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Characteristics of the mantle source region of sodium lamprophyres and petrogenetic tectonic setting in north-eastern Hunan, China

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Abstract A set of unique sodium lamprophyres is developed in the Cenozoic intraconti-nental extensional zone of northeastern Hunan. These lamprophyres are significantly different in major and trace elements and Sr, Nd isotopes from ordinary potassic lamprophyres. The rocks are characterized as being enriched in Na_2O and high in TiO_2 and weakly enriched in Nb, Ta, Nd and LREE with no negative Eu anomaly. The trace elements and Sr, Nd isotopic compositions are typical of the mantle source region of oceanic island basalts (OIB). The average initial $^{87}Sr/^{86}Sr$ ratio is 0.705332, and the average initial $^{143}Nd/^{144}Nd$ ratio is 0.512650, with $\varepsilon_{Nd}(t)$ being +3.5—+3.9, marking a mantle source region of unique sodium lamprophyres. The lamprophyres were formed by metasomatism of the primitive mantle at the bottom of lithosphere by vola-tile-containing fluids/melts from the asthenosphere. The measured Rb-Sr isochron age of sodium lamprophyre is 136.61 Ma, representing a period in which the tectonic setting changed from compressive to extensional. Sodium lamprophyres were formed in a mantle plume tectonic set-ting characterized by mantle upwelling from the asthenosphere within the continent. As-theno-spheric mantle upwelling is the principal geodynamic factor leading to the formation of sodium lamprophyres and constraining the Yanshanian intracontinental extensional activity in northeast-ern Hunan, China.

Keywords: sodium lamprophyre, mantle source region, tectonic setting, genesis, northeastern Hunan.

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In recent years more and more attention has been paid to the close association of gold with lamprophyres and the unique tectonic setting of their occurrence[1]. Among the lamprophyre types dealt with in the previous studies, calc-alkaline lamprophyres and K-rich lamprophyres in the alkaline lamprophyres are the most important types. Little has been reported about sodium lamprophyres in the alkaline lamprophyres. Recently sodium lamprophyres have been found in northeastern Hunan, which constitute another new rock type. Meanwhile, a new path has been opened up for the study of characteristics of mantle source region of sodium lamprophyres and petrogenetic tectonic setting. Studies of potassic lamprophyres have indicated that their mantle source region is characterized by the dominance of enriched metasomatic mantle[2—6]. Owing to metasomatism by subducted residual oceanic crust or contamination by continental crust materials, the mantle source region, which is characterized by enrichments in LILE and LREE, low $^{143}Nd/^{144}Nd$ ratios, high $^{87}Sr/^{86}Sr$ ratios and negative $\varepsilon_{Nd}(t)$ values, was formed. The petrogenetic tectonic settings are mostly the modern or ancient continental marginal active zones or island-arc belts. Whether sodium lamprophyres and potassic lamprophyres have similar mantle source regions, whether there exists a continuous mantle evolutionary zone between the two types of lamprophyres, whether there exists a relatively independent mantle source region of sodium lamprophyres, and what the characteristics of petrogenetic tectonic setting of sodium lamprophyresare are the fundamental problems of common concern. Whether the available genetic models of lamprophyres are applicable to sodium lamprophyres is also a problem worthy to discuss in detail. The aim of this study is to constrain the characteristics of source region in terms of trace elements and Sr, Nd isotopes of sodium lamprophyres and their properties and petrogenetic tectonic setting on the basis of comparative studies between potassic lamprophyres and sodium lamprophyres so as to present evidence suggesting that the sodium lamprophyres are a new type, which are different from potassic lamprophyres, viewed either from the composition of their source region and petrogenetic tectonic setting or from their genesis. On the basis of the analysis of the available genetic models of lamprophyres, the genetic model of sodium lamprophyres has been put forward, i.e. the rocks were formed by the way of metasomatism of the primitive mantle by fluids/melts from the asthenosphere.

1 Sodium lamprophyres and geological settings in northeastern Hunan

Sodium lamprophyres in northeastern Hunan are exposed at the northeastern terminal of the Cenozoic lithospheric extensional zone in the east of Hunan and Guangxi[7]. The lamprophyres, as nearly SN-extending dyke swarms, intruded into the Yanshanian biotite monzonitic granites and Middle Proterozoic Lengjiaxi Group strata at Wangxiang and Jiaxiling in the northwestern part of Liuyang, with the regionally NE-extending left-handed shear deep fault passing by the granite massifs on the western flank. Lamprophyres intruded into the granites along the second-ordered SN-extending fractures of the deep fault (fig. 1). The rocks occur as dykes, which are measured at several ten meters to several hundred meters in length and 0.4—6 m in width. Most of the dykes are erectility with respect to their geological attitude. The biotite K- Ar age of the biotite monzonitic granite is 161 Ma[8], therefore indicating that the lower intrusive age limit of the lamprophyre dykes should be Early Cretaceous. During geological field investigations no cross-penetrating and cross-cutting relations were recognized among the dykes. The dykes all are of parallel and oblique occurrence along the SN-extending second- ordered fractures, reflecting that the intrusion of lamprophyres should be designated to a phase of magmatic intrusion. Regionally geological investigations have demonstrated that no Himalayan period magmatic activity has been found in the northeastern part of Hunan or even in the whole area of southeastern Hunan[8]. So the intrusion of lamprophyres can be restricted to the Yanshanian period. In order to confirm the rock-forming age of lamprophyres, fresh rock samples were collected from different lamprophyre dykes at Jiaoxiling, Hunan for the determination of

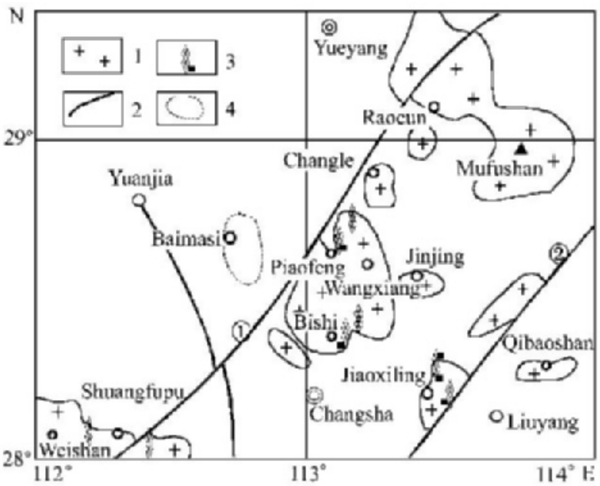

Fig. 1. Sketch map showing the distribution of sodium lamprophyres in northeastern Hunan. 1, Early Yanshanian granite; 2, lithospheric deep fault; 3, sodium lamprophyre and sample location; 4, concealed granite massif. ①, Xinning-Huitang deep fault; ②, Changshou-Shuangpai deep fault.

Table 1 Sr, Nd isotopic compositions of sodium lamprophyres in northeastern Hunan

Sample No.	w (Rb)/10^{-6}	w (Sr)/10^{-6}	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr \pm \sigma$	Rb-Sr isochron age	$(^{87}Sr/^{86}Sr)_0$	$\varepsilon_{Sr}(t)$
Jg2	45.280	474.000	0.275700	0.705898±20		0.705366	+14.54
Jg3	63.370	462.900	0.395300	0.706070±20	(136.6±11)Ma	0.705308	+13.71
Jg5	50.100	896.300	0.161400	0.705647±20		0.705336	+14.10
Jg6	13.540	807.700	0.048380	0.705411±16		0.705318	+13.84
Sample No.	w(Sm)/10^{-6}	w(Nd)/10^{-6}	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd \pm \sigma$	Rb-Sr isochron age	$(^{143}Nd/^{144}Nd)_0$	$\varepsilon_{Nd}(t)$
Jg3	11.6000	62.190	0.11290	0.512756±10		0.512654	+3.8
Jg6	12.6100	62.600	0.12190	0.512749±9	(136.6±11)Ma	0.512639	+3.5
Jg2	11.9000	60.580	0.11680	0.512768±11		0.512664	+3.9
Jg5	12.4200	63.100	0.12060	0.512752±12		0.512644	+3.6

Determined at Isotopic Laboratory, Institute of Geology and Geophysics, Chinese Academy of Sciences.

their Rb-Sr isochron ages. The measurements of Rb, Sr and Sm, Nd isotopes were conducted on the VG354 solid isotope mass spectrometer. The international standard samples NBS607 and BCR-1 were also analyzed simultaneously. The results are: $^{87}Sr/^{86}Sr=1.20014\pm0.00003$, and $^{143}Nd/^{144}Nd=0.512633\pm0.000009$. Strontium isotope mass fractionation was corrected by using $^{86}Sr/^{88}Sr=0.1194$, the blank background for the entire Rb-Sr analytical procedure was about $(2—5)\times10^{-10}$g. The age calculation was conducted using the York regression analytical method. The Nd isotope fractionation was corrected by using $^{146}Nd/^{144}Nd=0.7219$, the blank background for the entire Sm-Nd analytical procedure was approximately 5×10^{-11}g, the calculation parameters $\lambda_{Rb}=1.41\times10^{-11}$/a, $\lambda_{Sm}=6.54\times10^{-12}$/a, $(^{87}Sr/^{86}Sr)_{UR}=0.7045$, $(^{87}Rb/^{86}Sr)_{UR}=0.0816$, $(^{143}Nd/^{144}Nd)_{UR}=0.512638$, and $(^{147}Sm/^{144}Nd)_{UR}=0.1967$. The whole-rock Rb-Sr isochron age obtained is 136.61Ma (table 1, fig. 2). The result is in good consistency with the intrusive relationship of the lamprophyre dykes. Therefore this age can represent the rock-forming age of the lamprophyres.

The lamprophyres are dark green in color and the major types are spessartite, barkevite lamprophyre and garganite. The mineral composition is dominated by hornblende or barkevikite (30%—37%), pyroxene (5%), biotite (5%—10%) and other dark-colored minerals; light-colored minerals are dominated by plagioclase (40%—50%); accessory minerals are mainly apatite, illmenite, magnetite, spinel and zircon. The rocks possess typical lamprophyric texture and mosaic texture. The phenocrysts are dominated by hornblende, pyroxene, biotite and plagioclase, the same as in the matrix. Spheroidal weathering of sodium lamprophyre dykes is seen on the earth surface and fresh rocks, which have been weakly altered (mainly chloritization and sericitization), and can be seen inside the spher-oidal weathering lamprophyre dykes and in some artificial exposure

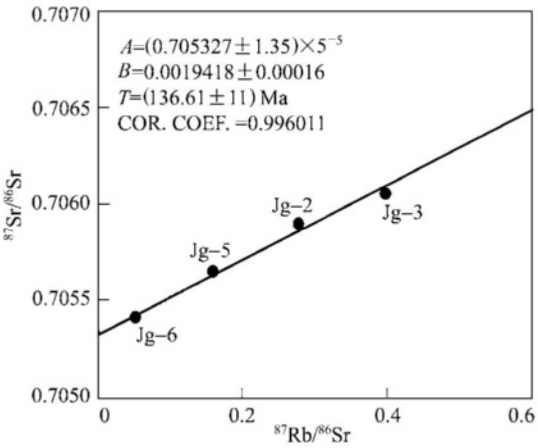

Fig. 2. Rb-Sr isochron age of the sodium lamprophyres in north-east-ern Hunan.

The contents of SiO_2 in the lamprophyres are within the range of 45.78%—51.63%, with higher contents of FeO, MgO and Na_2O, indicating these lamprophyres belong to basic rocks. K_2O+Na_2O accounts for 4.05%—6.56%, with σ values varying between 12.52 and 2.05, mostly greater than 7, indicating that the rocks belong to alkaline lamprophyres. Na_2O accounts for 2.79%—4.08% and K_2O/Na_2O ratios are all less than unity (0.54 on average), indicating that the rocks belong to Na-rich rock series, which are still richer in Na_2O than the sodium barkevite lamprophyre proposed by Wimmenauer (1973)(table 2)[9].

Table 2 Chemical analyses of the sodium lamprophyres in northeastern Hunan (%)

Element	Spessartite (Jg2)	Spessartite (Jg3)	Barkevite lampro-phyre /(Jg4)	Barkevite lampro-phyre /(Jg5)	Barkevite lampro-phyre /(Jg6)	Spessartite （Jg7）	Garganite （Jg8）	Barkevite lampro-phyre /(Jg9)	Barkevite lampro-phyre /(Jg10)	Barkevite lampro-phyre /(ZY)
SiO_2	51.63	50.99	47.31	46.49	48.42	48.19	47.82	47.17	45.78	44.67
TiO_2	2.12	1.75	2.75	2.50	2.60	2.28	2.64	3.17	2.75	2.46
Al_2O_3	15.82	16.06	15.35	17.01	14.64	16.14	13.25	13.88	13.98	14.35
Fe_2O_3	4.30	4.00	5.92	5.60	5.75	3.75	4.72	5.70	5.72	4.50
FeO	5.10	5.70	5.98	5.90	5.95	5.56	5.92	5.90	5.78	7.19
MnO	0.14	0.13	0.16	0.21	0.20	0.13	0.15	0.18	0.14	—
MgO	5.50	6.60	6.70	7.30	7.00	6.53	6.58	6.46	5.51	7.02
CaO	7.00	7.70	6.70	6.60	6.90	4.69	6.83	7.51	7.66	9.45
Na_2O	3.00	2.79	3.71	3.33	3.89	3.66	3.78	4.02	4.08	2.99
K_2O	1.33	1.26	1.88	1.91	1.42	2.90	2.06	2.16	1.82	1.91
P_2O_5	0.63	0.50	1.00	1.17	1.10	0.67	0.98	0.61	0.75	—
LOS	2.91	1.83	1.96	1.60	1.40	4.24	2.12	2.87	5.22	4.7
Na_2O+K_2O	4.33	4.05	5.59	5.24	5.31	6.56	5.84	6.18	5.90	4.90
K_2O/Na_2O	0.44	0.45	0.51	0.57	0.37	0.79	0.54	0.54	0.45	0.64
σ	2.17	2.05	9.44	7.87	5.20	8.29	7.08	9.16	12.52	14.38
Mg#	52.1	56.0	51.4	54.4	52.9	56.3	53.9	66.11	62.67	52.7

Jg2—Jg10 samples are measured by the Analysis Laboratory, Institute of Geochemistry, Chinese Academy of Sciences, oxides in weight per-cent. ZY sample is cited from Wimmenauer (1973)[9]. $\sigma = (Na_2O + K_2O)^2/SiO^2-43$; $Mg^{\#}=100\ Mg/(Mg+Fe^{2+})$.

According to the scheme of classification of lamprophyres proposed by Rock (1987)[10], the rocks fall within the field of alkaline lamprophyres. As viewed in the classification scheme of alkaline lamprophyres proposed by Lu Fengxiang[11], the data points of the rocks all fall within the field of sodium lamprophyres, just in contact with the Laowangzai potassic lamprophyres of Yunnan Province, which fall within another distinctively different field (fig. 3), indicating that the lamprophyres in northeastern Hunan belong to sodium lamprophyres. These sodium lamprophyres have an-other outstanding feature, i.e. high in TiO_2 contents, within the range of 1.75—3.17 (table 2). As seen in the TiO_2-$Mg^{\#}$ plot, the rocks, just like the Emeishan high-Ti basalts[12], belong to high-Ti basic rocks.

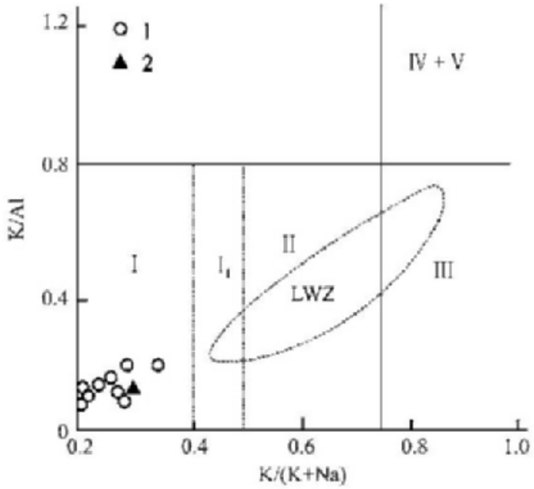

Fig. 3. Classification scheme of lamprophyres[11]. Ⅰ, Sodium lam-prophyre; I_1, weak potassic lamprophyre; II, potassic lamrophyre; III, ultrapotassic lamprophyre; IV, overpotassic lamprophyre; V, lam-proite, 1, Sodium lamprophyre in northeastern Hunan; 2, barkevikite lampro-phyre[9]; LWZ, Laowangzhai potassic lamprophyres[2].

2 Characteristics of the mantle source region of sodium lamprophyres

2.1 Trace elements

The primitive mantle-normalized trace element patterns of sodium lamprophyres showed that sodium lamprophyres in northeastern Hunan are not so obviously enriched in LILE. Some samples even show weak depletion in K and Sr. Of the HFSE, Ta, Nb, Nd and P are slightly enriched, with no sign of depletion or enrichment in Ti, Zr and Hf. But the heavy REE Yb, Y and Lu are of depletion. The sodium lamprophyres possess features of typical OIB mantle source region (fig. 4). The rocks are significantly different from the high-K/Ti and low-Ti potassic rocks associated with the subduction belt[13]. There are two possibilities to explain the depletion of K and Sr: low-degree partial melting of the K- and Sr-rich source region and crystallization-differentiation of K-rich hornblende and phlogopite in the source region[14]. The absence of obviously negative Eu anomaly and no regular variation of δEu with Mg# value (tables 2 and 3), and the existence of positive correlations between La/Sm and La indicated that magmatism is dominated by partial melting. So the partial depletion of K and Sr may be a manifestation of the nature of the mantle source region.

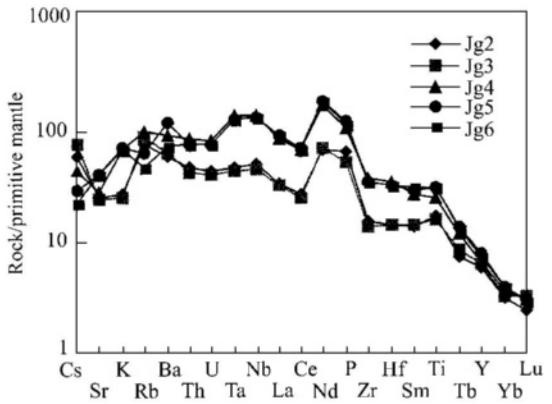

Fig. 4. Primitive mantle spider diagram of trace elements in sodium lamprophyres of northeastern Hunan. Primitive mantle values from ref.[17]. Sample numbers are the same as those in table 2.

Nb/Ta ratios are 17.88—18.25, averaging 18.01; Zr/Hf ratios are 35.46—39.11, averaging 38.19, respectively close to and higher than those of the primitive mantle (Nb/Ta= 17.5±2.0; Zr/Hf=36.27), but far greater than those of the continental crust (Nb/Ta=12—13; Zr/Hf=11), indicating that magmas from the source region were only slightly contaminated by crustal materials during their ascending. Nb/Ta ratios in the volcanic rocks are related to partial melting of the source region because the partition coefficients of mantle minerals (clino-augite, orthopyroxene, olivine, etc.) generally show a relationship of $D_{Nb}/D_{Ta} < 1$[15]. So Nb/Ta ratios in magmatic melts produced from melting of the primitive mantle are slightly greater than those of the primitive mantle[16]. It is, therefore, reflected that sodium lamprophyres in northeastern Hunan were derived from partial melting of the primitive mantle. The Nd-normalized La, Ce, P, Zr, Ti and Y curves of the primitive mantle are of right-inclined, non-divergent distribution, indicating that the source region is homogeneous in composition and has not been obviously contaminated by crustal materials.

As the strongly incompatible elements such as Rb, Ba, Th, Nb, Ta, La have similar whole-rock partition coefficients, partial melting and crystallization-differentiation cannot cause strong fractionation among these elements. So the ratios of these elements can be used to constrain the characteristics of the mantle source region[18]. In the different diagrams of element ratios, sodium lamprophyres in northeastern Hunan all fall within the field of OIB-type mantle source regions (fig. 5). Studies of modern oceanic island basalts have demonstrated that the production of the OIB-type mantle source regions can be explained by the following mixing models: (i) the mixing of two

Table 3 Trace element contents of sodium lamprophyres in northeastern Hunan/μg/g

Element	Jg2	Jg3	Jg4	Jg5	Jg6	Element	Jg2	Jg3	Jg4	Jg5	Jg6
Sc	14.48	17.54	15.24	16.71	16.23	La	23.677	22.679	58.567	64.154	64.041
V	154.15	158.78	232.16	249.87	257.20	Ce	48.169	44.897	120.39	123.96	119.23
Cr	112.99	166.62	101.92	101.81	99.97	Pr	5.613	5.678	14.088	15.417	15.212
Co	42.01	45.92	43.27	47.70	50.31	Nd	24.652	24.832	60.229	65.681	65.428
Ni	106.92	125.68	99.38	97.35	98.95	Sm	6.260	6.413	12.322	13.233	13.793
Cu	42.40	45.13	40.81	37.77	35.39	Eu	2.046	2.149	3.913	4.179	4.215
Zn	123.26	127.83	161.86	154.76	177.12	Gd	5.751	6.585	10.583	11.995	11.933
Cs	1.90	2.47	1.39	0.93	0.74	Tb	0.852	0.953	1.331	1.525	1.472
Sr	539.46	521.93	1015.8	865.46	865.10	Dy	4.644	5.21	6.939	7.505	7.427
Rb	49.05	55.64	63.28	40.19	29.65	Ho	0.792	0.99	1.134	1.253	1.219
Ba	408.33	448.55	644.12	769.32	509.61	Er	2.119	2.346	2.741	2.996	2.894
Th	4.05	3.55	7.19	6.54	6.51	Tm	0.285	0.31	0.321	0.34	0.341
U	0.92	0.85	1.73	1.61	1.63	Yb	1.572	1.685	1.876	1.966	2.002
Ta	1.97	1.82	5.54	5.22	5.24	Lu	0.184	0.249	0.228	0.227	0.226
Nb	35.90	32.46	98.89	93.84	94.96	δEu	1.05	1.02	1.06	1.02	1.01
Zr	173.82	160.37	427.01	390.67	399.99	ΣREE	126.62	124.98	294.66	314.43	309.43
Hf	4.56	4.52	10.75	10.12	10.23	(La/Yb)n	12.87	9.11	25.67	28.25	28.33
Y	27.14	29.64	30.75	36.18	34.08						

Trace elements determined by ICP-Mass Spectrometry at the Institute of Geochemistry, Chinese Academy of Sciences.

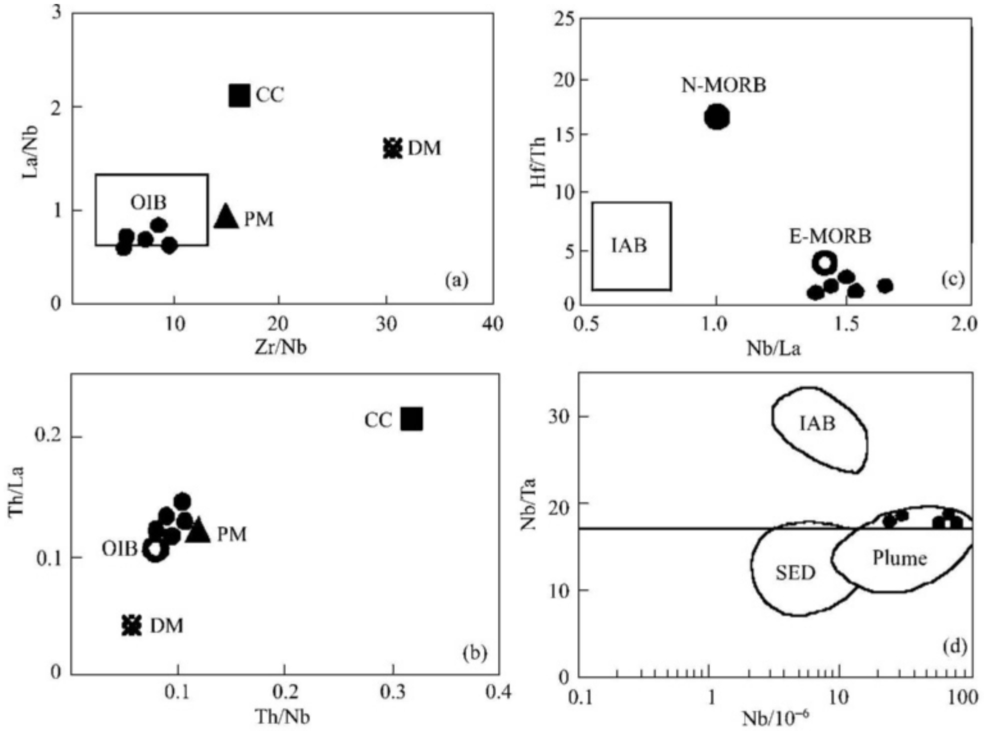

Fig. 5. Correlation diagrams of element ratios in sodium lamprophyres of northeastern Hunan. PM, Primitive mantle; DM, de-pleted mantle; CC, continental crust; OIB, oceanic island basalt; IAB, island-arc basalt; N-MORB, normal mid-ocean ridge basalt; E-MORB, transitional mid-ocean ridge basalt; SED, sediment, Plume, mantle plume. The data source from refs. [18, 19] .

different components in the mantle plume source region, and (ii) the mixing of relatively depleted mantle materials with those from the asthenospheric mantle differing significantly in isotopic composition during their ascending or the mixing of the asthenospheric mantle with the lithospheric primitive mantle[19,20]. The tectonic conditions of mantle plumes and asthenospheric mantle upwelling are the factors controlling the formation of the OIB-type mantle source regions. As the possibility of large-scale contamination by crustal materials has been excluded and all the projecting points of rocks fall near the primitive mantle (fig. 5), the OIB-type mantle source region of sodium lamprophyres in northeastern Hunan seems to have resulted from metasomatism of the relatively homogeneous primitive mantle by ascending asthenospheric mantle, and sodium lamprophyres are the “exposures” of magmas from this unique mantle source region.

2.2 Sr and Nd isotopes

As calculated in terms of Rb-Sr isochron ages, sodium lamprophyres in northeastern Hunan have an average initial $^{87}Sr/^{86}Sr$ ratio of 0.705332 and an average initial $^{143}Nd/^{144}Nd$ ratio of 0.512650, with $\varepsilon_{Nd}(t)$ being +3.5— +3.9 (table 1). The rocks show a weak Nd isotopic depletion and possess the characteristics of the mantle source region for homogeneous oceanic island basalts (OIB) (fig. 6), just in consistency with the genetic implications reflected by the trace element data. The Sr, Nd isotopic composition of sodium lamprophyres is conformable with the Kerguelen volcanic rocks (fig. 6). In their further investigations Storey et al.(1989) proposed that lamprophyres in the Kerguelen volcanic rock series could be used as a marker of the top of mantle plume[27]. At present time, it is consistently accepted that the intracontinental OIB-type volcanic rocks originated from the earthquake discontinuity at the depth of 670 km and the transitional zone between the core and the mantle[28]. As the Sr, Nd isotopic composition and trace element data of sodium lamprophyres are not biased towards those of the OIB-type volcanic rocks, it is evidenced that the asthenospheric mantle was involved in the formation of the mantle source region. And asthenospheric mantle upwelling resulted in a mantle-plume petrogenetic tectonic setting.

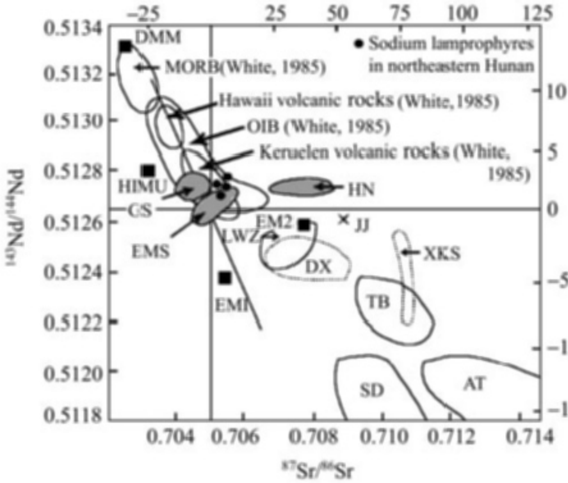

Fig. 6. ($^{87}Sr/^{86}Sr$)-($^{143}Nd/^{144}Nd$) diagram of the sodium lamprophyres in northeastern Hunan. LWZ, Laowangzhai potassic lamprophyre[2]; DX, potassic lamprophyre in western Yunnan[3]; TB, North Tibet potassic lamprophyre[4]; SD, lamproites in Shandong[6, 21]; XKS, Xikuangshan calc-alkaline lamprophyre[22]; AT, Australian lamproite[5]; HN, Gezhen sodium lamprophyre on Hainan Island[23]; JJ, Jiaojia sodium lam-pro-phyre in Jiaodong[24]; GS, kamafugite in Gansu[25]; EMS, Emeishan basalt[12]; DMM, depleted mantle; HIMU, U/Pb-high mantle; EM1, enriched mantle 1; EM2, enriched mantle 2. The mantle end member data are cited from ref. [19] .

Comparing lamprophyres both at home and abroad, for instance, the Laowanzai potassic lamprophyres of Yunnan[2], potassic lamprophyres in western Yunnan[3], those in northern Tibet[4], lamproites in Shandong[6,21], calc-alkaline lamprophyres at Xikuangshan[22] and lamproites in Australia[5], shows that the characteristics of the enriched mantle, and sodium lamprophyres in northeastern Hunan display significant differences in this aspect (fig. 6), implicating that sodium, potassic and calc-alkaline lamprophyres have their respective mantle source regions. Sodium lamprophyres in northeastern Hunan are similar to the Gezhen sodium lamprophyres on Hainan Island and those in the Jiaojia gold deposit, Jiaodong Peninsula with respect to their major elements, but the latter's Sr isotopic values are obviously increased[23, 24], demonstrating the characteristics of metasomatic mantle source region due to the mixing of the primitive mantle with continental crust materials (fig. 6). As viewed from their Sr, Nd isotopic composition, sodium lamprophyres in northeastern Hunan share much in common with domestic volcanic rocks formed under mantle plume conditions, for instance the Emeishan basalt[12], Cenozoic kamafugite[25] in western Qinling, Gansu Province and Proterozoic basalts in the Qinling area[29], indicating that these volcanic rocks have similar mantle source regions (fig. 6).

Isotopic studies of the mantle source regions of the OIB-type volcanic rocks have shown that different OIB-type volcanic rocks are approximately of parallel mantle arrays, indicating that the mantle source region of the OIB-type volcanic rocks is mixed with varying degrees, and of different mantle end-members[20]. Sodium lamprophyres in northeastern Hunan are located near the right side of the mantle array line, beyond any mantle end-members, just between HIMU, EM1 and EM2. This may reflect the mixing of a variety of different mantle end-members. Although $\varepsilon_{Nd}(t)$ is greater than zero for sodium lamprophyres in northeastern Hunan, their $f_{Sm/Nd}$ values are less than zero (−0.38 — −0.43). This phenomenon is considered to be related to crustal contamination and mantle metasomatism[30]. According to the trace elements data, the possibility of crustal contamination has been ruled out, so a reasonable explanation of this phenomenon is that the mantle source region was subjected to mantle metasomatism. In fact, mantle plume materials from the asthenosphere would inevitably metasomatize the lithospheric primitive mantle when they ascended to the lithospheric mantle. Nd isotope weak depletion and Sr isotope weak enrichment in the sodium lamprophyres of northeastern Hunan also indicate that the lithospheric primitive mantle has been metasomatized by volatile-containing fluids/melts from the asthenosphere. Such mantle metasomatism occurred mainly at the thermal boundary layer at the bottom of the lithosphere, leading to the formation of abnormal mantle source region characterized by weak enrichment in LILE and LREE and weak depletion in K and Sr. Such abnormal mantle source region is characterized by slightly high Nb/Ta and Zr/Hf ratios compared with the primitive mantle source region. What should be pointed out is that metasomatism between the volatile-containing fluids/melts from the asthenosphere and the lithospheric primitive mantle is quite different from that between the primitive mantle and the recycling relic oceanic crust and continental crust materials, the former did not cause large-range variations in Nd, Sr isotopic composition, and any strong enrichment in LILE and LREE, and any depletion in Ta and Nd. This presents a better explanation of weak depletion in Nd isotope, weak enrichment in Sr isotope, LILE and LREE and enrichment in Na_2O and TiO_2. From the above it is deduced that the magmas producing sodium lamprophyres originated from the thermal boundary layer at the bottom of the lithosphere.

3 Discussion

Sodium lamprophyres in northeastern Hunan, dated at 136 Ma, occurred within the South China continent. Although the time is close to that of subduction of the Cenozoic Izanaqi oceanic plate[31], no strong enrichment in LILE and depletion in Nd, Ta and Ti can be seen in the trace element-normalized diagrams (fig. 3), and the trace element patterns of sodium lamprophyres in northeastern Hunan are different from those of oceanic plate subduction-associated volcanic rocks, indicating that oceanic plate subduction did not have influence on the region at that time and it is an intracontinental tectonic setting.

Analysis of various tectonic features tells us that following Late Jurassic-Early Cretaceous, an intracontinental extensional tectonic setting prevailed in the eastern part of Hunan[7]. However, as for the dynamic background for the formation of the intracontinental extensional zone, there is no unity in thinking. Some researchers advocated the hypothesis of intracontinental rift and some others supported the hypothesis of intracontinental shear-extension. Trace element and isotope studies of sodium lamprophyres in northeastern Hunan suggested that there had existed intracontinental mantle plume (or hot spot) in northeastern Hunan, and the 136Ma-old sodium lamprophyres there were emplaced just prior to large-scale intracontinental extension. So it is considered that the intracontinental extension event during the post-Early Cretaceous was first caused by asthenospheric mantle upwelling under intracontin-ental mantle plume (or hot spot) tectonic conditions. Since the hypothesis of mantle plumes was put forward[32], geological workers have not only succeeded in deciphering the origin of oceanic island chain, but also widely applied this hypothesis to the origin of some continental basalts. The geochemical composition of OIB is regarded as a proxy of the magmatic composition of mantle plume in the deep interior[33]. Whether continental basalts originated from the mantle plume source region is generally determined in terms of the comparison of their chemical composition and isotopic composition. The other two major factors determining the existence of mantle plumes are the large-scale thermodynamic activities and the upwelling of asthenospheric mantle. Trace element and Sr, Nd isotope data from sodium lamprophyres in northeastern Hunan all reflect the geochemical composition of the OIB-type volcanic rocks. The Th/Hf-Ta/Hf diagram also reflects a mantle plume tectonic setting (fig. 7). Prior to the emplacement of sodium lamprophyres in northeastern Hunan, there had occurred large-scale intrusion of Early Yanshanian continental crust remelting-type granites, forming dome-shaped, hot spot-like rockbodies. Following the intrusion of sodium lamprophyres, large-scale anorogenic-type granites were formed[34]. In the Upper Cretaceous Daijiaping Formation strata exposed at Chunhuashan and Gaoqiao of Changsha, Yingjiashan and Xilou of Liuyang, two olivine basalt layers are developed with the lower layer being measured at 20 m in thickness and the upper at 10 m in thickness[8], indicating that with the intrusion of sodium lamprophyres, there occurred large-scale thermodynamic activities, as marked by the thermal events of basic and acid magmatic activities. The heat energy provided by mantle plumes first led to remelting of the ancient continental crust and then the formation of acid magmas, followed by the eruption of basic magmas. The Taiwan-Heishui geoscience transect across southeastern Hunan fully proves that there exists a low-velocity zone of mantle upwelling in the extensional thinning zone toward the lithosphere in northeastern and southeastern Hunan[35]. All this goes to show that the sodium lamprophyres in northeastern Hunan were formed in a mantle plume tectonic setting. Mantle plume activities constitute the dynamic background for the event of Cenozoic intracontinental extension.

This Yanshanian regionally tectonic event in southeastern China has involved two significantly dif-ferent tectonic stages, i.e. Early-Middle Jurassic compression-shearing and Early Cretaceous extension. Studies of basaltic rocks in southeastern Hunan also proposed that in the region of southeastern Hunan a Late Yanshanian lithospheric extensional thinning zone was developed[36]. The intrusion of sodium lam-prophyres in northeastern Hunan occurred just at the initial stage of lithospheric extension during the Late Yanshanian period, reflecting that the rocks are the product, at the time, of relaxation- extension fol-lowing crustal compression. It is indicated that there was a tectonically transformational period during the Late Yanshanian period in southeastern China, which is probably similar to the 140—85 Ma extension of the Dabieshan orogenic belt[37]. This tectonic extension event started with asthenospheric mantle upwelling and was controlled by intracontinental mantle hot spot structure.

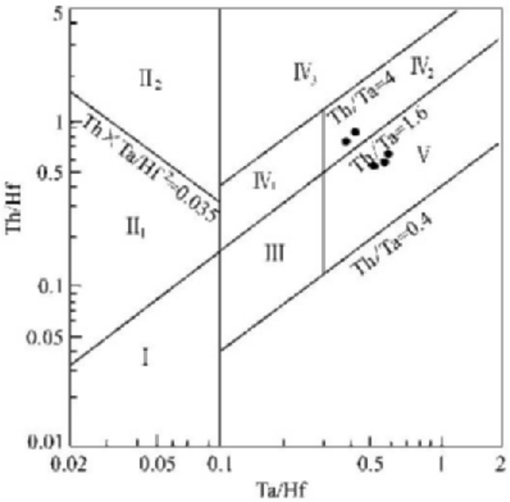

Fig. 7. Th/Hf-Ta/Hf diagram of the sodium lamprophyres in north-eastern Hunan. I, Plate divergent margin; II_1, oceanic island arc basalt field; II_2, continental margin island-arc and continental margin volcanic arc basalt field; III, T-MORB and E-MORB field; IV_1, intracontinental rift tholeiite field; IV_2, intracontinental rift alkaline basalt field; IV_3, continental extensional zone (or initial rift) basalt field; V, mantle plume basalt field. The diagram is cited from ref. [26].

There are significant differences in mineral com-position, major elements, trace elements and Sr, Nd isotopes, mantle source region and petrogenetic tec-tonic setting between sodium lamprophyres and potas-sic lamprophyres, and it is impossible for the two types of rocks to have some genetic or evolutionary connection. Whether it would imply the existence of independent magmas producing sodium lamprophyres still needs to further study. At present, three genetic models of lamprophyres have been put forward: (i) The genetic model of partial melting of fertile me-tasomatic mantle. Lamprophyres are the products of varying-degree partial melting of ε_{Sr}-high and ε_{Nd}- low mantle source regions, their formation also is related to mantle metasomatism and contamination by recycling oceanic or crustal materials, for example, the Laowangzai lamprophyres of Yunnan Province, potas-sic volcanic rocks in western Yunnan Province, K-rich volcanic rocks and lamproites in Shandong Province; (ii) The genetic model of basic magma-continental crust contamination. Mafic magmas from the mantle source regions were contaminated by crustal materials when they ascended to the lower part of the crust where hornblende was stable, forming lamprophyric magmas from the ε_{Sr}-high and ε_{Nd}-low mantle source regions, for example, the calc-alkaline lamprophyre suit in the Yilgarn area, Australia can be explained by this genetic model[38]; (iii) The crystalliza-tion-differentiation model. Magmatic crystalliza-tion-differentiation or melting differentiation would make the slightly basic components of magma enrich in the lower part of the magma chamber to form lam-prophyric magma. When the upper part was con-densed, the lamprophyric magma in the lower part would intrude along faults[9]. Unfortunately, all these genetic models are hard to explain why sodium lam-prophyres are high in ε_{Nd} and low in ε_{Sr}, why LILE are not significantly enriched and why there is no de-pletion in Ta, Nb and Ti. A more reasonable genetic model is: the primitive mantle was contaminated by fluids/melts from the asthenosphere, leading to the formation of abnormal mantle source regions charac-terized as being low in ε_{Sr} and high in ε_{Nd} and slightly enriched in LILE and Ta, Nb and Ti. It is partial melt-ing of the abnormal mantle source regions that led to the formation of sodium lamprophyres. So it can be concluded that this genetic model is a unique genetic model.

4 Conclusions

The petrochemistry and trace elements of lamprophyres in northeastern Hunan indicate that the rocks are Na-rich lamprophyres, which are quite different from calc-alkaline and potassic lamprophyres commonly seen, belonging to Na_2O-rich and TiO_2-high sodium lamprophyres. Their trace element and Sr, Nd isotope characteristics are consistent with the geochemical characteristics of those typical oce-anic island basalts (OIB).

The mantle source region of sodium lamprophyres features Nd isotope weak depletion and Sr isotope weak enrichment, being obviously different from that of calc-alkaline, potassic lamprophyres and lamproite, implicating that sodium lamprophyres have relatively independent mantle source regions. There is no sign of cognate evolution between the mantle source region of sodium lamprophyres and that of potassic lamprophyres. The mantle source region of such sodium lamprophyres was formed by the way of metasomatism of the primitive mantle at the bottom of the lithosphere by volatile-containing fluids/melts from the asthenosphere. Crustal materials seldom take part in such deep-interior mantle metasomatism. Sodium lamprophyres seem to have been derived directly from the deep-interior abnormal mantle source region, with enrichment in Na_2O and TiO_2, weak enrichment in LILE, Ta, Nb and LREE and weak depletion in K and Sr. This is a unique genetic model of lamprophyres, i.e. lamprophyres were formed from metasomatism of the primitive mantle by volatile-containing fluids/melts from the asthenosphere.

Sodium lamprophyres were formed within the continent and their trace elements and Sr, Nd isotopes reflect that during the Early Cretaceous the region of northeastern Hunan was not situated on the active continental margin of the Pacific plate, but, in a mantle hot spot tectonic setting with the characteristics of mantle plumes. Intracontinental mantle hot spots (or mantle plumes) led to post-Early Cretaceous large-scale intracontinental extension in northeastern Hunan. The formation of sodium lamprophyre dykes may be indicative of the beginning of early mantle upwelling and extension (136.61 Ma) in northeastern Hunan, reflecting that sodium lamprophyres are the products during the relaxation-extension period fol-lowing crustal compression. It is indicated that during the Late Yanshanian period there occurred a tectonic transformation from compression to extension in southeastern China, and it is also reflected that early intracontinental extension in northeastern Hunan Province is an initiative tectonic event that resulted from asthenospheric mantle upwelling.

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