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Hf-Nd isotopic and trace element constraints on the genesis of alkaline and calc-alkaline lamprophyres

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Major and trace element, Nd and for the first time Hf isotopic compositions of Central European Hercynian and Alpine alkaline (nephelinites) and calc-alkaline (minettes) lamprophyres are reported. The alkaline dikes have significantly higher initial ϵ_{Nd} values (+ 3.9 to + 5.2) than the calc-alkaline dikes (− 1 to − 7). Their initial ϵ_{Hf} values range between + 1.9 and + 6.0. Both groups show the typical high level of incompatible-element enrichment. In addition the calc-alkaline lamprophyres are characterized by an overabundance of Cs relative to Rb, high Ba/La and Ba/Sr ratios as well as depletion in Nb, Ti and Ta. Covariations between initial ϵ_{Hf}-ϵ_{Nd} and trace elements suggest that crust–mantle mixing processes were involved in the formation of the calc-alkaline mafic magmas.

These data give way to a general, refined model of lamprophyre genesis and provide information about enrichment processes in the subcontinental lithospheric mantle.

It is suggested that alkaline and calc-alkaline lamprophyres originate from similar mantle segments. Alkaline lamprophyres can be generated by 10% partial melting of a metasomatically enriched garnet peridotite. Calc-alkaline lamprophyres, however, can be generated in subduction related environments by mixing of 5–15% sedimentary melts, strongly enriched in K, Rb, Zr, Hf, Y and REE, produced by partial melting of subducted oceanic sediments, with a metasomatically enriched mantle source similar to that suggested for the ultramafic alkaline dikes.

1. Introduction

Calc-alkaline lamprophyres (e.g. minettes) and alkali basalts (e.g. nephelinites, basanites, carbonatites, lamproites, kimberlites) are generally characterized by large absolute contents in REE (rare earth elements) and other incompatible trace elements as well as by strong LREE enrichment suggesting in some cases a genetic link among these rock types [1].

Alkali basalts (sensu lato) have been extensively studied during the last decades leading to mantle metasomatism as a favoured mechanism to account for the enrichment in highly incompatible elements [2–4].

Calc-alkaline lamprophyres, however, have been much less studied and today far less coherent literature for their genesis is available [5]. Bachinsky and Scott [1] suggest that partial melting of a

metasomatically enriched mantle produces, depending on its CO_2/H_2O ratio, either minette magmas or carbonatitic–kimberlitic and/or ultrapotassic magmas. Petrological, trace element and isotope investigations, recently performed, led to the suggestion that the calc-alkaline lamprophyric magmas formed in a subduction related environment by partial melting of a mantle enriched by recycling of crustal material [6–8].

Since alkaline and calc-alkaline mafic dikes are extreme products of mantle enrichment processes their trace element and isotopic signature can provide important information about these processes, the extent of trace element fractionation during magma genesis and the general chemical and isotopic characteristics of the subcontinental lithospheric mantle source.

The aim of this study is (1) to gain new information about the chemical and isotopic characteristics of the subcontinental lithospheric mantle source, (2) to provide insight in mantle enrichment processes, and (3) to find new criteria for the

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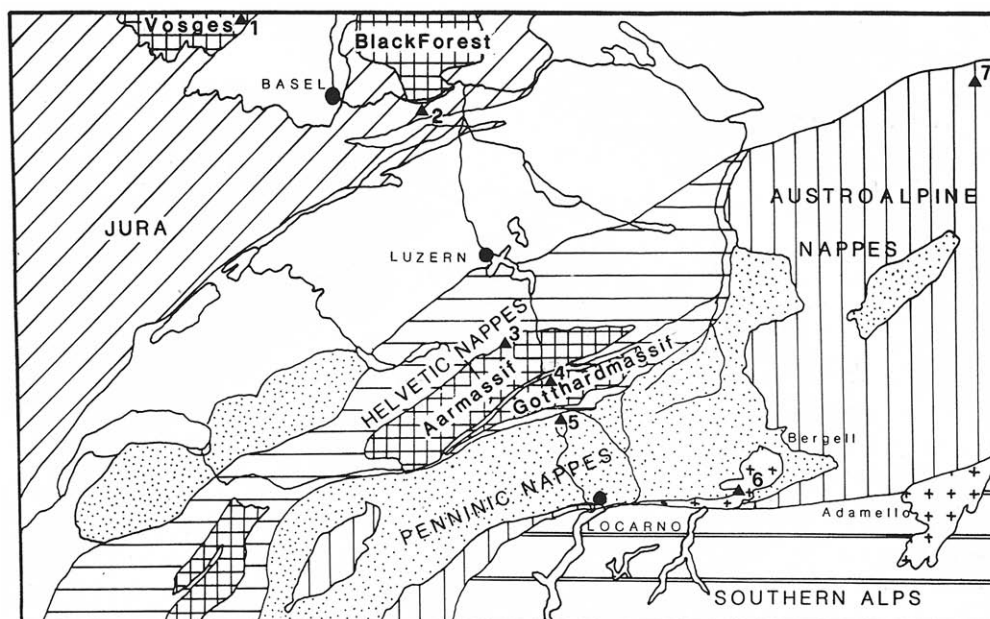
Fig. 1. Sketch map showing the investigated terranes and the sample locations: *1* = V79x; *2* = S13; *3* = Su; *4* = Sh; *5* = Mat1; *6* = P861; *7* = EJX, 145, E(II)10, E(I)14.

TABLE 1

Major and trace element data of lamprophyres

	Mat1	Su2	Su3	V79x	S13	Sh	E(II)	E(1)	EJX	145
SiO_2	55.75	44.30	47.79	48.64	62.25	57.38	40.75	39.82	39.29	39.49
TiO_2	0.87	1.12	1.05	1.65	1.44	1.29	3.58	3.07	3.13	3.07
Al_2O_3	16.45	13.33	14.32	13.89	15.10	16.37	13.90	12.14	12.13	12.60
Fe_2O_3	7.51	7.57	7.44	5.13	3.61	7.38	5.80	5.33	5.28	6.15
FeO	n.d.	n.d.	n.d.	2.67	2.32	n.d.	5.71	5.72	6.06	4.75
MnO	0.10	0.13	0.12	0.16	0.06	0.11	0.17	0.19	0.19	0.20
MgO	5.39	6.26	8.37	6.29	4.07	3.11	8.17	11.88	11.46	10.37
CaO	7.68	9.89	7.97	7.16	1.58	5.10	10.76	12.63	12.43	13.34
Na_2O	3.04	1.96	2.17	2.63	2.44	3.57	3.56	2.17	2.48	2.25
K_2O	1.12	2.77	4.11	4.06	4.67	2.89	1.32	0.98	0.84	0.79
P_2O_5	0.24	1.25	1.22	0.80	0.60	0.51	0.88	0.72	0.83	0.95
H_2O^+	0.67	2.17	2.73	3.04	1.87	0.74	4.03	4.46	4.68	6.72
CO_2	0.04	6.90	1.05	4.54	0.05	0.03	0.16	0.27	0.19	0.26
Total	98.86	97.65	98.34	100.66	100.06	98.48	98.79	99.38	98.95	100.94
Ba	202	958	1828	1572	1171	932	680	630	713	1014
Rb	28	118	95	148	289	64	27	25	22	29
Sr	401	675	855	511	177	341	875	779	907	927
Nb	< 4	21	32	25	24	10	122	97	103	112
La	n.d.	n.d.	n.d.	149	99	n.d.	64	51	52	55
Ce	< 15	97	147	216	100	65	118	98	107	113
Y	8	13	18	37	52	28	21	20	20	21
Zr	126	302	327	394	401	320	322	293	316	319
Cr	138	327	207	383	444	38	136	423	438	432
Ni	24	164	130	212	114	22	119	298	319	265

TABLE 2

Sm-Nd isotope data of calk-alkaline lamprophyres

Sample	Nd (ppm)	Sm (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	ϵ_{Nd}^{290}
Su2	48.01	8.40	0.0158	0.512345 (10)	−2.3
Su2 [a]	25.73	5.19	0.1219	0.512298 (17)	−3.8
Su3	71.48	11.78	0.0996	0.512106 (19)	−6.7
Sh [b]	55.4	10.9	0.1112	0.512331 (12)	−2.7
V79x	70.81	11.65	0.0994	0.512299 (06)	−2.9
S13	29.92	6.26	0.1265	0.512251 (12)	−4.9
Mat1	25.65	5.36	0.1262	0.512416 (10)	−1.7

[a] Phlogopite.
[b] Bossart et al. [21].
Notes for Tables 2–4:
$^{147}Sm/^{144}Nd$ and $^{176}Lu/^{177}Hf$ ratios are determined to a precision of 0.3% at the 2σ mean level.
Uncertainties of the Nd and Hf isotopic compositions are at the 2σ mean level.
ϵ_{Hf}-ϵ_{Nd} values are deviations in parts per 10^4 from chondritic Hf and Nd.

calc-alkaline lamprophyre magma genesis by studying trace elements and for the first time combined Nd-Hf isotopes in closely associated calc-alkaline Carboniferous/Permian dikes from Central Europe (Fig. 1). They are compared to Tertiary mafic and Cretaceous alkaline mafic dikes.

2. Samples and analytical procedures

The mafic dike samples chosen for this investigation originate from regions previously extensively studied [6,7,9,10]. Major and trace elements have been analyzed by X-ray fluorescence, using an automated Philips sequential spectrometer at Lausanne and Zürich. USGS reference rock samples were used for calibration. For corrections the synthetic background method, based on measured major element concentration, was used. Background, interference, mass absorption and standard deviation were computed. Maximal relative errors in XRF-analyses are based mainly on the calibration. The relative errors for trace element concentrations are approximately: ±5% for concentrations of 1000 ppm, ±10% for concentrations of 100 ppm and ±20% for concentrations of 10 ppm. Major and trace element data are compiled in Table 1.

The Sm-Nd/Lu-Hf isotope and concentration analyses were carried out at the Laboratory for Isotope Geochemistry and Mass-spectrometry, ETH Zürich. The total blank for Nd was 0.2–0.3 ng. Elemental Sm and Nd were measured on double filaments using a Finnigan Mat 261 mass spectrometer. The $^{143}Nd/^{144}Nd$ ratios are normalized to a $^{146}Nd/^{144}Nd = 0.7219$. The mean values of 8 analyses of the La Jolla standard [11] and 10 analyses of the nNdβ standard [12] were 0.511859 ± 0.000004 ($2\sigma_m$) and 0.511891 ± 0.000005 ($2\sigma_m$), respectively. Sm-Nd isotope data are compiled in Tables 2 and 3.

The Lu-Hf technique has recently been established at the ETH (Zürich) using the method of Patchett and Tatsumoto [13]. Lu and Hf were measured on a Finnigan MAT 261 mass spectrometer by the triple filament technique. The

TABLE 3

Sm-Nd isotope data of alkaline lamprophyres

Sample	Nd (ppm)	Sm (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	ϵ_{Nd}^{100}
E(II)10	63.58	11.41	0.1085	0.512841 (18)	+5.04
E(I)14	55.36	10.13	0.1106	0.512783 (10)	+3.89
EJX	57.81	10.20	0.1066	0.512812 (15)	+4.51
145	66.04	11.76	0.1077	0.512847 (04)	+5.18

See Table 2 for notes.

TABLE 4

Lu-Hf isotope data of lamprophyres

Sample	age [Ma]	Hf (ppm)	Lu (ppm)	$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	ϵ_{Hf} [a]
V79/x	290	10.01	0.276	0.00391	0.282768 (36)	+ 4.12
Su/2	290	7.33	0.562	0.01088	0.282861 (31)	+ 6.01
S13	290	10.34	2.02	0.02773	0.282839 (35)	+ 1.87
Sh	290	8.50	0.522	0.00871	0.282805 (104)	+ 4.47
Sh, Z	290	n.d.	n.d.	n.d.	0.282700 (30)	+ 2.4
Mat1	290	3.74	n.d.	n.d.	n.d.	
P861	30	5.83	0.263	0.00638	0.282768 (83)	− 1.21
P861, Z	30	n.d.	n.d.	n.d.	0.282737 (44)	− 2.18
EJX	100	7.05	0.194	0.00390	0.282921 (81)	+ 5.67
					0.282943 (100)	+ 6.45

See Table 2 for notes.

[a] Initial ϵ_{Hf} values.

$^{176}Hf/^{177}Hf$ ratios are normalized to a $^{179}Hf/^{177}Hf = 0.7325$. The average value of 7 runs of the JMC-475 standard [14], analyzed over the period of this study, was 0.282177 ± 0.000023 ($2\sigma_m$). In comparison 6 measurements of the same standard, performed just prior to this work yielded an average value of 0.282171 ± 14 [15]. Lu-Hf isotope data are compiled in Table 4.

3. Major and trace element geochemistry

For a rough characterization the mafic dike data points are plotted on a $(K_2O + Na_2O)$ vs. SiO_2 diagram (Fig. 2). With the exception of the alkaline mafic dikes show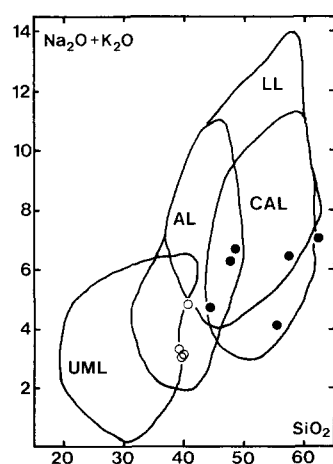ing lower SiO_2 and Na_2O/K_2O contents, all samples plot within the field of calc-alkaline lamprophyres defined by Rock [16].

Incompatible-element concentrations are normalized to estimated primitive mantle abundances [17,18] and compiled in Figs. 3, 4. The calc-alkaline mafic dikes show a much stronger dispersion in their trace element patterns than the alkaline lamprophyres belonging to a common dike suite. Nevertheless, some features of the calc-al-

Fig. 2. $(K_2O + Na_2O)$ vs. SiO_2 diagram for alkaline (open circles) and calc-alkaline (filled circles) lamprophyres. UML = ultramafic lamprophyres; AL = alkaline lamprophyres; LL = lamproites; CAL = calc-alkaline lamprophyres.
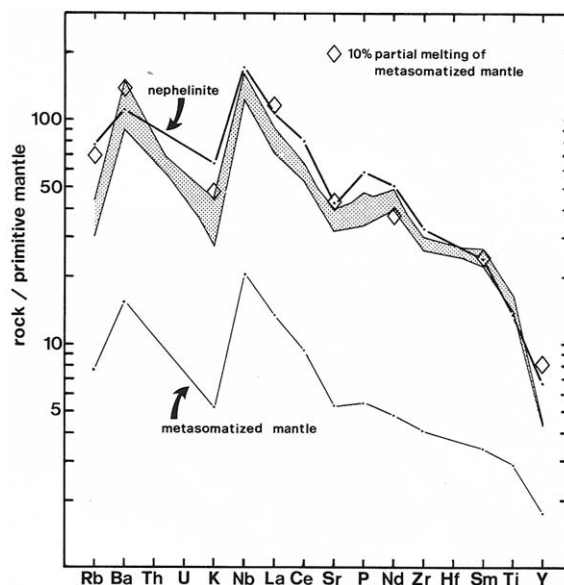

Fig. 3. Primitive mantle-normalized abundances of incompatible elements in four alkaline lamprophyres (hatched pattern). The curve for the metasomatized mantle is from Chauve and Jahn [25]. Normalizing values from [17,18].
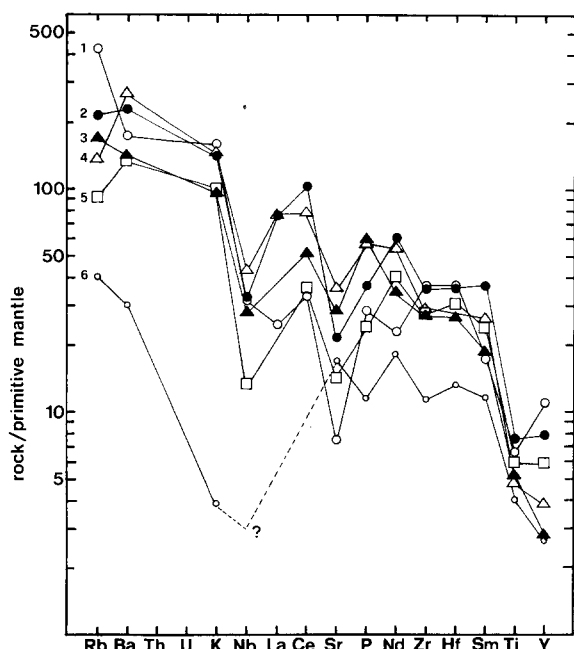
Fig. 4. Primitive mantle-normalized abundances of incompatible elements in calc-alkaline lamprophyres. 1 = S13; 2 = V79X; 3 = Su2; 4 = Su3; 5 = Sh; 6 = Mat1.

kaline dike patterns are characteristic and significantly different from those of the alkaline rocks. The former show pronounced negative anomalies of Nb and Ti commonly observed in subduction related lavas [19]. The patterns of the alkaline dikes, characterized by similar overall abundances, show positive Ba-Nb and negative K-Rb anomalies typical for nephelinitic melts.

REE studies previously performed on calc-alkaline lamprophyres [6,7,10] point to LREE enrichment of 60 to 300 times chondritic. The patterns follow a general alkali basaltic trend.

4. Isotope geochemistry

The isotope data are compiled in histograms of Fig. 5 and compared with data published for other calc-alkaline lamprophyres from Western European Hercynian orogenic belts [6,21].

The initial Sr isotopic compositions range between 0.7052 and 0.7102 and are thus higher than bulk-earth values (B.E.) and partly lower than
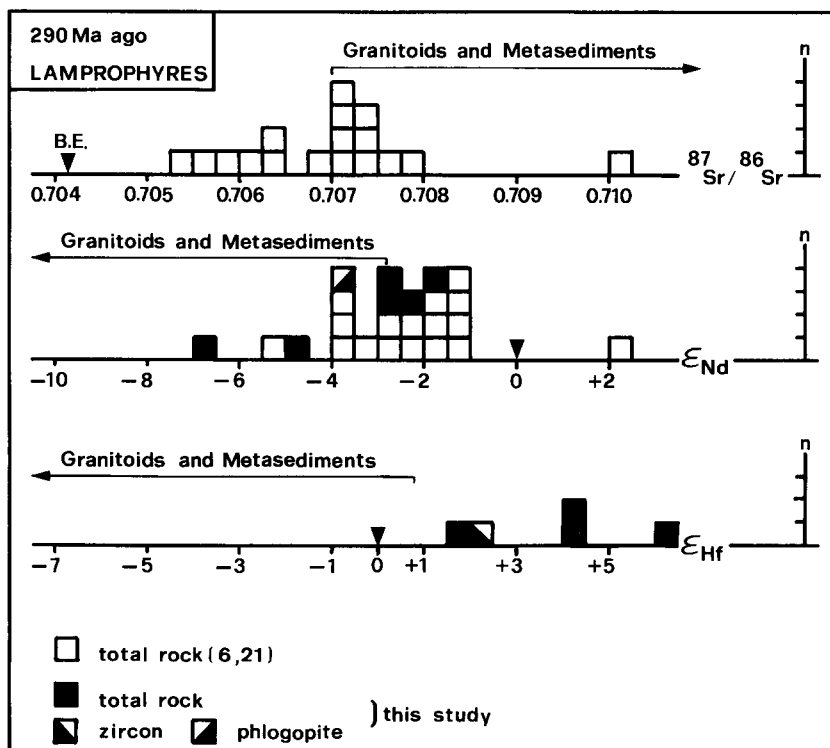

Fig. 5. Frequency diagram for Sr-Nd-Hf initial isotopic compositions in Hercynian calc-alkaline lamprophyres.

those of meta-granitoids and meta-sediments from the Central Alps [22].

The initial ϵ_{Nd} values determined in this study are perfectly in agreement with those of the literature and vary with one exception between -1 and -7. Some of these values are similar to those of Alpine granitoid rocks [22,23]. The Cretaceous alkaline dikes (not shown in the histogram), however, have significantly higher initial ϵ_{Nd} values showing a limited spread between $+3.9$ and $+5.2$ (Table 3).

In contrast with the initial ϵ_{Nd} values, the initial ϵ_{Hf} values of the calc-alkaline lamprophyres range between $+1.5$ and $+6$ and are higher than those found in zircons of Hercynian central-Alpine granitoids which range between -7 and 0 [15]. The age corrected ϵ_{Hf}-ϵ_{Nd} values of the calc-

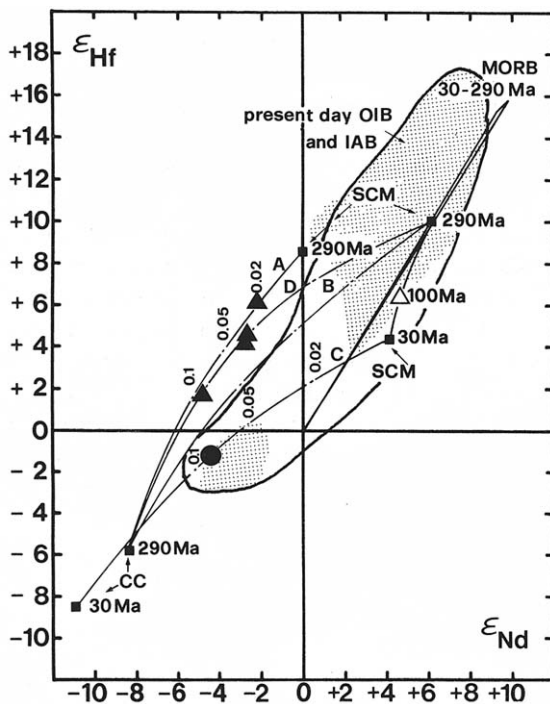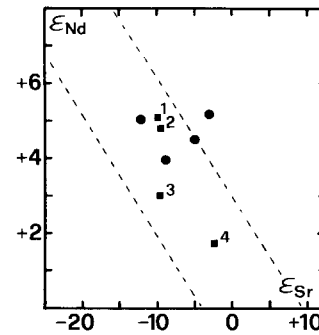Fig. 7. ϵ_{Nd} vs. ϵ_{Sr} diagram. Initial values of alkaline lamprophyres (filled circles) compared with average values of alkaline basalts from other European Provinces. 1 = Massif Central [25]; 2 = Hegau [26]; 3 = Kaiserstuhl [27]; 4 = Eifel [28]. Sr isotope data of alkaline lamprophyres from Trommsdorff et al. [9]. Dashed lines: mantle array.

Fig. 6. ϵ_{Hf} vs. ϵ_{Nd} diagram. Filled triangles and filled circle: 290 Ma old and 30 Ma old calc-alkaline lamprophyres (ϵ_{Nd} value of 30 Ma old dike analyzed by F. v. Blanckenburg, personal communication, 1988). Open triangle: 100 Ma old ultramafic alkaline lamprophyre. Filled squares: crustal (CC) and subcontinental mantle (SCM) mixing endmembers 30 Ma and 290 Ma ago. The following concentration ratios have been used for calculations: $C^C(\mathrm{Hf})/C^{SCM}(\mathrm{Hf}) = 9.4$; $C^C(\mathrm{Nd})/C^{SCM}(\mathrm{Nd}) = 16.7$ for mixing curves A, B, C. $C^C(\mathrm{Nd})/C^{SCM}(\mathrm{Nd}) = 30$ for curve D. OIB = present-day ocean island basalts. IAB = present-day island arc basalts (hatched fields).

alkaline lamprophyres are positively correlated but plot in the quadrant with high ϵ_{Hf} and low ϵ_{Nd} values (Fig. 6) close to or in the field of present-day ocean island basalts (OIB) [24] and island arc basalts (IAB) [14].

The ϵ_{Hf}-ϵ_{Nd} values of the one 100 Ma old alkaline dike sample, however, are close to the mantle array. Also in the ϵ_{Nd} vs. ϵ_{Sr} diagram (Fig. 7) the four alkaline dike samples plot in or close to the mantle array and show isotopic similarities with average alkaline rocks from other European provinces.

5. Discussion

5.1. The alkaline lamprophyres

The trace element and isotopic data, presented in this paper not only stress the differences in genesis and origin for alkaline and calc-alkaline lamprophyres but allow to decipher the trace element and isotopic characteristics of their potential subcontinental mantle source.

The alkaline dikes show trace element distribution patterns and trace element abundances very similar to those of nephelinites (Fig. 3). As shown in Fig. 7 their initial Nd and Sr isotopic compositions are close to average values of other European basanitic rocks from the Massif Central [25] as well as of melilitites from the Hegau [26] and carbonatites and phonolites from the Kaiserstuhl [27]. The alkali basalts from the Eifel [28] show somewhat lower average ϵ_{Nd}-ϵ_{Sr} values. The aver-

age ϵ_{Nd} values of all these alkaline rocks show a narrow range between $+2$ and $+5$. These features may indicate that all these rocks originated from similar subcontinental mantle segments. The isotopically intermediate positions of the alkaline dike samples on or close to the mantle array (Figs. 6 and 7) may suggest that the subcontinental mantle source of the alkaline lamprophyres were simply generated by mixing of a depleted with a chondritic mantle reservoir. Similarly, Wasserburg and DePaolo [29] derived the sources of alkali basalts by mixing of liquids from the lower mantle ($\epsilon_{Nd} = 0$) with those from the upper oceanic mantle ($\epsilon_{Nd} = +12$). However, mass balance calculations show that simple mixing of these two isotopically distinct liquids will not produce REE patterns similar to those of alkali basalts [25]. Such an origin is also inconsistent with the anomalously high Ba/Rb and Nb/K ratios of ~ 30 and 0.01, respectively. Both ratios are much higher than typical for a primitive or MORB mantle source [17,30].

The generally large enrichment in the alkali basalts of incompatible elements requires an unrealistically small degree of partial melting deep in the lithosphere. Mantle metasomatism became a favoured mechanism to account for this enrichment [2–4,31]. As an alternative Alibert et al. [26] explain this enrichment by a steady zone refining model suggesting that the ascending melts become enriched in strongly incompatible elements by leaching of wall rocks. The genesis of the alkali basalts from the Massif Central has been modeled by high degrees of partial melting (10–20%) of a metasomatically enriched mantle [25]. The trace element pattern of this mantle, semiquantitatively derived by mixing of a depleted mantle source (95%) with an enriched fluid (5%), is reproduced in the incompatibility order diagram (Fig. 3). It is perfectly in agreement with the pattern of the ultramafic lamprophyres.

Using a metasomatized mantle peridotite with a residual mineralogy of 65% olivine, 20% Opx, 10% Cpx and 5% garnet, trace element characteristics as previously proposed [25] and partitioning coefficients according to Jahn et al. [32], it can be calculated that at least 10% melting of this mantle is necessary to produce the trace element characteristics of the alkaline lamprophyres (Fig. 3).

It is therefore suggested that the genesis of the ultramafic, alkaline lamprophyres is very close to that of continental alkali basalt and that both rock suites originated from enriched subcontinental mantle segments.

5.2. The calc-alkaline lamprophyres

The Nd isotope data presented in this study support recent observations that the lamprophyres of the Western European Hercynian orogen generally have Pb, Sr and Nd isotopic signatures close to those of Hercynian crustal rocks [6]. The Hf isotope data, however, allow the recognition of an additional depleted mantle component. Thus, the initial ϵ_{Hf}-ϵ_{Nd} values of the Hercynian lamprophyres plot in the quadrant with high ϵ_{Hf} but low ϵ_{Nd} values (Fig. 6). The ϵ_{Hf}-ϵ_{Nd} values appear to be positively correlated suggesting that mixing or assimilation processes were involved during the source formation of the lamprophyric magmas. In order to test this hypothesis, initial ϵ_{Hf} and ϵ_{Nd} values are plotted versus element contents (Figs. 8, 9) as previously proposed [33]. Mixing trends, however, are only to be expected if the endmembers are constant and if no other differentiation processes such as fractional crystallization occurred simultaneously with the assimilation process [34]. The covariations are readily interpretable in terms of mixing between a mantle component with ϵ_{Hf}-ϵ_{Nd} values higher than $+6$ and -1.5, respectively, and a less radiogenic endmember much more enriched in K, Rb, Hf, Zr, Y and with higher Ba/La and Ba/Sr ratios than typical for estimated bulk continental crust [35].

The ϵ_{Hf}-ϵ_{Nd} values, however, are not correlated with Nd and the remaining REE suggesting that secondary processes like fractional crystallization of accessory REE-rich minerals altered the original REE patterns [36].

Although some evidence for lamprophyre–wallrock interactions exists (e.g. crustal zircon xenocrysts in sample Sh [21]; low ϵ_{Nd} value in phlogopite of sample Su-2), it is improbable that partial melting and assimilation of crustal country rock are responsible for the strong enrichment in the less radiogenic mixing endmember. This is supported by a recent experimental study on a mafic minette indicating that lamprophyric magmas were emplaced at high temperatures and chilled rapidly without reequilibration in the upper crust [37]. Similarly Spera [38] suggests, that
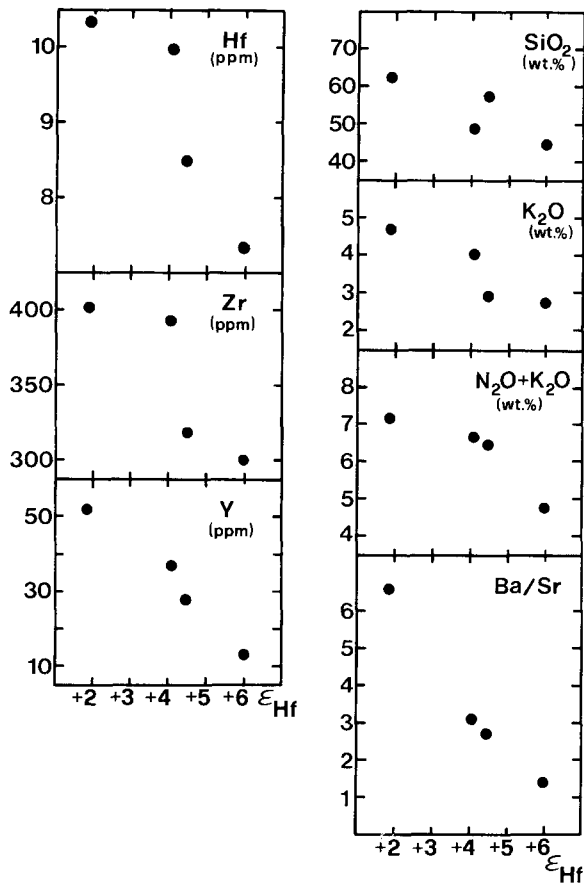
Fig. 8. ϵ_{Hf} vs. trace element concentrations of calc-alkaline lamprophyres.

lamprophyric dikes. These features are typical for subduction-related magmas (e.g. [19]).

(3) The lamprophyres show initial Nd-Hf isotopic compositions which plot in or close to the field of present-day OIB [24] and IAB [14] (Fig. 6).

(4) As shown by Turpin et al. [6] the rocks show an overabundance of Cs relative to Rb compared with MORB. This has been commonly explained by involvement of Cs-enriched sediments in arc magma genesis [40].

Thus, it is possible that similar to the IAB magma sources a direct relationship exists between subduction and lamprophyre magmatism. The lamprophyric source might have been formed by mixing of upper mantle melts with partial
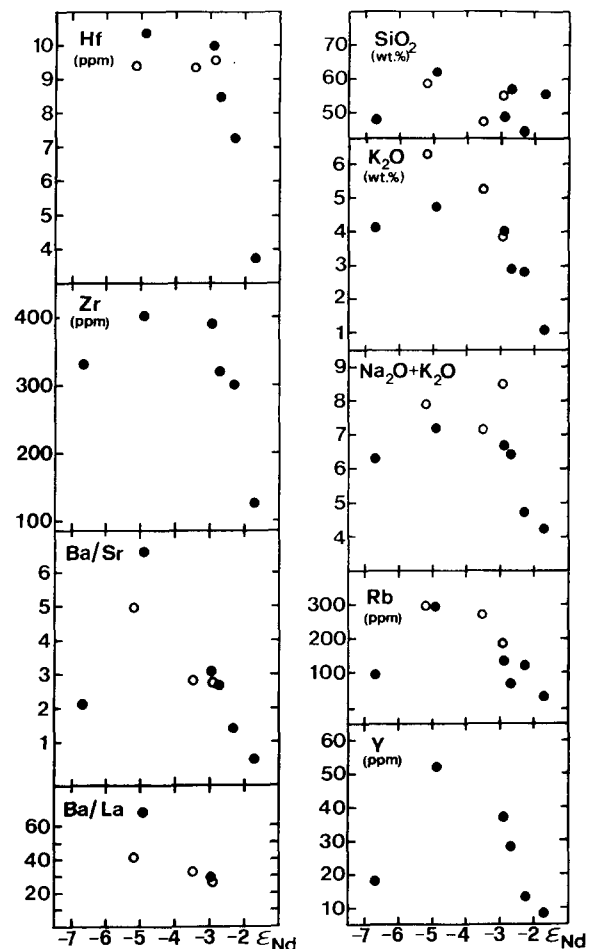
they are transported rapidly through fractures in the lithosphere and thus had not enough time to strongly interact with the wallrock.

We therefore suggest that mixing has already taken place in the mantle during formation of the sources of the lamprophyres. Many geochemical features of the lamprophyres are typical for subduction-related rocks like island arc basalts (IAB):

(1) The Ba/La ratios for the lamprophyres with the most crustal ϵ_{Nd} values are much higher than those of MORB or OIB but typical for IAB [39]. It is generally accepted that pelagic and terrigenous sediments have higher Ba/La ratios than MORB and OIB. Similarly, the high Ba/Sr ratios may be regarded as indicative of a sedimentary origin.

(2) The samples show distinct negative Nb and Ti anomalies and Turpin et al. [6] additionally observed a depletion in Ta for the Hercynian

Fig. 9. ϵ_{Nd} vs. trace element concentrations of calc-alkaline lamprophyres. Open circles: data from literature [6].

melts of altered subducted oceanic crust including its sedimentary cover. According to thermodynamic considerations such melting and mixing processes in a subduction environment finally lead to local formation of geochemically isolated hybrid lamprophyric magmas rich in incompatible elements [41]. Recent experiments confirm that melt extraction of subducted oceanic crust produces hybrid magmas more enriched in incompatible elements than typical average continental crust [42].

In such a model the relatively high initial Sr isotopic compositions and low ϵ_{Nd} values may be regarded as indicative of the existence of subducted sediments within the subcontinental-type mantle. This is also supported by the Pb isotopic data of Turpin et al. [6] which are similar to those measured for the Hercynian continental crust.

We suggest that at least two components are involved in the genesis of the lamprophyric magmas: (1) a hybrid magma strongly enriched in K_2O and highly incompatible elements predominantly derived by partial melting of subducted oceanic sediments, and (2) a metasomatically enriched subcontinental mantle.

Supposing that the sediments have been partially molten just before the generation of the lamprophyric magmas some 290 Ma ago and that these sediments represent ~ 1.7 Ga old recycled crustal material [43] initial ϵ_{Hf}-ϵ_{Nd} values of ~ -6 and ~ -9, respectively, can be calculated for the sedimentary melts. These values allow a very rough estimate of some of the trace and major element contents in these sedimentary melts by extrapolation to crustal ϵ_{Hf}-ϵ_{Nd} values (Figs. 8, 9). The resulting concentrations in the sediment-derived melts are $\sim 10\%$ K_2O, ~ 16 ppm Hf, ~ 700 ppm Zr, ~ 600 ppm Rb and ~ 130 ppm Y.

Considering the lamprophyre sample with the highest ϵ_{Hf}-ϵ_{Nd} values, concentrations of $K_2O < 1\%$, Rb < 28 ppm, Y < 8 ppm, Zr < 120 ppm and Hf < 3 ppm in the mantle-derived melts can be estimated. Such an enriched subcontinental mantle source should yield minimum ϵ_{Hf} and ϵ_{Nd} values of $+6$ and -1.5, respectively. With the exception of the lower ϵ_{Nd} values the deduced features allow a mantle source similar to that suggested for the ultramafic, alkaline lamprophyres. The Hf and Nd concentrations in such a mantle are approximately 8 and 11 times higher

than in chondrites [25]. Additionally, the source is characterized by low $f_{Sm/Nd} \sim -0.28$ and $f_{Lu/Hf} \sim -0.75$ (notation of DePaolo and Wasserburg [44]). Thus, suggesting that this enriched mantle was also the source of the ultramafic, alkaline lamprophyres and that it existed already in the Hercynian, ϵ_{Hf} and ϵ_{Nd} values of $+9.7$ and $+6$, respectively, can be calculated for the 290 Ma old subcontinental mantle. Thirty Ma ago this mantle would have ϵ_{Hf}-ϵ_{Nd} values of $+4.5$ and $+4.2$, respectively.

Mixing of the sedimentary melts with such a metasomatically enriched mantle generates concave-upward curves which fit well the lamprophyre data points if low sedimentary melt/enriched mantle concentration ratios of 9.4 for Hf and 16.7 for Nd are assumed. The Nd/Hf ratios of the sedimentary melts would be about two times greater than the enriched mantle value of ~ 6. Using these model parameters and 16 ppm Hf as a minimum concentration value for the sedimentary melt it must contain more than 150 ppm Nd. The model implies that the lamprophyres can be produced by mixing of 5–15% hybrid sedimentary melts with a metasomatically enriched mantle. This also holds for the one 30 Ma old calc-alkaline lamprophyre from the Bergell intrusion.

According to a recently discussed mixing model for volcanic arc magmas [45] basalt-depleted peridotites situated in the subducted lithospheric plate might be considered as additional members also participating in the lamprophyre genesis. However, their influence on the trace-element features of the mafic dike magmas must have been comparatively small because of their low Hf and Nd contents (Nd ~ 0.8 ppm; Hf ~ 0.18 ppm) and therefore can be excluded for model calculations.

6. Summary and conclusions

(1) The ultramafic, alkaline lamprophyres show high levels of incompatible-element enrichment. Their trace element concentrations normalized to primitive mantle abundances are characterized by similar overall abundances with positive Ba and Nb spikes, typical for nephelinitic melts. They show higher ϵ_{Nd}-ϵ_{Hf} values than the calc-alkaline lamprophyres. Isotopically they are comparable to other continental alkali basalts from Central Europe. They could have been generated by 10%

partial melting of a metasomatically enriched garnet peridotite.

(2) Negative Nb, Ti and Ta anomalies, over-abundance of Cs relative to Rb, high Ba/La and Ba/Sr ratios and covariations between $\epsilon_{Hf}-\epsilon_{Nd}$ values and trace elements suggest that the calc-alkaline lamprophyric magmas formed in a subduction-related environment by mixing of 5–15% sedimentary melts, generated by partial melting of subducted oceanic sediments and strongly enriched in K, Rb, Zr, Hf and REE, with a metasomatically enriched mantle source similar to that suggested for the ultramafic, alkaline lamprophyres.

Acknowledgements

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