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Geochemistry of late Mesozoic lamprophyre dykes from the Taihang Mountains, north China, and implications for the sub-continental lithospheric mantle

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Abstract – Many late Mesozoic lamprophyre dykes occur in the Taihang Mountains (north China). These lamprophyres are rich in large ion lithophile elements (e.g. Rb, Sr, Ba and K) and light REE, and have highly differentiated REE patterns. They show large but regular variations in chemical and Nd–Sr isotopic compositions. All these suggest that the lamprophyres were produced from differentiation of a parental magma, coupled with contamination by lower crust. The parental magma was derived from melting of a long-term enriched sub-continental lithospheric mantle source as is indicated by the highly enriched isotopic signatures of the lamprophyres. Mantle enrichment in the area was probably produced by interaction of volatile-rich melts released from the asthenosphere with the above lithosphere in middle Proterozoic times.

Keywords: geochemistry, lamprophyres, lithosphere, Mesozoic, northern China.

1. Introduction

Generally, the presence of Archaean crustal rocks has been associated with the existence of a thick Archaean mantle lithosphere keel, as in the cases of the South African craton (Boyd & Gurney, 1986) and the Western Australian craton (Anderson, Tanimoto & Zhang, 1992). However, a thick cratonic keel does not underlie the eastern part of the North China craton (Ma, 1987; Liu, 1992; Xu *et al*. 1996; Xu *et al*. 1998; Menzies & Xu, 1998; Griffin *et al*. 1998). This has prompted many recent studies documenting the evolution of the lithospheric mantle underlying the area (e.g. Menzies, Fan & Zhang, 1993; Menzies & Xu, 1998; Fan *et al*. 2000; Zheng *et al*. 2001). The eastern North China craton is thought of as an important natural laboratory for the study of major lithospheric processes. Understanding of these processes in eastern China may provide analogues that can help to interpret lithospheric processes in other regions and time periods (Griffin *et al*. 1998). Geophysical and geochemical data consistently indicate that the old (Archaean?), cold lithospheric mantle beneath the eastern North China craton was significantly consumed, and a young, hot lithosphere with oceanic affinity formed during the process of Mesozoic to Cenozoic intra-continental extension. However, the exact geochemical signature of the lithosphere remains at issue. Lamprophyres are generally accepted to be produced by small degree melting of enriched sub-continental lithospheric mantle (McKenzie, 1989; Thompson *et al*. 1989; Gibson *et al*. 1995; Fowler & Henney, 1996). Such melts thus preserve the best evidence for the composition of sub-continental lithospheric mantle, particularly for the origin of mantle enrichment. In this paper, we present elemental and Sr–Nd isotopic data for the late Mesozoic lamprophyres from the Taihang Mountains (north China), and compare them with those for lamprophyres from the Jiaodong Peninsula (Fig. 1) to document the geochemical characteristics of the lithospheric mantle underlying the eastern North China craton.

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2. Geological setting and petrography

The basement rocks of the North China craton are Archaean to Early Proterozoic gneisses of amphibolite to granulite facies (Jahn *et al*. 1988). The North China craton was stabilized by early Proterozoic time, as indicated by thick sequences of mid- to late Proterozoic quartzites and limestones; much of it remained stable up to Triassic time, with sedimentary sequences dominated by shallow-water and subaerial sediments. However, much of the craton has been remobilized since late Mesozoic time, with the development of large sedimentary basins and intensive magmatism that occurred mainly to the east of a north–south gravity lineament (Fig. 1; Griffin *et al*. 1998; Fan *et al*. 2000). The Mesozoic magmatism is characterized by intrusion of voluminous granitoids and related rocks and widespread volcanism throughout the eastern North China craton (Fig. 1). These rocks were cut by minor,

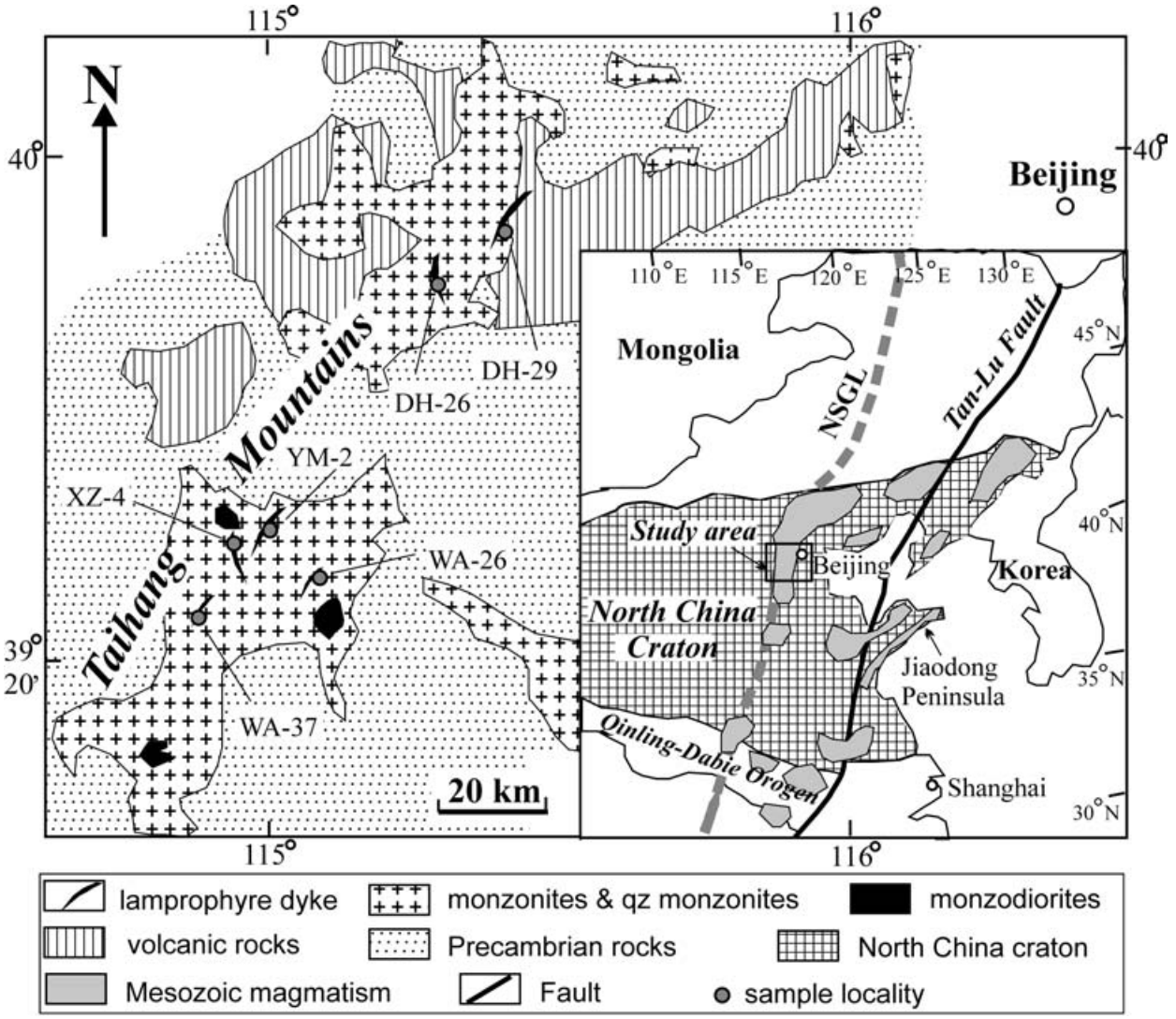

Figure 1. Geological sketch map of the Taihang Mountains (North China). Inset shows distribution of the Mesozoic magmatic rocks in the eastern North China craton. NSGL – north–south gravity lineament (Griffin *et al*. 1998). See text for details.

but widespread, late stage calc-alkaline lamprophyres that occur as dykes or small intrusions. The Taihang Mountains lie to the west of Beijing and comprise mainly monzonites–monzogranites and related mafic rocks. Davis *et al*. (1998) reported zircon U–Pb ages of 130–145 Ma for the granitoids. Lamprophyres in this region were dated at *c*. 120 Ma using Ar–Ar and Rb–Sr methods (Shao *et al*. 2001). Similarly, lamprophyre dykes in the Jiaodong Peninsula show comparable Ar–Ar ages of 119–125 Ma (Qiu *et al*. 1997; Xu & Xu, 2000). The Tan-Lu Fault is a major wrench fault system that cuts across the eastern North China craton (Fig. 1).

Principal rock types of the lamprophyres in the Taihang area, and in the Jiaodong Peninsula as well, are kersantites and spessartites. They are porphyritic in mafic minerals, typically biotite-phlogopite and hornblende, with minor secondary chlorite. Groundmass phases are varying amounts of plagioclase, apatite, minor K-feldspar, Fe–Ti oxides, and mica and hornblende microphenocrysts.

3. Analytical methods

Chemical analyses were done at the Chinese Academy of Geological Sciences (Beijing). Major elements were analysed using X-ray fluorescence (XRF) methods with analytical uncertainties $< 5\%$. Trace elements were analysed by inductively coupled plasma-mass spectrometry (ICP-MS). Analytical uncertainties are 10% for elements with abundances < 10 ppm, and around 5% for those > 10 ppm.

Nd–Sr isotopic analyses were performed at the Institute of Geology and Geophysics, Chinese Academy of Sciences (Beijing). Samples were dissolved using acid ($HF + HClO_4$) in sealed Savillex® beakers on a hot plate for one week. Separation of Rb, Sr and light REE was done through a cation-exchange column

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Table 1. Chemical and Nd–Sr isotopic analyses for lamprophyres from the Taihang Mountains

Sample no.	XZ4	WA-26	YM-2	WA-37	DH-26	DH-29
Major elements (wt %)						
SiO_2	47.39	56.37	46.61	56.09	58.63	63.6
TiO_2	1.67	1.26	1.75	1.22	0.88	0.68
Al_2O_3	17.81	16.07	17.38	15.38	16.76	16.02
FeO	10.29	7.62	10.08	7.18	7.07	5.34
MnO	0.17	0.15	0.17	0.10	0.11	0.08
MgO	5.30	4.18	6.20	5.37	2.99	1.65
CaO	7.20	5.91	8.37	5.29	5.63	3.45
Na_2O	4.25	5.63	3.76	4.28	3.74	4.13
K_2O	4.15	2.50	3.97	2.91	3.02	3.47
P_2O_5	1.28	0.45	1.06	0.53	0.29	0.20
LOI	0.54	0.51	1.00	1.84	1.04	0.98
Total	100.05	100.65	100.35	100.19	100.16	99.60
Trace elements (ppm)						
Rb	106	53.2	110	55	74	156
Sr	2878	1198	1593	1109	858	505
Ba	4039	1157	4965	1604	977	829
Zr	207	153	209	169	155	224
Hf	5.4	4.6	5.7	4.9	5.5	7.8
U	2.8	2.5	2.4	2.8	1.5	3.3
Th	12	4.9	10	15	9.1	16
Pb	8.7	9.1	10	8.1	7.5	12
Nb	71	12	78	18	9	12
Ta	3.2	0.6	3.7	1.1	0.9	1.2
V	183	157	202	134	125	76
Y	14.6	13.0	19.3	11.8	14.0	11.1
Cr	2.6	84	38	110	15	8.2
Co	28	17	30	25	16	8.1
Ni	21	25	33	83	9.1	6
Zn	96	90	94	71	61	59
La	127.70	47.36	103.50	68.41	37.05	44.52
Ce	245.00	100.80	197.60	127.8	73.6	87.2
Pr	20.17	10.50	21.66	12.1	7.5	7.39
Nd	79.95	41.79	78.99	48.5	28.94	31.38
Sm	11.62	7.42	10.23	7.93	5.16	5.39
Eu	2.89	1.79	2.64	2.18	1.42	1.09
Gd	8.00	5.15	8.86	6.2	4.33	4.77
Tb	0.90	0.62	1.07	0.79	0.66	0.63
Dy	4.03	3.38	4.52	3.25	3.12	2.7
Ho	0.69	0.60	0.82	0.55	0.59	0.47
Er	1.80	1.61	2.39	1.47	1.59	1.31
Tm	0.20	0.18	0.30	0.2	0.21	0.18
Yb	1.40	1.07	1.76	1.24	1.34	1.02
Lu	0.21	0.18	0.29	0.21	0.21	0.17
Eu/Eu*	0.93	0.90	0.86	0.96	0.93	0.67
$(La/Yb)_N$	60.23	29.23	38.83	36.43	18.26	28.82
$^{87}Sr/^{86}Sr$	0.705560	0.707045	0.705384	0.705790	0.706659	0.708129
$2\sigma m$	14	15	15	16	20	11
$I_{Sr}(120)$	0.70523	0.70683	0.70520	0.70554	0.70623	0.70659
$^{143}Nd/^{144}Nd$	0.512010	0.511787	0.512124	0.512120	0.511884	0.511801
$2\sigma m$	10	10	9	7	9	6
$\varepsilon_{Nd}(0)$	− 12.3	− 16.6	− 10	− 10.1	− 14.7	− 16.3
$\varepsilon_{Nd}(120)$	− 10.5	− 15.2	− 8.3	− 8.6	− 13.4	− 14.9
$T_{DM}(Ga)$	1.5	1.88	1.42	1.36	1.84	1.87

(packed with Bio-Rad AG50Wx8 resin). Sm and Nd were further purified using a second cation-exchange column, conditioned and cleaned with dilute HCl.

Mass analyses were performed using a multi-collector VG354 mass spectrometer as described by Qiao (1988) and Yang & Zhou (2001). $^{87}Sr/^{86}Sr$ ratios were normalized against $^{86}Sr/^{88}Sr = 0.1194$. $^{143}Nd/^{144}Nd$ ratios were normalized against $^{146}Nd/^{144}Nd = 0.7219$. $^{87}Sr/^{86}Sr$ ratios were adjusted to NBS-987 Sr standard = 0.710250, and the $^{143}Nd/^{144}Nd$ ratios to La Jolla Nd standard = 0.511860. The uncertainty in concentration analyses by isotopic dilution is 1–2% for Rb, 0.5% for Sr, and 0.2–0.5% for Sm and Nd depending upon concentration levels. Procedural blanks are: Rb = 100 pg, Sr = 400 pg, Sm = 50 pg and Nd = 50–100 pg.

4. Results

Chemical and isotopic analyses for six samples are presented in Table 1. The lamprophyres exhibit a large variation in chemical compositions, with SiO_2 = 46.6–63.6%, CaO = 8.37–3.45%, MgO = 6.2–1.65%, TiO_2 = 1.75–0.68%, and P_2O_5 = 1.28–0.2%.

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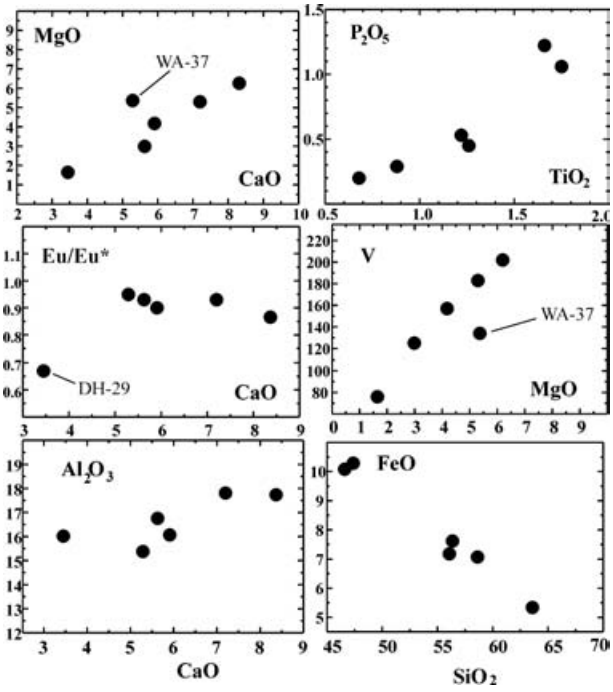

Figure 2. Plots of CaO–MgO, TiO_2–P_2O_5, CaO–Eu/Eu*, MgO–V, CaO–Al_2O_3 and SiO_2–FeO, showing regular variation in chemical compositions for the Taihang lamprophyres. See text for details.

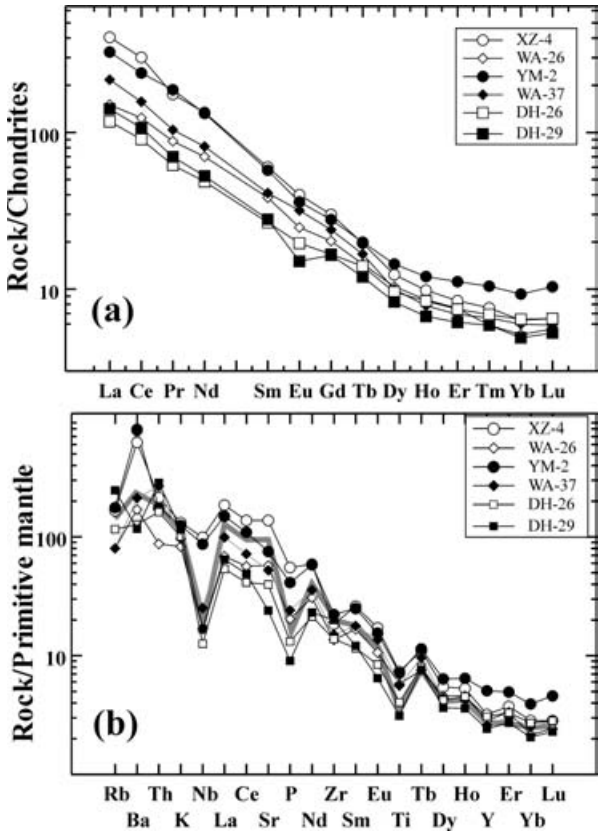

Figure 3. (a) Chondrite-normalized REE patterns for the Taihang lamprophyres. Chondrite values are from Masuda, Nakamura & Tanaka (1973), further divided by 1.2. (b) Primitive mantle (PM)-normalized spidergrams. PM values are from Sun & McDonough (1989). Also shown for comparison is the coeval lamprophyre from Jiaodong area (coarse grey line; Qiu *et al*. 1997).

Of particular note is that the lamprophyres show systematic variation in plots of CaO–MgO, CaO–Al_2O_3, SiO_2–FeO, TiO_2–P_2O_5 and MgO–V (Fig. 2), suggesting that they are probably products of differentiation from a parental magma. This is in agreement with their similar REE patterns that are significantly differentiated, with $(La/Yb)_N = 18.3–60.2$ and negligible Eu anomalies (except DH-29; Fig. 3a). Moreover, the lamprophyres are highly enriched in large ion lithophile elements (LILE), such as Ba, Sr, K and Rb, as well as LREE (Table 1; Fig. 3b), but have low U abundance (1.5–3.3 ppm). Isotopically, they have low and varied ε_{Nd} values (−8.3 to −15.2) and moderate high I_{Sr} ratios (0.7052 to 0.7068) at their intrusion age of 120 Ma (Table 1), with ε_{Nd} and I_{Sr} inversely correlated (Fig. 4). In addition, the isotopic compositions of the lamprophyres fall outside the ranges for oceanic basalt, ruling out an asthenospheric or mantle plume source.

5. Discussion

The positive correlations in plots of CaO–MgO, MgO–V and SiO_2–FeO suggest that fractionation of ferromagnesian phases such as amphibole and biotite is significant during magma evolution. Fractionation of apatite and Fe–Ti oxides also played an important role as is indicated by the positive correlation between P_2O_5 and TiO_2. WA-37 departs from the evolution trends in the CaO–MgO and MgO–V diagrams, due probably to amphibole cumulates as is confirmed by petrographical observation. This is compatible with the relatively high Cr (110 ppm), Ni (83 ppm) and MgO (5.37%) of the sample, compared with other lamprophyres at the same SiO_2 level. Abundance of Al_2O_3 decreases slightly with decreasing CaO, suggesting that removal of plagioclase during magma evolution is subordinate. This is supported by the flat trend shown by most samples in the plot of CaO v. Eu/Eu*, with the exception of DH-29 (Fig. 2) which probably underwent significant fractionation of plagioclase during magma ascent, consistent with the negative Eu anomaly for the sample in the REE patterns (Fig. 3a). However, magma evolution did not take place in a closed system, as is indicated by the varied but inversely correlated I_{Sr} and $\varepsilon_{Nd}(T)$ values of the lamprophyres (Fig. 4). Lower crustal (LCC) contamination appears to have played an important role during magma evolution, as most data points extend toward the field for the lower continental crust. Nevertheless, WA-37 seems to have unexpectedly high $\varepsilon_{Nd}(T)$ (−8.6; comparable with −8.3 for the most primitive YM-2), considering that it has relatively high I_{Sr} (0.70554) and silica

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content (56.09%). This is probably accounted for by upper crustal (UCC) contamination, because the upper continental crust has $\varepsilon_{Nd}(T)$ value (about −10) similar to, but I_{Sr} ratio (>0.715) much higher than, WA-37 (Taylor & McLennan, 1985). Contamination by upper continental crust would not notably change the Nd isotopic compositions of WA-37. To determine the proportions of crustal components in the source, we need to know the isotopic compositions of the magma that is parental to the lamprophyres.

YM-2 is the most basic of the lamprophyres, as is suggested by the highest MgO (6.2%), CaO (8.37%) and TiO_2 (1.75%) and lowest SiO_2 (46.61%), and by the most 'primitive' isotopic compositions ($I_{Sr} = 0.7052$, $\varepsilon_{Nd}(120\ Ma) = -8.3$). The relatively high MgO and low SiO_2, and the low $\varepsilon_{Nd}(120\ Ma)$ value of the sample, which is considerably less radiogenic than that of depleted asthenospheric mantle at this time ($\varepsilon_{Nd} = +5$: Basu *et al*. 1991), suggest a long-term enriched sub-continental lithospheric mantle origin for it, and thus for all the lamprophyres of this study. However, YM-2 is not primitive mantle-derived melt, because it has relatively low compatible Cr (38 ppm), Co (30 ppm) and Ni (33 ppm), implying that it experienced significant fractionation of olivine and pyroxene during ascent to crustal level. In these circumstances, we must evaluate the influence of lower crustal contamination on the geochemistry of the sample, because enriched isotope and element signatures could be derived from both crustal contamination and enriched sub-continental lithospheric mantle sources. We think that crustal contamination is not a viable option to explain the enriched isotope and trace element geochemistry of the lamprophyre (YM-2), because the lamprophyre has abundances of LIL elements such as Rb (110 ppm), Sr (1593 ppm), Ba (4965 ppm) and K (3.97%) and of LREE much higher than lower crust (Taylor & McLennan, 1985). Thus, the high Sr and Nd (79 ppm) make the Sr–Nd isotopic compositions of the lamprophyre insensitive to crustal contamination. Calculations using a simple mixing model (Langmuir *et al*. 1978) indicate that 20% (probably the maximum in view of the low SiO_2 of YM-2) of lower crustal contamination would lower the ε_{Nd} value by 1.2 units and raise I_{Sr} by 0.00005 for the isotopic compositions of YM-2, assuming that the lower crust of the North China craton has Sr = 300 ppm, Nd = 24 ppm, $I_{Sr} = 0.708$ and $\varepsilon_{Nd}(120\ Ma) = -25$ (Jahn *et al*. 1988). Therefore, crustal contamination was a minor contributor to the enriched isotopic and elemental geochemistry of the lamprophyre. In other words, YM-2 nearly preserves the isotopic characteristics of the enriched sub-continental lithospheric mantle source, and thus of the parental magma of the lamprophyres. Isotopic modelling using an AFC (coupled assimilation and fractional crystallization) process (DePaolo, 1981) suggests that the proportions of lower crustal components incorporated in the source of other lamprophyres are less than 36%, assuming YM-2 represents the parental magma (Fig. 4).

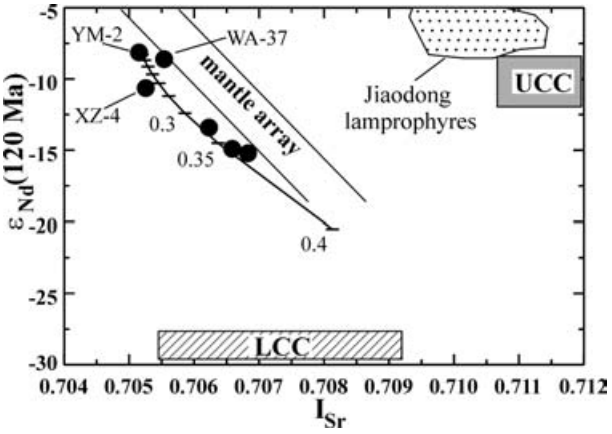

Figure 4. Sr–Nd isotopic ratio diagram for lamprophyres from the Taihang Mountains. Also shown for comparison are published Sr–Nd isotopic data for the Jiaodong lamprophyres of similar age (Xu & Xu, 2000; Qiu *et al*. 1997). Fields for the upper continental crust (UCC) and lower continental crust (LCC) are from Jahn *et al*. (1988). Two end-members used for AFC isotopic modelling are the local lower crust, with Sr = 300 ppm, $I_{Sr} = 0.708$, Nd = 24 ppm, $\varepsilon_{Nd}(T) = -25$ (Jahn *et al*. 1988), and the least contaminated lamprophyre (YM-2). Other parameters used include r = 0.29, $D_{Nd} = 1$ and $D_{Sr} = 1.4$. The numbers beside the calculated curve represent the proportions of lower crustal components involved during magma ascent.

The enriched isotopic signatures of the most primitive lamprophyres (YM-2, and, to a lesser extent, XZ-4) require significant time-integrated incompatible element enrichment for their mantle source. This is manifest in their high Ba, Sr, Rb, K and LREE abundances. The isotopic compositions of the lithospheric mantle beneath the Taihang area resemble those for EM1 (enriched mantle with low $^{143}Nd/^{144}Nd$ and moderate high $^{87}Sr/^{86}Sr$; Fig. 4) as defined by Zindler & Hart (1986), which was strongly enriched in LREE and, to a lesser extent, Rb relative to HREE and Sr by ancient mantle metasomatism. The relatively low U abundances (1.5–3.3 ppm) of the lamprophyres are consistent with their generation from an EM1-like mantle source (Hofmann, 1997). An EM1-like source is also documented by the Cenozoic basalts in eastern China (Tatsumoto *et al*. 1992).

The origin of mantle enrichment remains highly debatable. Two models have been proposed to interpret mantle enrichment: (1) metasomatism by melts/fluids released from the subducting slab (Maury, Defant & Joron, 1992), (2) interaction between lithospheric mantle and volatile-rich, low-density melts that have migrated from the asthenosphere and accumulated in the above lithosphere (McKenzie, 1989; Gibson *et al*. 1995). The two most primitive lamprophyres (YM-2 and XZ-4) show minor negative Nb, and, to a lesser extent, P and Ti, anomalies in the spidergrams (Fig. 3b), in contrast to the significant depletion of Nb (and P

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and Ti) shown by other lamprophyres. The original Nb (and P and Ti) anomalies in the spidergrams for the two samples are expected to be smaller or even absent, because they have undergone significant fractionation of pyroxene and amphibole (and apatite?), which tends to reduce significantly the Nb, Ti and P abundances. We suggest that the highly negative Nb (and P and Ti) anomalies of the evolved lamprophyres resulted probably from crustal contamination as is required by their isotope data, and that the minor Nb anomalies shown by YM-2 and XZ-4 may represent the lithospheric mantle source signature. If this is correct, the mantle enrichment may be produced by interaction of asthenospheric mantle-derived melts/fluids with lithospheric mantle, rather than by subduction-related processes. The EM1-like isotopic signatures could have been developed through time-integrated effects of the metasomatic event. In contrast, the least crustally contaminated lamprophyres of similar ages (Qiu *et al*. 1997) from the Jiaodong Peninsula, near and to the east of the Tan-Lu Fault (Fig. 1), show distinct isotopic signatures, with $\varepsilon_{Nd}(120\ Ma) = -2$ to -9 and $I_{Sr} > 0.710$ (Fig. 4; Xu & Xu, 2000; Qiu *et al*. 1997), suggesting that they originated from a sub-continental lithospheric mantle source reminiscent of EM2 (enriched mantle with moderate low $^{143}Nd/^{144}Nd$ and high $^{87}Sr/^{86}Sr$; Zindler & Hart, 1986). Taking into account their significant negative Nb, Ti and P anomalies in the spidergrams (Fig. 3b), the enrichment of the mantle source beneath the Jiaodong Peninsula was probably produced during ancient subduction processes, in which significant amounts of recycled material of continental origin were involved (Hofmann, 1997). The reason for the different origins of mantle enrichment on both sides of the Tan-Lu Fault is not clear. Upwelling of the asthenospheric mantle, triggered by intensive intra-continental extension in the Mesozoic (Menzies, Fan & Zhang, 1993; Fan *et al*. 2000), probably provided the heat for melting the enriched portions of the sub-continental lithospheric mantle underlying the North China craton.

6. Conclusions

The Taihang lamprophyres were produced by low degree melting of a long-term incompatible element-enriched mantle source, followed by coupled fractionation of ferromagnesian phases and lower crustal contamination during magma ascent. Mantle enrichment may have occurred in middle Proterozoic time during the processes of interaction between asthenosphere-derived melts/volatile compounds and lithospheric mantle.

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References

ANDERSON, D. L., TANIMOTO, T. & ZHANG, Y. 1992. Plate tectonics and hotspots: the third dimension. *Science* **256**, 1645–50.

BASU, A. R., WANG, J. W., HUANG, W. K., XIE, G. H. & TATSUMOTO, M. 1991. Major element, REE, and Pb, Nd and Sr isotopic geochemistry of Cenozoic volcanic rocks of eastern China: implications for their origin from suboceanic-type mantle reservoirs. *Earth and Planetary Science Letters* **105**, 149–69.

BOYD, F. R. & GURNEY, J. 1986. Diamonds and the African lithosphere. *Science* **239**, 472–7.

DAVIS, G. A., QIAN, X. L., ZHENG, Y. D. & WANG, C. 1998. Mesozoic deformation and plutonism in the Yunmeng Shan: a Chinese metamorphic core complex north of Beijing. In *The Tectonic Evolution of Asia* (eds A. Yin and T. M. Harrison), pp. 253–80. Cambridge University Press.

DEPAOLO, D. J. 1981. Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization. *Earth and Planetary Science Letters* **53**, 189–202.

FAN, W. M., ZHANG, H. F., BAKER, J., JARVIS, K. E., MASON, P. R. D. & MENZIES, M. A. 2000. On and off the north China craton: where is the Archean keel? *Journal of Petrology* **41**, 933–50.

FOWLER, M. B. & HENNEY, P. J. 1996. Mixed Caledonian appinite magmas: implications for lamprophyre fractionation and high Ba–Sr granite genesis. *Contributions to Mineralogy and Petrology* **126**, 199–215.

GIBSON, S. A., THOMPSON, R. N., LEONARDOS, O. H., DICKIN, A. P. & MITCHELL, J. G. 1995. The late Cretaceous impact of the Trindade mantle plume: evidence from large-volume, mafic, potassic magmatism in SE Brazil. *Journal of Petrology* **36**, 189–229.

GRIFFIN, W. L., ZHANG, A., O'REILLY, S. Y. & RYAN, C. G. 1998. Phanerozoic evolution of the lithosphere beneath the Sino-Korean craton. In *Mantle Dynamics and Plate Interactions in East Asia* (eds M. F. J. Flower, S. L. Chung, C. H. Lo and T. Y. Lee), pp. 107–26. American Geophysical Union, Geophysical Monograph no. 27.

HOFMANN, A. W. 1997. Mantle geochemistry: the message from oceanic volcanism. *Nature* **385**, 219–29.

JAHN, B. M., AUVRAY, B., SHEN, Q. H., LIU, D. Y., ZHANG, Z., DONG, Y. J., YE, X. J., ZHANG, Q. Z., CORNICHET, J. & MACE, J. 1988. Archean crustal evolution in China: the Taishan complex, and evidence for juvenile crustal addition from long-term depleted mantle. *Precambrian Research* **38**, 381–403.

LANGMUIR, C. H., VOCKE, R. D., HANSON, G. N. & HART, S. R. 1978. A general mixing equation with applications to Icelandic basalts. *Earth and Planetary Science Letters* **37**, 380–92.

LIU, D. Y. 1992. Seismic tomography in China. *International Geological Congress, Tokyo* **3**, 668.

MA, X. Y. 1987. *Lithospheric dynamics map of China and adjacent seas (1:4,000,000) and explanatory notes.* Beijing: Geological Publishing House.

MASUDA, A., NAKAMURA, N. & TANAKA, T. 1973. Fine structures of mutually normalized rare-earth patterns of chondrites. *Geochimica et Cosmochimica Acta* **37**, 239–48.

MAURY, R., DEFANT, C. & JORON, M. J. 1992. Metasomatism of the sub-arc mantle inferred from trace elements in Philippines xenoliths. *Nature* **360**, 661.

McKenzie, D. P. 1989. Some remarks on the movement of small melt fractions in the mantle. *Earth and Planetary Science Letters* **95**, 53–72.

Menzies, M. A., Fan, W. M. & Zhang, M. 1993. Palaeozoic and Cenozoic lithoprobes and loss of > 120 km of Archean lithosphere, Sino-Korean craton, China. In *Magmatic Processes and Plate Tectonics* (eds H. M. Prichard, T. Alabaster, N. B. W. Harris and C. R. Neary), pp. 71–81. Geological Society of London, Special Publication no. 76.

Menzies, M. A. & Xu, Y. G. 1998. Phanerozoic evolution of the lithosphere beneath the Sino-Korean craton. In *Mantle Dynamics and Plate Interactions in East Asia* (eds M. F. J. Flower, S. L. Chung, C. H. Lo and T. Y. Lee), pp. 155–65. Geophysical Monograph: American Geophysical Union, no. 27.

Qiao, G. 1988. Normalization of isotopic dilution analyses – a new program for isotope mass spectrometric analysis. *Scientia Sinica (ser. A)* **31**, 1263–8.

Qiu, J. S., Wang, D. Z., Zeng, J. H. & McInnes, B. I. A. 1997. Study on trace element and Nd–Sr isotopic geochemistry of the Mesozoic K-rich volcanic rocks and lamprophyres in Shandong province. *Geological Journal of China Universities* **3**, 384–95 (in Chinese with English abstract).

Shao, J., Li, X. H., Zhang, L. Q., Mu, B. L. & Liu, Y. L. 2001. Geochemical constraints on the petrogenesis of the Mesozoic bi-modal dyke swarms in Nankou-Guyaju, NW Beijing. *Geochemica* **30**, 517–24 (in Chinese with English abstract).

Sun, S. S. & McDonough, W. E. 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In *Magmatism in the Ocean Basins* (eds A. D. Saunders and M. J. Norry), pp. 313–45. Geological Society of London, Special Publication no. 42.

Tatsumoto, M., Basu, A. R., Huang, W. K., Wang, J. W. & Xie, G. H. 1992. Sr, Nd, and Pb isotopes of ultramafic xenoliths in volcanic rocks of eastern China: enriched components EM1 and EM2 in subcontinental lithosphere. *Earth and Planetary Science Letters* **113**, 107–28.

Taylor, S. R. & McLennan, S. M. 1985. *The Continental Crust: Its Composition and Evolution.* Oxford: Blackwell, Geoscience Texts, pp. 91–2

Thompson, R. N., Leat, P. T., Dickin, A. P., Morrison, M. A., Hendry, G. L. & Gibson, S. A. 1989. Strongly potassic mafic magmas from lithospheric mantle sources during continental extension and heating: evidence from Miocene minettes of northwest Colorado, U.S.A. *Earth and Planetary Science Letters* **98**, 139–53.

Xu, H. & Xu, G. P. 2000. Geochemical characteristics of the lamprophyres from Jiaodong: implications for petrogenesis. *Acta Petrologica et Mineralogica* **19**, 36–43 (in Chinese with English abstract).

Xu, X., O'Reilly, S. Y., Griffin, W. L. & Zhou, X. M. 1998. The nature of the Cenozoic lithosphere at Nushan, eastern China. In *Mantle Dynamics and Plate Interactions in East Asia* (eds M. F. J. Flower, S. L. Chung, C. H. Lo and T. Y. Lee), pp. 167–96. American Geophysical Union, Geophysical Monograph no. 27.

Xu, Y. G., Menzies, M. A., Mattery, D. P. & Lowry, D. 1996. The nature of the lithospheric mantle near the Tancheng-Lujiang wrench fault, China: an integration of texture, chemistry and isotopes. *Chemical Geology* **134**, 67–81.

Yang, J. H. & Zhou, X. H. 2001. Rb–Sr, Sm–Nd, and Pb isotope systematics of pyrite: implications for the age and genesis of lode gold deposits. *Geology* **29**, 711–14.

Zheng, J. P., O'Reilly, S. Y., Griffin, W. L., Lu, F., Zhang, M. & Pearson, N. J. 2001. Relict refractory mantle beneath the eastern North China block: significance for lithosphere evolution. *Lithos* **57**, 43–66.

Zindler, A. & Hart, S. R. 1986. Chemical geodynamics. *Annual Review of Earth and Planetary Sciences* **14**, 493–571.