail. The similarity in most lithologies with the adjacent Ötztal nappe (Purtscheller and Rammelmair, 1982) does not necessarily imply the same tectonic position, as the post-detachment histories of the two nappes do not correspond (e.g. effect of Alpine metamorphism). The position of the Silvretta nappe before the Alpine detachment is highly uncertain. If the dykes are the result and early indicators of the break-up of Pangaea during extensive tectonic stresses, a subduction of a continental slab at that time seems quite unlikely. It is therefore most probable that the subduction represents an older event (Variscan?). For the uncertainties involved with the plate-tectonic position of the Silvretta nappe before its detachment to the north, a discussion of the underlying mantle is purely hypothetical. Yet it appears quite reasonable to propose an (at least in parts) inhomogeneous mantle which gave its trace element and isotopic signature to the magmas from which the diabases evolved. It has, however, to be taken into account that the Silvretta basement represents a rather small part of old continental crust and the limited extension raises the question of whether the proposition of an inhomogeneous mantle can be justified.

Acknowledgements

I wish to thank the many people who contributed to the ideas and arguments presented in this paper. I am especially indepted to the ancient staff of the Institute of Isotope Geology at Berne, in particular E. Jäger, M. Flisch and U. Ziegler. At the Institute of Mineralogy and Petrography in Fribourg, G. Galetti, P. Bourqui and O. Marbacher helped with their analytical skills. For stimulating discussions I wish to thank C. Hawkesworth, J. Hergt and M. Maggetti. I am also indepted to M. Thöni and T. Nägler for careful and critical review of an earlier version. It is a pleasure to acknowledge the Schweizerischer Nationalfonds for the financial assistance of this study (NF 20-5538.88).

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Manuscript received May 5, 1992; revised manuscript accepted August 24, 1992.